Designing a tool for emission forecasting at construction projects

Bachelor Thesis – Darryll Klein Koerkamp

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DURA VERMEER

University of Twente

Bachelor thesis

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Management summary

At large construction projects, a lot of emissions are created which have a negative environmental impact. Construction companies like Dura Vermeer want to reduce this negative environmental impact. Next to this, they want to be ahead of stricter regulations regarding their emissions.

Dura Vermeer has the ambition to achieve these goals. However, they do not know how to get there and they lack the tools. That is why an emission forecasting tool based on the needs of Dura Vermeer as a stakeholder needs to be developed. This research answers the question:

"How to design an emission forecasting tool that satisfies the ease of use, future-proof, accuracy, extent and detail, so that construction companies can investigate where emissions can be reduced and show they meet regulations for emissions at construction projects?"

The research contains three important steps to answer this research question. The first step is determining the requirements of Dura Vermeer for an emission forecasting tool. Secondly, the relevant input variables are determined and linked. Based on this the emission forecasting tool is created. Finally, the emission forecasting tool is validated on the requirements set at the first step.

From a total of six interviewees with different employees of Dura Vermeer, four of the most important requirements are derived. These are 'ease of use', 'accuracy', 'simulation possibility' and 'future proof'. The emission forecasting model should meet these requirements. Other relevant requirements are not considered essential for the first version of the model that is created in this research.

The interviewees regard the construction equipment at the construction site as the most important cause of emissions at construction projects. Since the initial emission forecasting model can only address a limited extent of all the causes at the beginning, a specific focus of the model is to investigate the construction equipment. Literature and old emission regulation calculations of Dura Vermeer confirm these machines are a big polluter.

This research provides an emission forecasting tool for construction equipment. The calculations are based on interviewee information in combination with sources from literature. The tool combines emission regulation calculations (AERIUS, 2020) with Dura Vermeers work package division and a construction equipment database.

The tool shows what data is needed in which detail to make the emission forecasts. However, needed input data is often unavailable or very hard to gather. This means that trade-offs need to be made between the important requirements. The tool cannot be easy to use and make accurate forecasts at the same time. Als the larger the extent of simulation possibilities, the harder it is to update the model to let it remain future proof.

This first version of the emission forecasting tool is not very suitable to directly achieve the goals of the stakeholders. However, it brings interesting insights in how the goals can be achieved and what data is needed to do this. This way the research contributes to construction companies as stakeholders. Now companies know what they regard important, what important variables are, how emission forecasts are created and which data should be collected to make better forecasts in the future.

Preface

Well there we are. This is my bachelor thesis for my Bachelor Industrial Engineering and Management at the University of Twente.

After a (way too) long path of struggling to finish this research, I can say I learned a lot. About independent working, expectation management, self-discipline, academic research and all that stuff. I cannot say I liked all of it, but I think I had to go through it some time in my life as a student.

I want to give a special thanks to Guido van Capelleveen for always being available as my supervisor to help me set the next step in my research. Always quickly available for a meeting and with good advice. Also thanks for letting me make my own mistakes regarding the planning (to many times). That was something I had to do myself. Thank you!

Next to this also a thanks to Bouwe van der Tuuk for always being a positive and involved supervisor from Dura Vermeer. Unfortunately we did not spend that many days at the office, however you helped me when necessary and let me free to do my own research. Thanks!

Last, a great thanks to the rest of the people who supported me in this (by bringing coffee or whatsoever).

Darryll Klein Koerkamp

Contents

Glossary of terms

ANWB = Royal Dutch Tourist Association (Koninklijke Nederlandse Toernistenbond)

MPG = Environmental Performance Buildings (Milieu Prestatie Gebouwen)

NOx = Nitrogen oxides

CO2 = Carbon dioxide

BIM = Building Information Model (Bouwwerk Informatie Model)

EPC = Energy Performance Coefficient (energieprestatiecoëfficiënt)

KPI = Key Performance Indicator

MPG = Environmental Performance Buildings (Milieu Prestatie Gebouwen)

NOx = Nitrogen oxides

RIVM = National Institute for Health and Environment (Rijksinstituut voor Volksgezondheid en Milieu)

1 Introduction

This research is conducted as the final assignment for the bachelor Industrial Engineering and Management at the University of Twente. It is executed at the company Dura Vermeer Bouw Hengelo BV. The topic of the research regards the sustainability of construction companies, in particular the emissions generated at construction projects.

This chapter introduces the different stakeholders of this research. It also explains the problem investigation and the choice of the core problem. Furthermore, it provides a theoretical framework for the research.

1.1 The stakeholders

1.1.1 Dura Vermeer Bouw Hengelo BV

Dura Vermeer Bouw Hengelo BV (DVBH) is one of the business units of the large-size construction company Dura Vermeer. Dura Vermeer is active throughout the Netherlands and they have the ambition to be in the top 3 of innovative construction companies. Its core values are safety, quality and reliability.

The four strategic priorities of Dura Vermeer are:

1. Increasing the focus on customer and market
2. Strengthening the organization
3. Improving financial results
4. Innovative ambitions

The fourth strategic priority contains three main topics:

1. Digitalization
2. Sustainability
3. (Further) innovation

Next to the general strategic priorities, DVBH focuses its logistics on four aspects:

1. Forecasting
2. Execution
3. Control
4. Improvement

1.1.2 Stakeholders within Dura Vermeer

Within Dura Vermeer, there are several stakeholders that could be involved with my research. A construction projects takes a lot of time and emissions are created at different stages in different ways. During the whole process, many people control different parts of the project. Because many different people are involved in different ways of emission creation, they are all stakeholders.

From a higher perspective, the directors are responsible for managing the strategic priorities of Dura Vermeer, including sustainability. Especially the director of preparations of the projects could be of importance.

Every construction project has a project leader, who is responsible for the entire project from the approval of permits until project completion. This person coordinates the global planning, important contacts, financial situation and other preconditions. The project leader should have the knowledge about who is in control of which practical decisions that influence emissions of construction projects. On the other hand, he can also see if findings of my research are applicable in the process in practice.

Next to this, every construction project has a construction site manager.This is someone who leads the day-to-day business on the construction site. This person knows a lot about the practical situation on the ground and could be important by measuring real-world data at construction projects.

DVBH also has a logistics manager who focusses on optimizing processes in the construction sector on different levels. The goals are accurate forecasting, manageable execution, measurable control and continues improvement. These goals are very relevant regarding the topic of emissions as well. Furthermore, optimizing a construction process could positively influence multiple aspects such as costs, emissions, overtime, etc.

On a broader perspective, Dura Vermeer has a sustainability manager who organizes different projects regarding the sustainability company wide. He can also give insights in the most relevant aspects of emissions at construction companies.

Last, as mentioned already Dura Vermeer is a large company and there are more people within the company that are stakeholders in my research in some way. In this research there is room to connect to them as well if it contributes to a better final result.

1.1.3 Stakeholders outside Dura Vermeer

Next to Dura Vermeer as a company and all the different stakeholders within the company, there are stakeholders outside Dura Vermeer that have to be taken into account. An improvement within Dura Vermeer, can influence other companies in their area of work. Furthermore, the effects for people around construction sites are an important factor when it regards emissions.

Dura Vermeer works with a lot of subcontractors and suppliers for each construction projects. For one project, there could be tens of partners. These partners also make choices about the construction projects that could influence the emissions generated. This is important, because this research could also need data from the partners and the results of this research can influence the collaborations with the different partners.

The people that live close to construction areas are probably not directly affected by this research. However, the general idea is to improve a sustainability aspect of construction projects, so this probably influences the environment of people living near constructions projects positively. In this research they are not taken into account a lot.

1.2 Problem identification

This section gives a description of the problem identification. It explains the problem context and visualizes the problem cluster. Furthermore, the core problem is chosen and supported by the motivation for the core problem and the norm and reality.

1.2.1 Problem context

Since sustainability is part of the strategy of Dura Vermeer, they also want to reduce the negative environmental impact of construction projects. A significant part of this is about reducing the emissions generated during construction projects.

At large construction projects, many trucks are used to deliver the materials and many machinery hours are used to build the new buildings. Depending on the type and year of construction, these trucks and machines cause high emissions of greenhouse gasses like CO_2 or NO_x, ultimately resulting into a negative environmental impact in small areas.

To be more sustainable, these emissions should be reduced. However, it is difficult to know how to reduce this efficiently, because it is often unclear where, which amount of emissions are created. For example, it is not known how much emissions can be reduced by using different machinery types or hire different suppliers.

This lack of data means that the current emissions forecasts are incomplete and undetailed on some levels. The reason behind this is that the tool used to forecast the emissions is insufficient, which is caused by the fact that the tool is not designed to be an emission-forecasting tool. The currently used tool is an extension of a logistic volume-prediction tool that provides input for the AERIUS Calculator of the Dutch government. The AERIUS Calculator is a tool that calculates nitrogen emissions as a result of the economic activities and the deposition on Natura 2000 areas (RIVM, 2020). DVBH lacks a tool that is designed for more extensive emission-forecasting.

Next to the fact that the forecasting tool is incomplete, it is also not validated and evaluated sufficiently. The forecasted data is not validated and not compared with real-world data to evaluate it. This real-world data should come from measurements at in-practice construction projects. At the moment DVBH started measuring this data partly already, however, it is in an early stage, so the steps to validation, evaluation and connection with a forecasting tool have not been made yet.

Besides the fact that these incomplete, not validated forecasts make it difficult for DVBH to reduce emissions and be more sustainable, there is another problem. In the future it is expected that the Dutch government will come with new, stricter measurements and regulations regarding the emissions of construction projects. There is a likely probability that DVBH will be responsible for showing the forecasted emissions at construction projects in more detail and be able to proof it is valid. If DVBH is not able to meet the expected future criteria, it might endanger the start of potential future construction projects.

1.2.2 Problem cluster and core problem

Figure 1 shows the problem cluster. In this cluster, all the network of problems as described in section 1.2 are placed in a framework which shows the causal relationship between the problems.

On the right side, there are two ultimate problems. The first is the problem that the emissions of construction projects have a negative environmental impact, which is not in line with the strategy of DVBH about sustainability. Second, there is the problem that the start of potential future construction projects is insecure, because of expected future regulations.

The cluster also shows two starting problems. The first one is that the company is lacking a tool designed for extensive emissions-forecasting. The second is that the method to measure real world data about emissions is relatively new.

The core problem is:

"The company lacks an extensive tool designed for emission-forecasting."

This problem is formulated in more detail in Chapter 2.2 to fit the problem-solving approach.

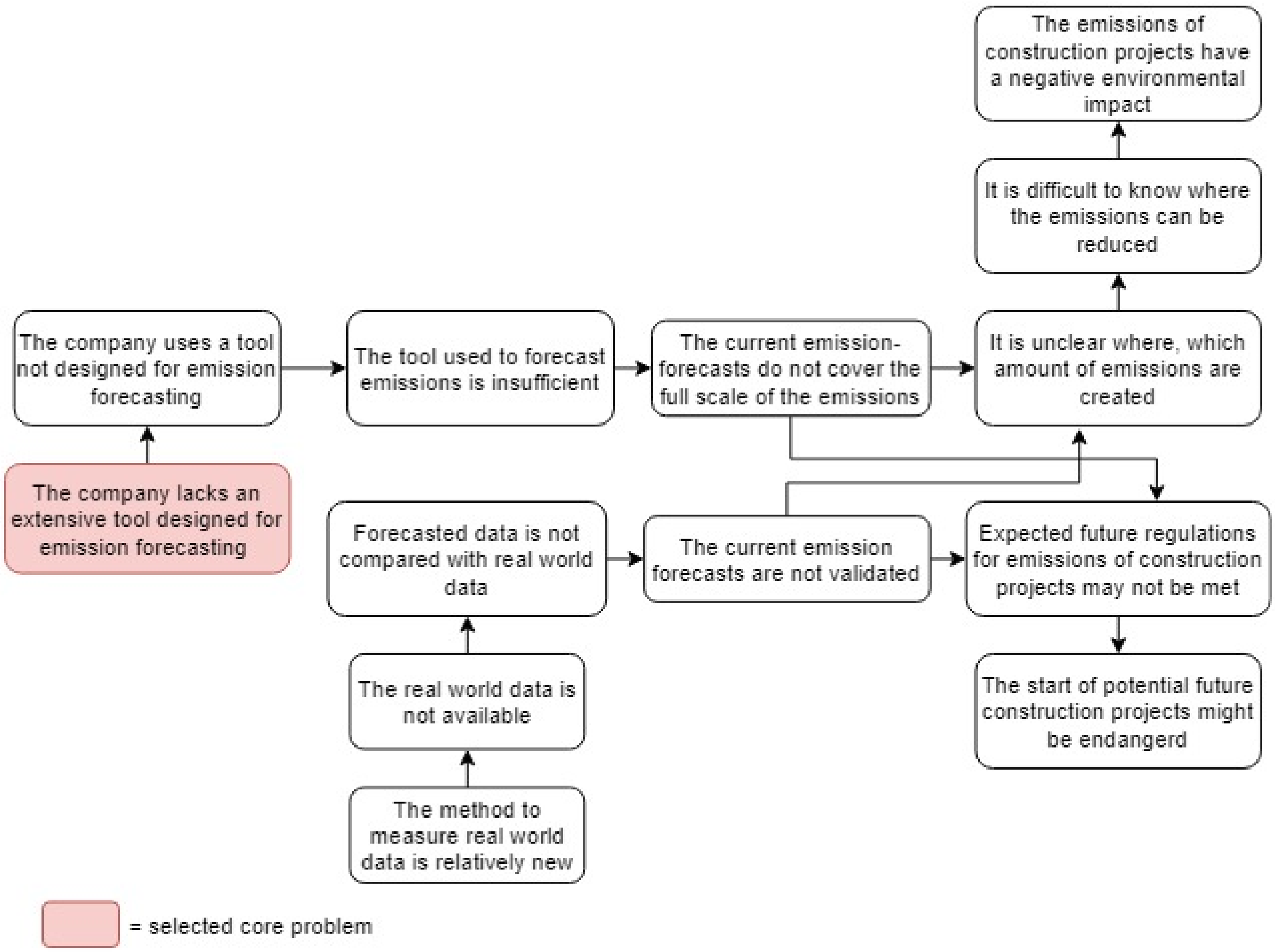

Figure 1 The problem cluster

1.2.3 Motivation of core problem

Heerkens and Van Winden (2012) have distinguished four criteria that a core problem should meet. In this section, the motivation for the core problem is explained by the hand of these four criteria.

First of all, it should be sufficiently clear the problem occurs and that it has a relationship with the other problems. As described in sections 1.2.1 and 1.2.2, it is clear that the problems occurs and that it has a relationship with the other problems mentioned.

Second, it should be a problem that has no cause itself. As shown in Figure 1, the problem itself is a cause of a line of problems, but there is no cause for the core problem itself. There also is no clear problem that could cause the problem that there is no design for an extensive emission forecast tool.

Third, the problem should be something that can be influenced. This is possible, since the first set-up for such a tool is already there (the extension of the volume-prediction model) and DVBH recently started to measure logistic data at construction sites that can serve as validation of a new emission forecasting tool. These data sources provide the start of a framework for the design of a new tool that can make more extensive forecasts.

The other starting problem at the beginning of the problem cluster (Figure 1), the one about the measuring of real-world data, is no core problem, since it cannot be influenced very much. The fact that the measuring method is relatively new and it takes time in practice to measure data, is not a process that is influenceable enough within this research to be a core problem. However, this problem should be kept in mind during the research, since the generated data can be used as real-world data to validate the tool.

The last criterion is that the most important core problem should be selected. This is not difficult, since the mentioned core problem is the only one left when taking the previous mentioned points into account.

1.2.4 Norm and reality

The reality is the situation as it is now, where the emission-forecasting is not very extensive and it is hard to see how different aspects influence the total emissions. DVBH has no tool that can be used to map and integrate the basic data that regards emissions. This is also why the extensive forecasting is not possible yet.

On the other hand, DVBH already generates data that is useful for future emission forecasting and validation. For example, the nitrogen-emission forecasts are already done based on volume predictions and the AERIUS Calculator. Furthermore, DVBH recently started to record all the trucks that enter construction sites, so CO_2-emission can be registered during the construction project.

The norm is that DVBH has an emission forecasting tool that provides a framework where all the different data-sets that regard emissions can be integrated. This regards the data that can be used to forecast the emissions as well as the data that is registered to measure emissions in practice to validate and improve the forecasting tool.

At the moment the most relevant emissions generated at construction projects are CO_2 or NO_x, according to DVBH and a general impression of emission regulations by governmental institutions.

To specify the norm further, it is important that the new tool should meet certain requirements to be of sufficient use for DVBH and construction companies in general. "A requirement is a property desired by some stakeholder" (Wieringa, 2014). In practice, it is hard for DVBH to specify their requirements for the tool. However, from conversations with the logistic manager of DVBH, some important requirements arose in a general way. The tool should be easy to use, future-proof, accurate, extensive, detailed and of course valid and reliable.

Since it turns out that it is hard to set the level of the requirements the tool should meet in such an early stage, more research is needed. In Section 2.5, a research question is formulated that should be answered to know what requirements the tool should meet.

1.3 Related literature

This section provides some contextual theoretical insights in established research on the topic of emission forecasting tools for construction projects. It explains the overlap and differences between used methods and what scientific knowledge is missing in this area of research. It answers the question:

"Which models and theories are known in literature for designing an emission forecasting tool for construction projects?"

This question is answered by conducting a systematic literature review. All the steps of the review can be found in Appendix A.

From the literature it becomes clear that in the last decade, relevant research is done regarding the topic of emission forecasting for construction projects. Noticeable is that the methods often differ in approach and perspective. Some researchers take a descriptive approach, which often is uses a more zoomed-out view (Zhanga et al., 2013; Sutthichaimethee & Kubaha, 2018; Ho et al., 2015) with as a goal to describe the situation as it is. Other researchers take more of a more narrowed down approach to develop an artifact that is useful for improvement in emission forecasting (Kim et al., 2015; Changbum & Lee, 2013; Zhang et al., 2019; Moon et al., 2014; Wong et al., 2013). This last group designs the tools with the goal to help the construction companies as stakeholders.

Nevertheless, all the researchers base their research on different theories, resulting in different methods and different goals. One research (Kim et al., 2015) integrates the emission forecasting with costs and scheduling in a management system, while others integrate the operating efficiency with the emission forecasts (Changbum & Lee, 2013). Some use extensive mathematical models (Zhang et al., 2019), while others visualize the forecasts in a Virtual-Prototyping-Simulation (Wong et al., 2013). One research (Moon et al., 2014) bases its forecasts on material-based decisions making. In short, there are many perspectives and theories about what input variables influence the eventual emissions.

Interesting to notice is that almost all studies use case-studies to validate their models (Kim et al., 2015; Zhanga et al., 2013; Changbum & Lee, 2013; Zhang et al., 2019; Moon et al., 2014; Wong et al., 2013). It appears that a case study in which the forecasted data is compared with real-world data is a useful method to test a theory or an artifact in this context. Research (Heidari & Marr, 2015) provides useful reference values for the real-world emissions as well as important factors to take into consideration when measuring in the real-world.

Another useful theory in this context is the Life-Cycle Analysis theory, that is used in most of the literature (Kim et al., 2015; Zhanga et al., 2013; Changbum & Lee, 2013; Zhang et al., 2019; Sutthichaimethee & Kubaha, 2018; Heidari & Marr, 2015; Moon et al., 2014; Wong et al., 2013). It provides relevant, scientifically proven data about emissions of material and objects in the construction context. This is often used as input for a model or as validation for a model.

However, the models are mostly scientifically founded and validated, it is often not tested how the models are used in practice by construction companies. It is important that a created model is applicable by the stakeholders in practice. This is something that is not extensively researched and can be added with this research. An important aspect is defining the correct requirements for the stakeholders of construction projects. Furthermore, the validation of a forecasting model should not only be done regarding the accuracy by a comparison with real-world data. A model should also be validated by stakeholders' opinions from within construction companies.

2 Problem solving approach

Chapter 1 gave the introduction to the stakeholders, the problem and some theoretical context. Now the topic of this research is covered, Chapter 2 explains the problem-solving approach. It contains the research methodology, goals and the scope. Furthermore, it contains the research questions and the methods to answer them.

2.1 Research methodology

2.1.1 The Design Science Methodology in general

The main object of the study is the emission forecasting tool for construction projects. In a more general way, this could be described as an artifact in a context, like in the Design Science Methodology of Wieringa (2014). This methodology describes the artifact (in this case the emission forecasting tool) as the object of study that is designed and investigated. This process iterates several times to create a valuable artifact.

The Design Science Methodology of Wieringa (2014) fits the research, since it has the goal of designing and investigating an artifact in a context. This methodology is divided into five steps, as shown in Figure 2.

Figure 2 The five steps of the Design Science Methodology of Wieringa (2014)

After Step 1: Problem investigation, Step 2: Treatment design starts in which the first version of the artifact is developed. Then in Step 3: Treatment validation, it is investigated if the treatment of the artifact solves the problem in context. These first three steps are the so called "design cycle" of Wieringa (2014). Iterations over this Step 2 and Step 3 can be made multiple times.

The whole cycle with the five elements is the "engineering cycle". In Step 4: Problem implementation, the artifact is placed in the real-world context for which it is made. In Step 5: Implementation evaluation, Step 4 is evaluated, after which it is possible to iterate over Step 2 to Step 5 again.

In all these steps, knowledge questions come up that need to be answered. For this, the Empirical Cycle of Wieringa (2014) can be used. The generic research question and the sub questions are shown in section 2.5.

2.1.2 Validation and Evaluation

An important aspect in the design science methodology of Wieringa (2014) regards the difference between validation (Step 3) and evaluation (Step 5). The validation is about justifying that the artifact contributes to stakeholder goals. "It consists about the investigating the effect and interactions between a prototype of the artifact and a model of the problem context and of comparing these with the requirements of the treatment." (Wieringa, 2014). This means that the artifact is not implemented by stakeholders themselves yet, but always by the researcher. The evaluation on the other hand is the investigation of the artifact in a real-world context when applied by the stakeholders, without interference of the researcher.

2.2 Goal

In Design Science there are multiple goals within one research. The first distinction can be made between *research goals* and *context goals*. Research goals are the goals as perceived by the researcher during the research. Context goals are the goals perceived by the stakeholders of the research.

The research goals exist out of three different kinds of goals. First, the *artifact design goal* is about creating an artifact in a context. Second, the *knowledge goals* are about gaining knowledge about the world. The goal of the researcher is to design a good artifact and for this he needs to gain information (knowledge goals). In some cases, it could be possible that a non-existent instrument is needed to answer the knowledge questions. For this, low-level *instrument design goals* are used.

The context goals exist out of two kinds of goals. The first goal is the effect of the artifact in the context, the goal is to *improve the problem context*. Reaching this goal should also serve the *stakeholder goals*.

Figure 3 shows a visual overview of the most important goals of this research.

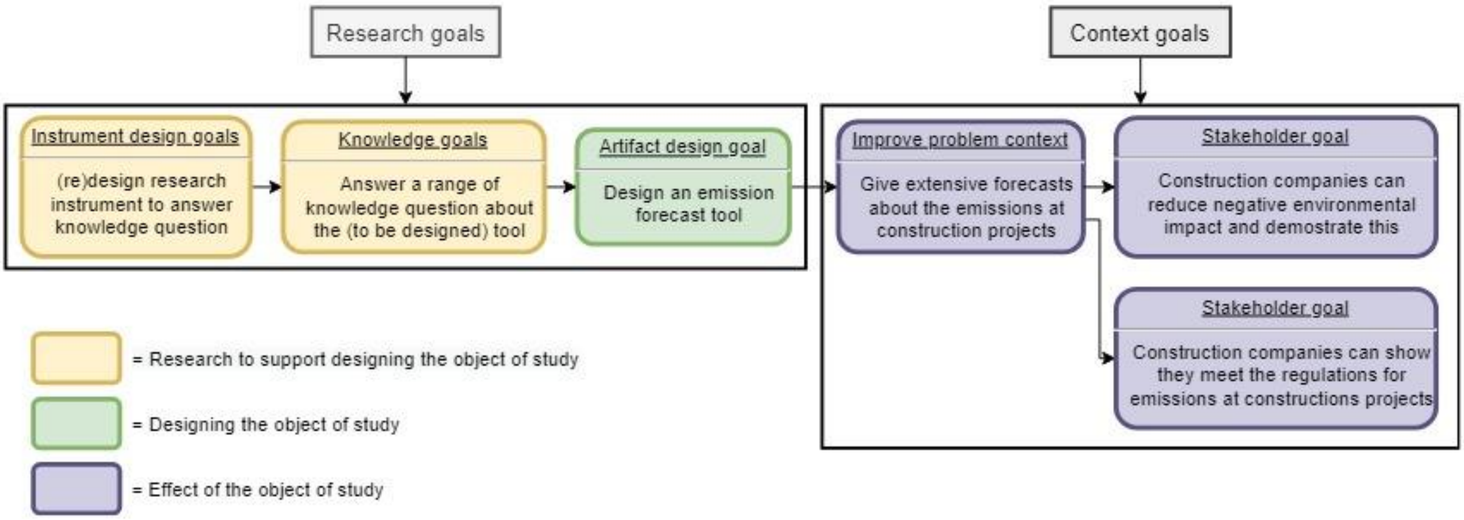

Figure 3 Global overview of the goals of the research

According to Wieringa (2014) the main goal of the research can be formulated as a technical research goal. Section 1.2.4 already provides information about what this goal should include and Figure 3 gives a global overview. However, it is important to understand what the main goal of the whole research is. Wieringa (2014) provides a clear template for this technical research goal, existing out of four elements.

First, the *problem context* which describes a context that has some conditions in which an improvement is needed. For this research the problem context is 'construction projects'.

Second, *(re)design an artifact*, describing what kind of artifact is designed or redesigned. An artifact is "something created by people for some practical purpose" (Wieringa, 2014). The to be made artifact is an 'emission forecasting tool'.

Third, the *requirements* are properties for the artifact that has to be created. Some level of this requirements should be obtained in order for the artifact to be sufficient. The preliminary requirements for the tool are 'ease of use, future-proof, accuracy, extent, detail and validity and reliability'. The validity and reliability are implicit requirements, which is why we can leave them out of the technical research goal. Since the exact requirements are not clear yet, a part of this research is about setting the requirements, as is explained in section 2.5.

Fourth and last, the *stakeholder goals* are important. A stakeholder is an entity that is affected by the new artifact in activity. The goal of the stakeholder is "a desire for which the stakeholder has committed resources" (Wieringa, 2014). In this case the biggest stakeholders are 'construction companies' and their goals are 'begin able to investigate where emissions can be reduced' and 'being able to show they meet regulations for emissions at construction projects.

These four elements can be combined in a technical research question. The goal of this research is to answer this question:

"How to design an emission forecasting tool that satisfies the ease of use, future-proof, accuracy, extent and detail, so that construction companies can investigate where emissions can be reduced and show they meet regulations for emissions at construction projects?"

2.3 Scope

2.3.1 Scope of the research methodology

The Design Science Methodology of Wieringa (2014) can be seen as a "science of the middle range". This middle range is achieved on two levels, *generalization* and *realism*.

For generalization, it means that the context in which the tool operates cannot be universally generalized for every emission forecasting task. However, it is broader than one specific case, since it fits the scope of construction projects in general.

For realism, it means that the conditions for which the tool is designed to operate are not idealized, as in theoretical physics or chemistry. On the other hand, these conditions do not always represent the practical situation completely. The middle range implies realistic conditions.

2.3.2 Scope of this research

In general, the middle range scope for this research means that the emission forecasting tool is designed to be functional for construction projects, however, not limited to one project. The conditions it is meant for are realistic, however, they do not always fully meet the conditions in practice. This section describes the scope per step of the research methodology in more detail.

'Step 1. Problem investigation' is already carried out partly in Chapter 1. However, since we have no full information about the requirements of the emission forecasting model, this part of the problem investigation is included in the research.

'Step 2. Treatment design' is focused on designing the emission forecasting tool. The basic element of this is a framework in which the data about the logistics, trucks, machinery and other aspects of emission can be integrated easily. The focus of calculations within the tool is emphasized on CO_2 and NO_x, since these currently are the most relevant emissions in the construction sector regarding regulations.

'Step 3. Treatment validation' is about the development of a design theory, which is a theory that predicts how the emissions forecasting tool interacts with the real-world construction projects. To develop this theory, several research methods for validation are used to give a complete validation analysis in the form of a design theory.

One method includes experimenting with modelled data to test the tool in an idealized context. A later method includes the investigating of the tool with real-world data. This data is generated at a construction project of DVBH in Zwolle, where 32 new houses are created.

As explained, the first three steps of the design science methodology are carried out completely. However, it is hard to carry out 'Step 4. Problem implementation' and 'Step 5. Implementation evaluation' within this research. The problem with these steps is that the emission forecasting tool has to be used by the construction company without interference of the researcher. Since the time for the research was set at approximately ten weeks, this means that the tool should be finished in a short period of time and then the construction company should use it at a project quickly. Furthermore, the projects are already expected to delay because of the Corona-crisis, which is happening during the period the research is set. This is why it is not possible to fit these steps in the scope of the research.

2.3.3 End products

The main end product is the emission forecasting tool (the artifact of this design science research). This tool provides a framework where the logistic data that regards emissions can be captured and connected to each other to make calculations, forecast emissions and validate them by the use of real-world data.

In addition to the model, a design theory is developed which explains to which extent the tool contributes to the goals of the stakeholders. This theory includes a validation analysis of the tool. This thesis forms design theory of this research.

2.4 Research questions

To answer the main technical research question (generic research question) stated in section 2.2 and realize the end products stated in section 2.3.3, a range of different research questions has to be answered to gain knowledge about the emission forecasting tool. These research questions are stated in this section and the sub sections explain the research design methods to answer them. They are structured in the different steps of the research methodology. Combining the answers to all these sub questions, results in answering the generic research question:

"How to design a emission forecasting tool that satisfies the ease of use, future-proof, accuracy, extent and detail, so that construction companies can investigate where emissions can be reduced and show they meet regulations for emissions at construction projects?"

Step 1. Problem investigation

Chapter 1 explains the first step of the research methodology. The problem is identified and investigated. The stakeholders are known and their goals are generally clear. Methods in current literature are discussed as well.

Step 2. Treatment design

The second step is about the treatment design in which the different aspects of the model are specified and shaped together. In this phase the requirements of the model are determined and connected to the goals of the stakeholders. Furthermore, the relevant input for the model is specified and connected to the requirements.

To work out the treatment design, we need to gather data about these aspects of the model. The first research question that needs to be answered is:

1. **What exact requirements should the emission forecasting tool meet?**
    1.1. **On what level should these requirements be met?**

Answering research question 1 is important to make sure the developed tool is practically applicable for DVBH. The requirements are derived from stakeholders. This is done by the use of interviews. Research question 1.1 is also answered in the interviews and supported by literature.

When the requirements are clear, the input the tool needs to function needs to be researched. The second research question is:

2. **Which input variables need to be included in the emission forecasting tool?**
    2.1. **How should these variables be connected to each other in the emission forecasting tool?**

Research question 2 is answered partly with the interviews as well. However, these answers are further supported by literature that distinguishes the important factors for emission creating in construction projects. The sources come from both inside and outside Dura Vermeer.

When the context, the requirements and the input variables are known, the emission forecasting tool can be designed.

Step 3. Treatment validation
After the tool is designed, it is validated to show if it does what it is meant to do. The question that is answered is:

3. **To which extent does the tool meet the set requirements?**

A good way to check the functioning of the tool is to let the stakeholders implement it in a real-world setting, however, this is not possible. As explained in Section 2.3.2 this is not feasible in the scope of this research. Nevertheless, there still are other ways to validate the model.

First of all, the tool is validated in a self-validating practical demonstration to check how the different parts of the tool work. The tool is assessed on the performance of its requirements as perceived by the researcher.

Second, a sensitivity analysis is carried out to see how the different variables of the tool function and how they relate to the results.

Besides from this, a user validation of the tool is discussed as future work. This validation could contribute to validate the usability and understandability of the tool. Next to this, users could check if the tool meets the set level of requirements for the users.

2.4.1 Research method

During the first part of the research, the research method used is mostly qualitative and exploratory. The second part however, includes a quantitative analysis done with the designed emission forecasting tool.

According to Cooper & Schindler (2014), exploratory research is needed if the area of investigation is new or still vague. This is the case for emission forecasting at DVBH. Important variables still have to be defined. This concerns specifying the requirements (research question 1 and 1.1) and exploring the input-variables for the emission forecasting tool (research question 2 and 2.1).

The end focus of the research is to design the tool for emission forecasting. First the context for the tool is described, then the tool explains where emissions are created and predicts it for the future. This is in line in with the focus of a quantitative research which is “describe, explain and predict” (Cooper & Schindler, 2014). Another quantitative aspect according to Cooper & Schindler is the fact that the output of the model is an attempt to a precise measurement of something, namely the emissions generated during construction projects.

The validation of the tool is a combination of qualitative and quantitative research. Sometimes the level of the requirements met by the tool can be measured by quantitative data, while others are measured qualitative.

2.4.2 Operationalization

This section explains the operationalization of the research questions per question.

Research question 1 is about the specifying the requirements the emission forecasting tool should meet. In this case the key variable is "requirements" and the goal is to create a specified set of requirements. Following the specified requirements, the desirable level of them is set (research question 1.1). The key variables for this depend on the specified requirement.

For research question 2, the key variables are "variables", since these are the factors that are specified with answering this question. The goal is to create a list of variables that significantly influence emissions at construction projects. The answer to research questions 2.1 explains the connection between these variables in a mathematical reflection. For example: "The product of Variable A and Variable B creates Variable C". Of course, this again depends on the findings of the main question 2.

Finally, research question 3 compares the set level of the requirements the tool should meet with the measured levels for the requirements. The key variable is the differences in these two levels. This can be both quantitative and qualitative. For the self-validating practical demonstration it is mostly qualitative and for the sensitivity analysis it is mostly quantitative.

2.4.3 Data collection methods

To answer research questions 1 about the requirements, more data should be collected from the stakeholders. This is done by a direct data collection technique, the interview. This interview contains questions that indicate the stakeholders' requirements. More in depth, also the desired level of these requirements is collected.

A data collection method for research question 2 is the interview as well. However, also literature sources from both inside and outside Dura Vermeer are used to support the findings in the interviews.

The interview consists out of a total of seven open questions divided in three topics. With these questions research questions 1 and 2 are answered. The first topic is about the interviewee, to determine the relevance of his answers. The second topic is about the relevant input variables for emission forecasting at construction project. The third topic is to determine the requirements of the model. The interview is conducted in Dutch, because this is the main language within DVBH. The interview can be found in Appendix B.

To collect data for research question 3, validation of the tool, the tool first is demonstrated with a practical situation as far as possible.

2.4.4 Data analysis methods

For research questions 1 and 2, the obtained, qualitative data exist out of samples from sources (humans for the interviews), that have to be analyzed to generate logical findings. The people interviewed are expected to have experience in the field of emissions or forecasting at construction projects. The main findings of the interview are described and explained per topic per interview. Then I use analogic generalization for this DVBH-case research, so meaning that the answers of the interviews are generalized for the requirements and input variables of the tool. This way it can be concluded that in cases similar to the DVBH-case, it is plausible that the found explanations are true.

For the validation, the level the requirements meet is derived. The self-validating demonstration as well as a sensitivity analysis determine the level om some important requirements.

2.4.5 Validity and reliability

This chapter gives an indication of the internal and external validity and reliability of the research design.

Internal validity is about the ability of the research instrument to measure what it is supposed to measure. In this research there are a lot of different research instruments. We have the interviews with stakeholders, where it could be difficult to completely estimate the expertise and goals of the stakeholders. Next to this, we have instruments measuring and estimation the emissions at real-world construction projects. This are relatively new methods, which are not broadly validated yet, however they generate data that validates my forecasting tool. Lastly, the forecasting tool itself is validated as explained previously.

Since this research is specifically built for DVBH and is only validated within DVBH, it is hard to generalize the findings of this research. However, the methodology used to design the emissions forecasting tool, can be generalized for other construction companies. With this the external validity is expected not to be that high on a detailed level, but only on a methodological level.

The reliability of the research is about the research instruments always measuring the same thing, independently or an error. For the interview part, it is not possible to say that each interview measures the exact same information. This is because different people may react different to the same questions, because of other interpretations. This is prevented as much as possible. Next to this, the emission forecasting tool uses deterministic calculation, which produces the same output with the same input, however, the input will differ per project and will not always be fully reliable. This causes a decreased reliability of the output of the tool as well.

3 The emission forecasting model

As explained in Chapter 2, the first and second research question are answered by the means of interviews. These interviews are conducted with several different stakeholders within Dura Vermeer. In a total of six interviews, it is determined what the most important requirements and what the most relevant input variables for the emission forecasting model are.

Section 3.1 describes the interviewees and explains the level of expertise of their answers in context. Section 3.2 answers research question 1 and 1.1 by explaining what the most relevant requirements of the emission forecasting model are as perceived by the stakeholders within Dura Vermeer. Section 3.3 distinguishes three different kinds of causes of emissions at construction projects and which of them is chosen as input for the model. Section 3.4 answers research question 2 in more detail by explaining the most relevant variables that influence the emissions at construction projects as perceived by the stakeholders within Dura Vermeer. Section 3.5 gives a model description of the final emission forecasting tool as follows out of the requirements and variables of Sections 3.2, 3.3 and 3.4.

3.1 The interviewees

Six different stakeholders were interviewed to answer research questions 1 and 2. These stakeholders worked around the different divisions of Dura Vermeer in The Netherlands. All of them have or have had a touch with the topic of emissions at construction projects.

Although all interviewees have quite some knowledge about the topic, their answers are not all regarded equally relevant to every part of the emission forecasting model. Table 1 gives overview of the level of expertise of the answers of every interviewee on the two main topics of the interview, the requirements and the input variables of the model. The relevance is one of the four following options:

1. Low
2. Moderate
3. High
4. Very high

After the overview with the level of expertise of the answers per interviewee per topic, every interviewee is described anonymously to explain their level of expertise to the interview in more detail.

Table 1 The relevance of the interview answers per interviewee per topic

Interviewee	**Level of expertise to "Requirements" (Research question 1 and 1.1)**	**Level of expertise to "Input variables" (Research question 2 and 2.2)**
1	Very high	Very high
2	Very high	Very high
3	High	High
4	High	Very high
5	Moderate	Moderate
6	Low	Very high

Interviewee 1

The first interview is conducted with a BIM-engineer of Dura Vermeer. A BIM-engineer normally is responsible for the 3D model-based process that gives insights in the architecture, engineering and other aspects of construction projects. However, this person is at the moment active in as consultant in the preparation of construction projects. Every new project for DVBH passes by him and he checks if it complies with regulations, including the emission-regulations. He sees that right now the regulations are not that strict, but he sees the need for it in the future. His level of expertise on both the requirements of such a model and the input variables is regarded very high.

Interviewee 2

This interviewee has had several functions within Dura Vermeer. He worked in project preparations, as construction site manager and logistic construction site manager. At the moment he works at the business operations office (in Dutch "Bedrijfsbureau"), where he works partly on the budget for construction projects and the planning for parts of the equipment. He works on "everything you need on the construction site, but will not remain in the end", for example cranes, site offices, scaffoldings, etc. Next to this, he worked on a project to estimate the CO2-footprint of construction projects, however never finished this. Because of his broad background at Dura Vermeer, he can give clear insights in what the relevant aspects are for emission forecasting, so his level of expertise on both topis is also regarded very high.

Interviewee 3

The third interviewee is a BIM-engineer of Dura Vermeer, who is working on an innovative emission reduction project. The goal of the project is to use logistic improvements to reduce the emissions on construction sites. He also is familiar with the currently used volume-prediction model and he sees the possibilities to include more logistic operations in the model, so emissions can be forecasted. He has clear insights in requirements and input for an emission forecasting model, but is focused a lot only on the logistic aspects. His level of expertise is regarded high on both the requirements and the input variables.

Interviewee 4

The fourth interviewee works as sustainability manager for Dura Vermeer. Since the start of 2019 he focusses on circularity, energy transition, emissions and green buildings company wide. His task includes stimulating all the sustainability of all the business units of Dura Vermeer company wide. He confirms that the topic of sustainability is relatively new for the construction sector and it is hard to get to data. His broad vision on sustainability in the construction sector gives interesting overview of relevant subjects. This knowledge makes his level of expertise on input variables very high. As a sustainability manager he will not be the one using the emission forecasting model, although he has a clear view on it. This makes his level of expertise for the requirements high.

Interviewee 5

The fifth interview was with a director of preparations of Dura Vermeer. He works at Dura Vermeer for over seventeen years and has had several functions such as project manager and company director. At the moment he is responsible for the logistic schedules and calculations of direct costs in the preparation phase of new construction projects. Next to this, he is the director who is responsible for the topic of sustainability and the emission of nitrogen within DVBH. His focus is on how to measure emissions in practice. He sees the need for registrations, but also for forecasting and optimizing. The experience in different functions and the topic of sustainability in his portfolio makes him a relevant interviewee. However, he mentioned that he will probably not be working with the model, so the answers of other people are more relevant regarding the requirements of the model. Since he has a very zoomed out view on the sustainability topic and he will not be working with the models, his level of expertise for both topics is regarded moderate.

Interviewee 6

This interviewee works at the department business operations office, where he is involved in construction projects in an early stage. He handles the construction site planning, the general construction site costs and logistic schedules. In his position he sees that the emission of nitrogen is becoming more and more relevant. Next to this he notices that reusing materials is becoming a thing, but he is not really involved in this. He has a clear look on the equipment used on construction sites, for which he knows a lot of emission creation variables. His level of expertise for input variables is very high. However, he does not see his involvement with the model, so his level of expertise is regarded low for the requirements.

3.2 The requirements

From the interviews, the requirements and their importance are derived. Table 2 shows all the requirements mentioned in the interviews. It shows which of the interviewees mentioned them and a short explanation with every requirement. These factors combined with the relevance of the answers gives a value of importance of every requirement. This is shown in the last column of Table 2. Every requirement is one of the following four levels of importance:

1. Not important
2. Limited important
3. Important
4. Very important

Table 2 The requirements and their importance

Requirement	Mentioned by interviewee	Explanation	Importance
Ease of use	1, 2, 3, 4	- Completion time should be short (30-60 minutes) - Clear structure, so usable without too much prior knowledge - Not too many input variables	Very important
Accuracy	1, 2, 3, 4, 5	- Important, however very complicated, so it may be "very rough" - Important, however not essential in first version - Should be improved by trial and error on long term (after this research)	Important
Simulation possibility	1, 2, 3, 4	- Provide options, so the influence of choices between materials or suppliers is seen - Model should show "greener" choices - Simulation with logistic improvements	Very important
Extent	1, 3, 5	- First model cannot cover everything - Within this research, focus on the biggest polluters.	Limited important
Future proof	1, 2, 4, 5	- Model should be expandable in extent and detail. - "Living model" that can be updated regularly - Clear framework rather than proof of details.	Very important
Link with BIM-model	2	- Important for DVBH, but not possible within scope of my research.	Not important
Include financial aspect	2, 4, 6	- Important for total picture, but could negatively influence the sustainability research. - Is important to cause change within Dura Vermeer - Model might show ways to use machines more efficiently, which cause less costs	Limited important

Cause behavioral change	4	- Employees of Dura Vermeer should think more about sustainable options.	Limited important

As shown in Table 2, the six interviews gave eight distinguishable requirements. Three of them are very important, one is important, three are limited important and one is not important. These levels of importance influence how much the requirements are taken into account in the emission forecasting model. The next part of this chapter shows for every potential requirement of the model what the main findings of the interviews are. The complete findings of every interview can be found in Appendix C.

Ease of use

The ease of use or usability of the model is mentioned by the first four interviewees. The level of expertise of their answers on the requirements are all regarded high or very high. This means the importance of the ease of use of the model can be accurately derived from their answers.

The first interviewee mentioned that the model should be "realistic" to use. With this he means that it should not take long to fill in the input data of the model, "it would be nice to do it in half an hour". If it is too complicated to work with the model, it will probably not be used.

Since the model is an extension of the currently used volume-prediction model, they could be worked out together. According to the second interviewee this should not take more than about two hours in total. Otherwise, it will be a waste of time.

Another part of the ease of use is the amount of prior knowledge it takes to give input for the model. This should be limited by only using the most important input variables instead of using over 100 variables that could influence the final output. The third interviewee mentioned this and recommended to appoint a key user within Dura Vermeer to make sure the usability would remain.

Last, also interviewee 4 thinks the ease of use is important. The model should give quick, rough forecasts in an early stadium. It should take about one hour to fill it in.

In short, a lot of valuable answers of the interviewees gave insights in the importance of the ease of use of the emission forecasting model. It should not take a lot of prior knowledge and not too many different input variables, so an early, rough forecast can be calculated easily. Very important is that it should only about 30 to 60 minutes to complete a forecast with the model.

Accuracy

The accuracy is the level to which the calculations of the emission forecasting model approach the real emissions in practice. Five of the interviewees gave their view on this requirement of the model. Although the accuracy may seem as the core value of the model, the interviewees gave an interesting vision on this requirement.

Interviewee 1 says that there will be a consideration between the accuracy and the ease of use of the model. At this moment he thinks that the accuracy is not of the greatest importance. It is fine if the model is "very rough", because there are too many different factors to take into account. To make it precise, the model would become too complicated.

The second interviewee said that the forecasts of the model should represent the reality. The requirement is to which extent this happens, so the accuracy of the forecasts. If the forecasts have a deviation of 30%, it would be quite big. However, he also mentioned that it still is a step forward, since there are no forecasts at the moment. The accuracy in general is very important, but not essential in the first version.

Furthermore, interviewee 3 sees that this field of research is relatively new in the construction sector, so for the scope of this research it is not possible to limit the research to the importance of accuracy. For this research, finding the most important variables is relevant and the accuracy should later be improved by trial and error.

The fourth interviewee mentioned that the model should provide a clear framework for emission forecasting, where it should not directly be focused on the proof of the concept. With this he means that not every part of the model can be accurate at the start of use, but it should be clear how this can be improved in the future. Based on his feeling, he says that the accuracy should at the start be about 80%, where it later can be improved to 90% - 95%.

For the fifth interviewee, every forecast is an improvement in comparison with the previous situation. The first version of the model should not be bound by the focus on details, however should provide a framework which can be updated regularly.

In short, most of the interviewees mention the accuracy of the model as essentially a very important requirement for the emission forecasting model. However, all interviewees see the big challenge in developing a new tool in a relatively new field of research for construction companies with a high accuracy. If the deviation of the forecasts is about 20-30 percent, it would be good for the first model. On the other hand, if this is not possible, the framework and its potential of the model is of more importance.

Simulation possibility

The possibility to simulate with the model to forecast emissions with different hypothetical input is mentioned by the first four interviewees, who all have a high or very high-level expertise on the requirements.

Interviewee 1 says the model should provide different options, so the user can experiment with choices regarding the construction process. For example, if we choose different materials or different suppliers, the model should show what the effect on the emissions would be.

The second interviewee mentions it would be better if the model gives options for emission reduction. This gives better insights to Dura Vermeer in what choices influence the emission and how they can reduce them.

Another simulation possibility is mentioned by Interviewee 3, he is interested in how logistic improvements influence the emissions. If this is possible, the interviewee can simulate for his research without having to test everything in practice. This would also reduce time and costs.

The fourth interviewee confirms the importance of simulation options in a general way. He wants insights in the alternative options than the regular choice, to see how improvements can be made.

It becomes clear Dura Vermeer is very interested in the requirement to simulate with the model to look for improvements in emission reduction next to only forecasting the emission of their set projects. What kind of simulation options the model provides is dependent on the input variables, which will be discussed in Section 3.4.

Extent

There are different causes for emissions, like different kinds of construction equipment, transport of materials, transport of people, etc. This requirement is about to which extent the model can forecast all the emissions that are generated by different causes at construction projects. Not all interviewees appoint the extent explicitly as a requirement, but Interviewees 1, 3 and 5 give a view on it.

Interviewee 1 says it is acceptable if the first version of the model does not cover all the aspects of emission creation at construction projects. The most important thing is to recognize the biggest polluters and forecast their emissions.

In addition, the third interviewee mentions there might be over 100 variables that influence the emissions, but it is important to limit the input for the model to the most relevant variables.

The fifth interviewee does not talk about the different causes, but mentions that forecasting all possible sustainability KPI's would be an extensive job. He confirms that the tons of CO_2 and the tons of NO_x are relevant KPI's.

The extent of the model is limited important for the emission forecasting model. It is of importance to focus on the biggest polluters and the most important variables, so that part of the CO_2 and NO_x emissions can be forecasted.

Future proof

Since this research is focused on developing a new emission forecasting tool in approximately 10 weeks, the tool will not cover every aspect of emissions created at construction projects. Four of the six interviewees pointed out that it is important that the model will remain and grow in value after this research. This is why it should be future proof.

One aspect of future proof is the expandability, pointed out by Interviewee 1. It is acceptable if the first version of the model does not cover all the aspects of emission creation at construction projects. In a later phase, it should be easy to add aspects of emission creation so that the model becomes more complete.

Next to the expandability, the model should be a "living model". The second interviewee means that it should be updated with new data regularly, so the model will remain relevant and not lose its usefulness. This could be seen as an aspect of making the model future-proof.

The fourth interviewee also says that not every part of the model can be accurate at the start of use, but it should be clear how this can be improved in the future. This is the case if the model provides a framework which can be updated regularly by new data, as Interviewee 5 suggests.

In short, a lot of interviewees with high level of expertise think the future proof is very important requirement for the model. This can be done by providing a clear structured framework, that can be easily expanded and updated with new data.

Link with BIM-model

The second interviewee mentioned the link between the model of this research and the BIM-models of Dura Vermeer as a requirement, because BIM-models are "the way of working" for them. These BIM-models include a lot of data about the architecture and engineering of a building. The interviewee noticed that this model might be complicated for people without knowledge of BIM-modeling. Although it would be of value for the future, it is regarded outside the scope of this research due to complexity.

Include financial aspect

Three of the interviewees mention the requirement to put in the financial aspect of the construction project to see how differences in sustainability choices influence the total costs of the project. They have different views on this requirement.

Interviewee 2 believes that the issue of money will negatively influence the research to insights in emission reduction. This is why the link to financial aspects is regarded less of value at the moment.

The fourth interviewee thinks that the financial aspect should be taken into account. He thinks that about 80% of the people do not intrinsically feel the need for sustainability. That is why the financial aspect should also be included to see that certain choices could influence both the sustainable and financial aspect positively.

The sixth interviewee mentions that if the model shows improvements in the forecasting of equipment hours of machinery, this should also be used for improving the budget (financials).

Since only half of the interviewees mention the financial aspect, of which the one with a very high expertise on the requirements thinks it limits the research to include it too much, the financial aspect is considered limited important.

Cause behavioral change

The fourth interviewee thinks that a model that gives insight in emission creation should cause behavioral change among the employees of Dura Vermeer. Except only providing insight in more sustainable options, it would be better if people start thinking about more sustainable construction methodologies. For example, how different material choices could influence the necessity of certain machines.

Although this requirement could be of importance for the long-term strategy and sustainability goals of Dura Vermeer, it is regarded limited important for this research. It is only mentioned by one interviewee and this research on itself will probably not have a lot of direct links with the behaviour of employees within Dura Vermeer.

3.3 Causes emissions at construction projects

Before the exact input variables of the emission forecasting model can be decided, it is important to distinguish the three main causes of emissions at construction projects. These causes can be derived from the interviews and are shown in Table 3 with their relevance to be included in the emission forecasting model. The first column shows the cause, the second which interviewees mentioned them, the third a short explanation and the fourth the relevance. Every cause is one of the following four levels of relevance:

1. Not relevant
2. Limited relevant
3. Relevant
4. Very relevant

Table 3 The main causes of emissions at construction projects

Cause	Mentioned by	Explanation	Relevance
Construction equipment	1, 2 ,3, 4, 5, 6	The emissions caused by construction equipment on the construction site (cranes, excavators, etc.)	Very relevant
Transportation	1, 2, 3, 4, 5	The emissions caused by transport vehicles when they drive to and from the construction site	Relevant
Materials	1, 2, 4, 5	The emissions caused by the production of the materials needed for the constructed building	Limited relevant

Construction equipment

The construction equipment is regarded as a very relevant cause of emissions at construction projects to be included in the emission forecasting model. All interviewees mention the significance of this cause. There are a few different reasons for this.

The first, second, fourth and sixth interviewee say that construction equipment is the biggest cause of emissions. They are all regarded as people with a high level of expertise on input variables of the model, so this is considered true. Interviewee 2 says construction equipment is the "biggest polluter by far" and interviewee 6 gives an example of a project where 11 tons of the 11,3 tons of NO_x emission on site is caused by the construction equipment. The machines often runs on fossil fuels and a large part of them have old polluting engines.

Second the current tests to meet NO_x-regulations are focused on emission creation at and around the construction site. This is not where emissions for materials are created and where only a small part of the transportation emissions are created here. The emissions of construction equipment is by far the biggest influence on meeting regulations at the moment.

Third, Dura Vermeer has an influence on the emissions of construction equipment. They are at the construction site active during the whole construction projects to decide and/or support in logistics, planning, and machine movement. Next to this Dura Vermeer chooses some of the machines themselves, which influences the emissions. However also a lot of machinery choice and planning is decided by subcontractors, more about this is explained later in section 3.4.

Fourth, improvements in less machine-emissions can potentially also have positive side effects. For example, an improvement to lower the running hours of machines reduces emissions, but also time and costs of manhours. More insights in the emission creation of machines could cause a win-win situation for the construction projects.

In short, the emissions of construction equipment are very relevant for the emissions forecasting model because of four reasons. First of all, the machines are the biggest cause of pollution. Second, they are very relevant for meeting emission regulations. Third, Dura Vermeer has an influence on these emissions. Last, improvements could have positive side effects for the construction projects.

Transportation

The transportation to and from the construction site is also mentioned by five of the six interviewees as an important cause for creation of emissions. This regards all the transport of materials, equipment and people. There are a few reasons because of which this is relevant.

First of all, the transports are a big polluter. For a construction project, a lot of transportation of materials is needed. For example, the number of trucks that is needed for a construction project to build 32 houses is about 600 trucks. All these transports are done with trucks that drive on fossil fuels and the materials come from different places in the country. Next to the materials, employees need to drive to and from the construction site every day to work on the project, however this aspect is regarded less relevant by the interviewees, since it effects are smaller.

Second, more insights in the emission creation of transport could also have the positive side effect to improve the transport logistics on the construction site. If it is better known which trucks cause emissions at which phase of the construction project, they also know when it is crowded and they can better regulate the logistics. However, this logistic improvement is already calculated by Dura Vermeer, so this potential improvement will be not very significant.

The influence of Dura Vermeer on the emissions of transport is not very clear from the interviews. Almost all materials are transported by suppliers outside Dura Vermeer. It is possible to choose suppliers that are close to the construction site, however there are a lot more important variables that influence the choice for a supplier. Next to this, Dura Vermeer could take into account to only order full truckloads of materials. The influence of this on the total amount of trucks is not yet clear.

For meeting the emission regulations, the transportation is of less importance. Regulations are mostly for emissions on the construction site and transport vehicles are often not very long active on the construction site. The biggest part of their emissions is more spread out over the whole route they drive.

In short, the transportation is relevant to take into account in the emission forecasting model. Transportations causes a lot of emissions and Dura Vermeer wants to be more sustainable in general. Furthermore, insights in improvements in transport emissions could have positive side effects, however, these improvements are already partly known. On the other side, the influence of Dura Vermeer on transport emissions is not that clear. In addition, the relevance for meeting regulations is of less important than compared to construction equipment. Transport emissions are important, but not very important to take into account in the emission forecasting model.

Materials

Four of the six interviewees mention the materials as a cause for emissions at construction projects. It is about the emissions generated at the creation of the materials that are needed for a construction project, like concrete and steel. The relevance of this cause is explained by the next points.

First of all, the interviewees who mention these emissions caused by the creation of materials often are not that interested in this cause in comparison with the other causes. They do not have a high level of knowledge of this cause. It is often mentioned as third cause and not with more information about the influencing variables of these emissions. Only interviewee four says “the embedded emissions in these used materials are very important”.

Multiple interviewees mention that these emissions are already forecasted in the MPG-calculation (Environmental Performance Buildings). This forecast is already extensively and (assumed) accurately done by external parties, so a new model that focusses on this, will probably not make a lot of improvements in the accuracy easily.

These MPG-calculation is also an emission regulation they should meet, so the materials are of interest. However, the focus of new regulations is more on emissions generated at the construction site, which has nothing to do with the MPG-calculation. That is why the emissions caused by the creation of materials are regarded less relevant on this point.

Concisely, the interviewees are less interested in the emissions caused by material creation then the other causes. They provide less information about the variables that cause these emission, also because they are already accurately forecasted by an external party for the MPG-calculation. On this level, a new model will probably improve less than with the other causes, which emissions are not yet calculated accurately. Last, the new expected regulations will focus more on emissions generated on the construction site, which is not the case for emissions caused by material creation.

Conclusion causes emissions at construction projects

There are three main causes of emissions at construction projects: the construction equipment, the transportation and the used materials. From the interviews it became clear that the construction equipment is a very relevant cause to include in the model, the transportation is relevant and then materials are regarded limited relevant. The construction equipment is regarded most relevant, since it is a big polluter and it is relevant for meeting emission regulations. Meeting emission regulations is one of the main problems found in the problem cluster (Figure 1) in Section 1.2.2. Next to this, Dura Vermeer has an influence on it and improvements on this cause can have positive side effects.

From the part of the interviews about the requirements a few things became clear regarding the input for the emission forecasting model. First of all, the completion time should not be too long. Second, the input variables should be limited to the most relevant ones. Third, a large extent is not of very high importance, if the model is expandable and focuses on the biggest polluters. With this information it can be concluded that the emission forecasting model should focus on the most relevant cause of emission and not every cause.

In short, the construction equipment is the most relevant cause for emission creation and the requirements the interviewees gave explain to focus on the most relevant cause. Furthermore, the time for this research is limited at approximately ten weeks, so the extent of the cannot be too large. Because of combination of these factors the emission forecasting model will only focus on the emissions caused by construction equipment on the construction site.

In Section 3.3.2 the input variables for calculating the emissions caused by construction equipment is explained. The information about more detailed input variables of the other causes can be found in Appendix C: The interview answers (complete).

3.4 Input variables for the model

This section explains the exact input variables for the emission forecasting model. These input variables partly come from the expertise of the interviewees and partly from other emission calculations found in literature. The combination of these two gives a comprehensive understanding of which data is needed to make the calculations in the model. The exact functioning of the model is explained in section 3.5.

From the interviews it becomes clear there are multiple ways to calculate (and forecast) the different emissions of construction equipment. First of all, it is important to distinguish the calculations of CO_2 and NO_x emissions. Second it is important to distinguish the 'fixed input variables' and the 'unfixed input variables'. Fixed input variables do not have a fixed value, but they are the general input variables that are always needed to calculate a certain emission. Unfixed input variables on the other hand are needed if a certain method for emission calculation is used, but not for every method.

3.4.1 CO_2

The calculation for CO_2 emission is relatively easy compared to the calculation for NO_x emission. This section explains the input variables for the CO_2 emission of construction equipment. According to the Environmental Protection Agency the emissions of CO_2 is the same for every liter of burned fuel. This means that the fixed input variable for CO_2 forecasting in the model is:

- CO_2 emission per unit of burned fuel

Almost all big construction equipment runs on electricity or on diesel. For electricity the CO_2 emission per unit of burned fuel is zero. For diesel, this is 2.668kg CO_2 per liter (10.1kg per gallon (Environmental Protection Agency, 2005)).

The CO_2 emission per unit of burned fuel combined with the forecasted fuel consumption gives the forecasted amount of created CO_2. There are multiple ways to forecast the fuel consumption per machine on the construction site. This can for example done by forecasting the fuel consumption per logistic action or the fuel consumption per operating hour. This means there are some unfixed input variables which need to be chosen. Since this is also relevant for forecasting the NO_x emission, this will be discussed later.

3.4.2 NO_x

The calculation of NO_x emission is not as easy as the CO_2 calculation. The NO_x emission depends on more variables than only the fuel consumption. The interviewees and some external sources give more information about this.

The fixed input variables

Some input variables are always needed to calculate the emission of NO_x per machine. Most of the interviewees mention these fixed input variables which have to be used in emission forecasting calculations. Fixed input variables in this case means that the variables are always needed in calculations, not that the value of the variable is the same in all calculations.

From the interviewees it becomes clear that these fixed input variables are all data about the construction equipment itself. This means that if a certain specific machine is chosen to be used, the value of the fixed input variables is fixed as well for that specific machine. The fixed input variables are:

- The type of machine
- The type of fuel
- Stage of emission of motor (is linked to the year of construction)
- Power

These input variables are suitable for the emission forecasting model if the data of these variables for construction projects is accessible for Dura Vermeer. They should know which specific machines will be used at a construction project and what emissions specifications mentioned above are. They can do this to some extent.

A small part of the construction equipment is owned by Dura Vermeer, so for this part the data is known. These are mostly electric cranes and small electric equipment. They do not cause emissions at the construction site.

A way larger part of the construction equipment is owned by subcontractors. These are the machines that normally cause a lot of emissions. Dura Vermeer often does not know what kind of equipment subcontractors have and which they will use at construction projects. This is a problem for a functionable emission forecasting model.

Data for fixed input variables from subcontractors

The problem of data accessibility of construction equipment of subcontractors needs to be solved. Without this access, Dura Vermeer cannot work with the model. Dura Vermeer works with dozens of subcontractors which all have many machines, so a general way to solve this problem is needed.

There are two options to handle this problem. The first one is to ask all subcontractors for each construction project what kind of machines they will use at the construction site and what the emissions specifications are. The second is to generate a database with all the machines and their specifications of subcontractors, so Dura Vermeer can ask for certain machines of certain subcontractors.

With the first option, it is be hard to get the data from the subcontractors for every project on time. There are a lot of subcontractors for every project and they differ in ways of communication and interest in helping with emission forecasting. To get them to collaborate every time again and again is very time-consuming.

The second option is time consuming as well, since there is more data needed for subcontractors at once. Gathering all this data takes time, however is not needed again and again for every project, which in the end is expected to save time. Furthermore, this option gives Dura Vermeer the possibility to simulate with emissions of the different machines the subcontractors have. This simulation possibility is one of the very important requirements mentioned by the interviewees.

Because of the total time saving and simulation possibility the second option is better. The emission forecasting model should include a database with all the construction equipment and their emissions specifications. With this the data of the fixed input variables is accessible for Dura Vermeer.

Within this research the emission forecasting model is designed with the database for construction equipment of subcontractors. A start is made with collecting the data from the subcontractors by contacting five subcontractors to see if this data collection is possible. The database is filled with data of two of the five contacted subcontractors to show it works. However, filling the database with the data of all the subcontractors is a lot of work and considered outside the scope of this research due to limited time.

A result of the choice for using data from subcontractors is that they need to collaborate to gain relevant model output. This is a risk, since not all subcontractors will see the need to share all their equipment data. However, this data is very relevant for the forecasts and it is expected that over time, more and more subcontractors see the need to collaborate in sustainability.

Unfixed input variables

If all the machines that are going to be used are known and their fixed emission data factors are known as well, it is important to know how much they are going to be used. There are different methods to calculate this, so it depends on the option chosen which variables are needed. Different interviewees explained different methods for these unfixed input variables.

Essentially in the interviews two different methods to forecast the workload per machine are mentioned. The first method is to forecast the number of logistic actions per machine. This is suggested by interviewees 2 and 3, who respectively have a very high and high level of expertise on the input variables of the model. The second method is to forecast the number of operating hours.

This is how it is done by the AERIUS tool interviewee 1 mentions and also interviewee 6 says this is a good option. They are both regarded as having a very high level of expertise on this topic.

Method 1

The number of logistic actions per machine can be forecasted by knowing the workload per logistic action and the total amount of workload. To combine the number of logistic actions with emission calculations, the created emissions per logistic action should be known or calculated as well. The input variables needed per machine for the first method are:

- Total amount of workload
- The workload per logistic action
- The created emissions per logistic action

Again, these input variables are checked for suitability by looking at the accessibility of the data of these variables by Dura Vermeer.

The total amount of workload can often be derived from the forecasted total load of certain materials. If for example 5000 m^3 of sand needs to be dug out. This stands in direct connection with the amount of workload excavators have to do. The total amount of materials is already calculated in the existing logistic volume-prediction model. The emissions forecasting model is an extension of this model.

The workload per logistic action is not known within Dura Vermeer. For example, how much scoops a excavator needs to dig out a certain amount of sand or how much liftings it takes a crane to lift a certain amount of pipes is unknown. This information was not easily traceable in files and not known by the logistic manager or the construction site manager. They also doubt if the subcontractors know it for their machines.

The created emissions per logistic action is also not known within Dura Vermeer. Besides this, it was also not findable in external files or literature. The assumption within Dura Vermeer is that this is also not known by subcontractors.

In short, Method 1 is not suitable for the emission forecasting model. The accessibility to data for two of the three unfixed input variables is bad. This means it is complicated and a lot of work to get that data if it is even possible at all. This is not in line with the requirement to make the model easy to use.

Method 2

The second method is to forecast the operating hours per machine. To combine the number of operating hours with emission calculations, the created emissions per operating hour should be known. The input variables needed per machine for the second method are:

- The number of operating hours
- The created emissions per operating hour

These variables are checked for suitability as well by looking at the accessibility of the data of these variables by Dura Vermeer.

The number of operating hours of construction equipment is not accurately forecasted by Dura Vermeer. However, the planners always plan certain periods in which certain tasks of the construction projects need to be fulfilled. By taking the number of days of a task and combine them with an estimation of the average operating hours per machine per day for that task, an estimated guess about the number of operating hours per machine can be made. This is not very accurate, but it gives an indication.

The created emissions per operating hour can be derived from a table with default data from the RIVM (The Dutch National Institute for Health and Environment). According to the RIVM (2015) every mobile equipment, like construction equipment has a certain NO_x-emission factor, given the kind of equipment, the type of fuel, the year of construction (this corresponds with the stage of emissions of the motor) and the power. This emission factor is given in gram/kWh and can easily be calculated to gram/h, when the power is known.

In short, method 2 is to some extent suitable for the emissions forecasting model. The first variable is hard to accurately forecast, but it is possible to make an estimated guess. The second variable can easily accurately be derived from a legit source, once the fixed variables are known.

Combined method

From the two methods mentioned in the interviews, the second is the most suitable, but still not very accurate. The first one would be more accurate; however, the data is not available or easily accessible by Dura Vermeer. A third possibility is to use a combination of the two methods to make a possible, more accurate forecasts.

The flaw in the second method is that the number of operating hours is not yet accurately forecasted by Dura Vermeer. However, the amount of workload from the first method is known. The amount of workload can also be an input variable to calculate the number of operating hours per machine. For the combined method only the following input variable has to be known:

- Operating time per amount of workload

The suitability of this method only depends on the availability of data for this variable, since the rest is explained in the previous sections already.

Multiple employees of Dura Vermeer are asked about the operating time per amount of workload. This data is not yet forecasted by logistic employees or project leaders; however, it is sometimes used for costs forecasts by financial employees. This means data for operating time per amount of workload is partly available already.

Files for costs forecasts from within Dura Vermeer show some of these data, especially for the cranes used by construction projects. This is because Dura Vermeer often is responsible for the cranes themselves, while other machines are often from subcontractors. Financial employees of Dura Vermeer expect that (a part of the) subcontractors also make costs forecast by calculating with the operating time per amount of workload. This means this data can be asked from subcontractors the same way as explained for the data for fixed input variables from subcontractors.

When more of this data is known, the combined method can make more accurate emission forecasts. It combines the total amount of workload with the operating time per amount of workload to calculate the operating hours. This combined with the known created emissions per operating hour from the second method gives the emissions.

3.4.3 Conclusion of input variables

Table 4 shows an overview of what input variables are used in the emission forecasting model. It shows for which emission forecasts, which variables are used and sometimes which sub variables are needed to calculate the input variables. Furthermore, the sources of the data are shown. All is derived from the explanations in section 3.4.1 and 3.4.2.

The only part that is not extensively explained is the why the last input variables for the CO_2 forecasts are chosen. This is about using the operating hours as input variables instead of using the logistic actions. As referred to in the last paragraph of section 3.4.1, this is for the same reason as for the NO_x emission forecasts. These variables are most suitable with the availability of the data.

In short, the CO_2 forecasts are done with one relatively simple method, while the NO_x forecasts are more complicated and done in multiple ways. The previously explained accurate method 1 would not be feasible because of lack of data. The combined method is sometimes feasible and used when possible. Method 2 can always be used, however uses more rough estimations. Since the ease of use and workability is regarded more important than the accuracy in the first version of the model, this is a logical choice.

Table 4 The input variables for the emission forecasting model

Emission	Input variable	Sub variables	Source data
CO_2	CO_2 emissions per unit of burned fuel		Environmental Protection Agency (EPA)
	Burned fuel per operating hour per machine		Dura Vermeer + subcontractors
	Number of operating hours per machine	Total amount of workload	Dura Vermeer
		Operating time per amount of workload	Dura Vermeer + subcontractors
NO_x	The type of machine		Dura Vermeer + subcontractors
	The type of fuel		Dura Vermeer + subcontractors
	Stage of emission of motor / year of construction		Dura Vermeer + subcontractors
	Power		Dura Vermeer + subcontractors
	The created emissions per operating hour		RIVM
	The number of operating hours		(Method 2, rough) Dura Vermeer
		Total amount of workload	(Combined method) Dura Vermeer
		Operating time per amount of workload	(Combined method) Dura Vermeer + subcontractors

3.5 Model description

The previous sections explained all the research that was needed before the model could be built. The requirements of the model, all the input variables and the reasoning behind the choices for them are known. The last step of the results is the actual emission forecasting model.

This section provides the complete model description. It gives technical insights of how the model works including used formulas and visualizations of the model. It explains from which parts the model is built and how the different parts are connected. Per part it also explains the data sources it uses and the model tasks that need to be done by employees of Dura Vermeer to work with the model.

Figure 5 shows a graphical overview of the different model parts. The blue rounded rectangles show these different model parts. For every part the data source(s) are shown above with grey rounded rectangles. Some model parts result in certain model tasks that need to be performed by the user of the model. The green rounded rectangles in the graphical overview show these tasks.

The model parts are separated to make a logical difference in how the model is setup. It distinguishes how data sources are used and when model tasks need to be performed. This is done to make the model more understandable and therefore to improve the ease of use.

The data sources are shown to make the user understand where data comes from, in case data needs to be updated are improved.

The model tasks are shown to make the user understand which tasks need to be performed every time the model is used. Parts without tasks are static for the user, which means they do not need any activity to be ready for the forecasting. Tasks regards model parts with dynamic data, for which choices need to be made for every construction project.

All the model parts are explained step by step in more detail below. For every part of the model a small element is visualized in the report. This is the element of excavating (in Dutch "afgraven (=grondwerk)), since this gives insights into the functioning of the model. Appendix D shows complete screenshots for every part of the model. The model itself is in Dutch to fit the problem owners' requirements (the main language within Dura Vermeer is Dutch).

Part 1: Work packages and workload

Every construction project can be divided into certain work packages that need to be fulfilled to complete the construction. This division can be used to later derive equipment that is needed to complete the packages and cause emissions. In total 25 packages are distinguished, for example demolition work, excavating, piling work, roof construction, etc. Each work task has a certain workload, for example 1,000 m^3 of excavating, 640 pieces of piling work, etc.

The source for these task division is the previously mentioned logistic volume prediction model of Dura Vermeer. Since the emission forecasting model is an extension of this model, it is easily connected.

The division of work packages and workload is already done in the source data, which makes this part of the model a static part, from which no tasks for the user are derived.

Figure 4 shows an example of the work package excavating with the corresponding workload. Appendix D.1 shows the complete division of work packages.

[redacted]

Figure 4 The work package and workload of excavating

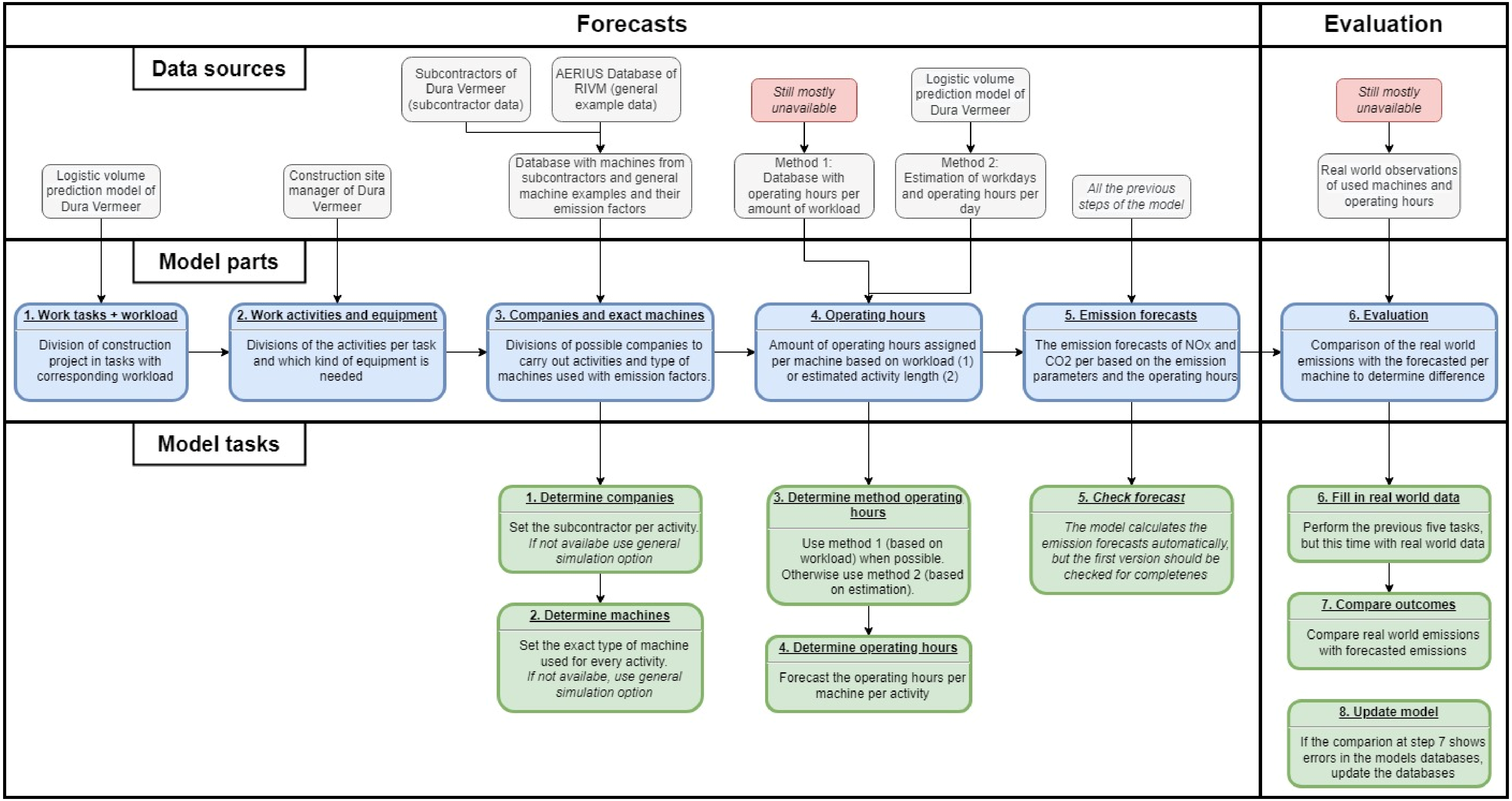

Figure 5 Graphical overview of the emission forecasting model with data sources, model parts and model tasks

Part 2: Work activities and equipment

For every work package certain activities need to be carried out during the construction. These activities determine what kind of equipment is needed to complete the activity. This is about general construction activity terms like lifting, pile driving, pouring, filling, etc. These activities are done by certain kinds of equipment, like cranes, excavators, pile drivers, etc.

The source for these activities and equipment is a construction site manager of Dura Vermeer who has many years of experience in managing construction projects on site and knows what activities and equipment is needed for every work package.

Since the model includes all equipment possibly used according to the construction site manager, this part is static for the user as well. No tasks are derived from this step.

Figure 6 shows an example of the activities and possible used equipment for the work package excavating. Appendix D.2 shows the complete division of work packages.

[redacted]

Figure 6 The activities and possibly used equipment of the work package excavating

Part 3: Companies and exact machines

Often a work package with its activities and its equipment is carried out by a subcontractor. These subcontractor companies determine which exact machines are used on the construction site. This is why it is important to know these companies, their machines and their emission factors. Part 3 of the model is about these machines.

The source for these companies and their machines is a machine database created for this research. This database should include all the possible subcontractors of Dura Vermeer and their machines. The machine data that needs to be known is explained in section 3.4.3 in Table 4 and this is automatically linked to emission factors. These emission factors are derived from the AERIUS database of the Dutch RIVM.

Filling the whole database is a lot of work. This is why it is done for a few subcontractors of Dura Vermeer to show the functioning of the model. Completing the database is regarded outside the scope of this research.

The machine database does also include general examples of machines with different emission factors. These can be used when the subcontractors or exact machines that are going to be used are not yet known when the model is used for forecasting. These general examples are derived from the AERIUS database as well. Since this database includes all possibilities, these general examples can be used to forecast the difference machine choices make and simulate with different outcomes.

This is the first non-static part of the model, because two tasks need to be performed by the user of the model. In the model yellow cells mean a task needs to be performed and a choice needs to be made by the user, as shown in Figure 8.

For every row, two tasks need to be performed. The first task is to determine the company (often subcontractor) who is responsible for the machines for every task and every work package. A choice needs to be made from the database with companies and machines. The second task is to determine which exact type of machine is going to be used. This is also a choice from the same database. The choices for exact machines are automatically linked to emission factor in the model. Figure 7 shows an example of the tasks for an excavator.

[redacted]

Figure 7 Task 1 and task 2, determining the company and exact machine used

Figure 8 shows an example of the companies and exact machines used for the work package excavating. Because of privacy reasons, no real company names are shown, but the simulation possibility is used. Appendix D.3 shows a complete

[redacted]

Figure 8 The companies and exact machines used with the emission factors

Part 4: Operating hours

After part 3 it is known which exact machines are going to be used at the construction projects and what their emission factors are. The only factor missing to calculate the emissions per machine is the operating hours. Part 4 is to determine these operating hours in two possible ways.

The different ways of calculating operating hours are explained at Chapter 3.4 at the section of unfixed input variables. In the model (see example Figure 9), the first method is the combined method of Chapter 3.4 and the second method is method 2.

The source for the first method ideally is a database with the exact operating hours for every workload (as shown in part 1). However, this is still mostly unavailable, which is why there is a second, more rough method.

The first method to calculate the operating hours:

$$OT_w * WL_t = OT_t$$

With:

- OT_w = Operating time per machine per amount of workload of related work package in hours
    - Mostly unavailable
- WL_t = Total amount of workload of related work package
    - Source: part 1 (from logistic volume prediction model)
- OT_t = Total operating time per machine for related work package in hours

The second method to calculate the operating hours:

$$WT * OT_d = OT_t$$

With:

- WT = Working time of related work package in days
    - Source: logistic volume prediction model
- OT_d = Operating time per working day in hours
    - Educated guess from user or employee
- OT_t = Total operating time per machine for related work package in hours

Task 3 that comes with part 4 is to determine which method to use to predict the operating hours. This means that if data for method 1 is available, this method should be used. Otherwise, Method 2 is used.

Task 4 is to forecast the operating hours by filling in the yellow cells in Figure 9. Ideally these data are known and the same for every project. However, in practice it would often be an educated guess by the user, since the data is not known.

Figure 9 shows an example of calculation of operating hours for the machines of the work package excavating. For the first row (the excavator) data for Method 1 is known, so this method is used. For the other three rows Method 2 is used. Appendix D.4 shows a complete example of determining the operating hours for a whole project.

[redacted]

Figure 9 The operating hours calculated with method 1 (row 1) and method 2 (row 2, 3, 4)

Part 5: Emission forecasts

Part 5 considers the actual emissions forecasts for every machine per work package. The emissions of both NO_x and CO_2 are forecasted. All the input variables explained in Section 3.4.3 are used.

The method to calculate the emission of NO_x:

$$OT_t * PWR * LD * EMF * \frac{1}{1000} = EMNO_x \;\; (AERIUS, 2020)$$

With:

- OT_t = Total operating time per machine for related work package in hours
  - Source: part 4 of the model
- PWR = Power of machine in kilowatt
  - Source: machine database
- LD = Load of machine in percentage
  - Source: machine database
- EMF = Emission factor in gram NO_x per kilowatt-hour
  - Source: machine database
- $\frac{1}{1000}$ = Division by thousand to go from grams to kilograms
- $EMNO_x$ = Total emission of NO_x of a machine for that related work package in kilogram

The method to calculate the emission of CO_2:

$$OT_t * FCD * 2.668 * \frac{1}{1000} = EMCO_2$$

With:

- OT_t = Total operating time per machine for related work package in hours
  - Source: part 4 of the model
- FCD = Fuel consumption diesel in liter per hour
  - Source: machine database
- 2.668 = Emission factor of CO_2 per liter diesel burned
  - Source: Environmental Protection Agency, 2005
- $\frac{1}{1000}$ = Division by thousand to go from grams to kilograms
- $EMCO_2$ = Total emission of CO_2 of a machine for that related work package in kg

No direct tasks are needed to complete part 5 of the model. However, task 5 is added, to check the emission forecast calculations. Since not all data is available to calculate the forecasts yet, a human check is necessary.

Figure 10 shows an example of the calculated forecasts of emissions of NO_x and CO_2. The cells are green to highlight the final forecasts of emissions. D.5 shows a complete example of emissions forecasts for a whole project.

[redacted]

Figure 10 The calculated emission forecasts of NO_x and CO_2 for the four machines used at excavating

Part 6: Evaluation

The last model part is the evaluation of the forecasts based on real world data, part 6 of the model. It consists of a second usage of the model, but this time with measured data from a construction project. This way the delta between the forecasted emissions and the actual emissions can be calculated.

The accuracy of the forecasts can be measured and evaluated for every machine and work package. This way, exact deviations in the forecasts can be recognized. This is important for improving future forecasts. The new knowledge can be used to determine inaccurate input data in the forecasts or flaws in the model. The next time the model is used the flaws can be left out and input data can be more accurate.

The source of these evaluation should be real-world measured data. This includes registration of the exact machines used for every work package, how long the machine is operating, etc. At the moment Dura Vermeer does not keep track of all the data needed for evaluation, which is why the correct data is still mostly unavailable. Data collections should be done more extensively for good evaluations.

The specific tasks can be distinguished in three tasks. Task 6 is filling in the model with measured data and calculating the real emissions of the construction project. Task 7 is the comparison of the real emissions with the forecasted emissions to gain knowledge about the deltas. Task 8 is improving the model with the gained knowledge (if necessary).

Figure 11 shows an example of emission deltas for the work package excavating. This includes the deltas of operating hours, emission factors per machine and total emissions of NO_x and CO_2 per machine. Appendix D.6 shows a complete example of the evaluation part of the model.

[redacted]

Figure 11 The deltas of the operating hours, emission factors and total emissions for the work package excavating

Conclusions model description

The six model parts with their sources and tasks form the complete emissions forecasting model. The model can be used for detailed emission forecasting of NO_x and CO_2 of machines on the construction site. However, some model parts require data which is not always available. This means a complete usage of the model will be not possible in this stage. The model does show which actions should be taken to make the model more complete with extra data. Furthermore, the model will improve with trial and error of the users in the first version.

4. Validation

To answer sub-question 3: "To which extent does the tool meet the set requirements?", we validate the emission forecasting model. Chapter 4 explains this validation.

The validation contains two levels of validation.

1. Chapter 4.1, provides a small self-reflection demonstration of the model implemented in a construction project of Dura Vermeer in practice. The tool is validated by the researcher on the set requirements. This provides insights in the level to which the tool and data can meet these requirement. Per part and task, it is explained how well it functions.
2. Chapter 4.2 is about a validation based on a sensitivity analysis. The influence of different values of the input variables on the emission forecasts is explained.

4.1 Self-reflection demonstration

The demonstration of the emission forecasting model is done for project Zwolle Breezicht of DVBH. This project covers the construction of 32 houses in a new neighborhood on the edge of the city of Zwolle. It is part of a bigger construction project in which DVBH also constructs more houses, however this demonstration will focus on these 32 houses.

Trying to use the emission forecasting model in a real-life situation gives complications. This is expected, since it became clear from the requirements that the first version of the model cannot be perfect. Interviewees said the first model can be "very rough" and should be "improved by trial and error on the long term".

This self-reflection shows to which extent the model can be used as a final functioning model which it should eventually be. Per model part and model task it is explained which complications arise and how serious these are. The complications are placed into perspective to which extent they influence the requirements acquired from the interviews.

A precise explanation of all the requirements is given in Chapter 3.2. The most important requirements to validate on are:

- Ease of use (very important)
- Accuracy (important)
- Simulation possibility (very important)
- Future proof (very important)

The requirements 'extent', 'link with BIM-model', 'include financial aspect' and 'cause behavioral change' are all limited or not important, which is why the focus of this validation is not on them.

Appendix E shows screenshots of the filled in model for the construction project. Since the functioning of the model is already made clear in Chapter 3.5 Model Description, this is not discussed in the demonstration.

Part 1: Work packages and workload

To start with the emission forecasting model, part 1 of the model, the data from the logistic volume model and task division should already be made. This is regarded fixed input for the emission forecasting model, since the logistic volume model was made before this research. This is good for the requirement 'ease of use'; however, this does not mean that the input parameters are perfect realistic.

A complication with using data of part 1 for the model, is that the logistic volume model is in practice not fixed on the long term. The division of work packages changes (and improves) with newer versions. This means that the work package division for the emission forecasting model should be updated as well.

This complication is not a problem on the short term, because then the data is fixed. However, to fulfill the requirement of 'future proof', which is regarded very important, this is not positive. It requires detailed manual updating of Excel sheets of the emission model with every update of the logistic model. In long term, this will however improve the 'accuracy'.

Part 2: Work activities and equipment

The work activities and equipment (part 2) of the model is also a fixed part for the short-term users of the model. This is again good for requirements 'ease of use', but it comes with the same problem on the long term. If way part 1 of the model changes or if the way of construction for a certain work package changes and different equipment is needed, this part should be updated manually as well.

Part 3: Companies and exact machines

Part 3 of the model is to determine all the companies/(sub)contractors for every work task. First the good company should be chosen (task 1) and then the exact machines should be chosen (task 2). This provides many possibilities, but also many complications, often resulting in a weighting one requirement to the other.

For the construction project Zwolle Breezicht, it was very hard to determine the companies and exact machines that were going to used. This information was not known withing DVBH and subcontractors did often not know this too. That is why a lot of assumptions were made about the exact machines that were going to be used or the general simulation option was chosen. From this process, the possibilities and complications became clear.

The possibility to choose many companies and many machines is very good for the requirement 'simulation possibility', because all combinations of machines and their emissions can be tested quickly. The complication however is that this is only possible when the database with companies and machines is completely filled and updated frequently. This again means updating it often on the long term will take a lot of work, which is not very 'future proof'.

On the other hand, the 'ease of use' on the short term is very high when the database is complete and updated before the model is used. Then it means the correct companies and machines can easily be selected from the list.

Here however, the 'accuracy' of the forecasts has to be weighted to the completion time (and with that 'ease of use'). It is very easy to use simulation examples as machines for emission forecasting, but this is not accurate, since the exact machine in practice may differ from a general example. On the other hand, to know the exact machine to be used is not very easy, since this often comes from other companies.

This regards one of the biggest complications of the model. Often when emissions forecasts need to be done, the subcontractors are not fixed yet and the exact machines the will use are not known at all. This means either a lot of time and effort should be put in to get this information for every forecast or less accuracy should be accepted.

Part 4: Operating hours

Determining the operating hours is also a very hard step in the process of demonstration. First the correct method should be chosen (task 3) and then the exact operating hours should be forecasted.

Most parts again depend on the availability of data, which is often not complete and hard to estimate. For example, the average operating hours per day for a machine for a certain work package are hard to estimate when that machine works on multiple work packages. For project Zwolle Breezicht rough estimations are made.

Determining the way of calculation (task 3) depends on the availability of data, which results in the same complications and trade-offs as at part 3, 'accuracy' versus 'ease of use'. On this level however, if the data for method 1 is attained correctly, it can be used on the longer term, which improves both 'accuracy' and 'ease of use', since it is not needed to update every forecast.

Then determining the operating hours with method 2 is a hard estimate, since no data is available on how long a machine works for a certain work package. This results in rough estimates which are bad for the 'accuracy' and are not easy to guess as well. This data will also differ per project, which makes it not 'future proof'.

Part 5: Emission forecasts

The emission forecasts made in the fifth part of the model are relatively easy. Also for project Zwolle Breezicht, the forecasts are made automatically based on the choices made in earlier parts of the model. The only task that needs to be done is checking the forecasts for completeness and correctness.

This part of the model has a high 'ease of use', since the forecasts are made automatically according to the formula explained in Chapter 3.5. If data for the calculation is unavailable the model automatically fills in question marks in the answers. For Zwolle Breezicht it is chosen to leave out these forecasts, while it is also possible to manually estimate some unavailable data.

Furthermore, the requirement 'future proof' is good for this part of the model, since the way of calculating emissions is a standard method, which does not need updates frequently. The 'accuracy' of the calculations itself is good as well, however the input variables determined in previous parts can have less accurate values.

Part 6: Evaluation

The evaluation part is not demonstrated for project Zwolle Breezicht, because the project was not finished when this research is conducted. This means it is hard to determine the complications that will derive in this step. However, some predictions about possible complications can be made.

Again, a problem with the availability of data can arise. At the moment Dura Vermeer does not register which exact machines are used and how many hours they operate. Without this data a evaluation cannot be made. This means that the evaluation will be impossible, inaccurate or probably time consuming. Methods for this still need to be determined.

Conclusions model demonstration

Most parts of the model can be used to make an emission forecast for a construction project. However, there are still a lot of complications with the first version of the model. Often trade-offs between multiple important requirements need to be made to work with different parts of the model.

For example, the 'ease of use' can often only be high, when a lower 'accuracy' is guaranteed. This lower 'accuracy' is sometimes also a result of a higher 'future proof' requirement. There seems to be a trade-off between 'ease of use' and 'future proof' as well. Last, the extension of the 'simulation possibility' causes a lower 'future proof' of the model.

Often the trade-offs regard problems with unavailable or hard to collect data. This is a logical result of making a model in a relatively new field of research in the construction sector, with previously unknown variables. It can be expected that the level of the requirements improves with more trial and error and more efficient and effective ways of data collection.

4.2 Sensitivity analysis

The second way of validating the model is a sensitivity analysis. A general case of a forecast with the model is compared with other forecasts on multiple levels. First of all, a general case is compared with a worst-case scenario and a best-case scenario. Second, the influence of the levels of some of the most important input variables is tested to determine what is most important.

4.2.1 Worst case – best case

In this part of the validation, a general case forecast is compared with a worst-case scenario and with a best-case scenario. This means that the general case is placed in context of a scale of very high possible emissions (worst case) to very low possible emissions (best case). This way an indication of the error bounds of a forecast can be made.

General example

The general case used is the demonstration of project Zwolle Breezicht from Chapter 4.1 and Appendix E. For this example, the following decisions are made:

- Possible (sub)contractors were chosen if available from the database, based on historic (sub)contractors.
  - Otherwise, the simulation possibility is used.
- Average exact machine (in terms of emission factors) was chosen from the database of the chosen (sub)contractor.
  - For the simulation options, an alternation between good and bad performing machines (in terms of emissions factors) were chosen.
- Operating hours were based on an estimation of workload and operating days

This results in an emission forecast of in total 176.9 kg NO_x of and 24047.2 kg of CO_2. The forecast of CO_2 is not complete due to some missing data.

Comparison

To compare the general case with the worst case and best-case scenarios, the evaluation part of the emission forecasting model is used. For both cases the evaluation is simulated with different input data (the worst and best cases). This part of the model automatically compares the output of both scenarios with each other. The comparison of the general case and the worst case can be found in Appendix F.1. The comparison of the general case and the best case can be found in Appendix F.2.

Worst case

The worst-case scenario still needs to be realistic, which is why the bases is the general case and some adjustments were made:

- Still the same (sub)contractors were chosen if available from the database.
- In this case, the (sub)contractors come with their oldest, least performing machines (in terms of emission factors)
- The operating hours were estimated higher than in the general case. We assume a maximum error of 30%, which is the amount with which the operating hours are increased for every activity.

This results in an emission forecast of in total 865.2 kg NO_x of and 16850.9 kg of CO_2. Again, the forecast of CO_2 is not complete due to some missing data.

Best case

The best-case scenario also is derived from the general case. The following choices made are:

- Still the same (sub)contractors were chosen if available from the database.
- In this case, the (sub)contractors come with their newest, best performing machines (in terms of emission factors)
- The operating hours were estimated lower than in the general case. We assume a maximum error of 30%, which is the amount with which the operating hours are increased for every activity.

This results in an emission forecast of in total 38.2 kg NO_x of and 10255.7 kg of CO_2. Again, the forecast of CO_2 is not complete due to some missing data.

Conclusion worst case – best case sensitivity analysis

Table 5 shows an overview of the created emissions of NO_x and CO_2 for the general, worst- and best-case scenarios for the project Zwolle Breezicht of DVBH. Next to this it compares the values of the different scenarios. The forecasts of CO_2 are not complete everywhere, which is why these comparisons are regarded less relevant than the NO_x comparisons.

Table 5 The forecasted emissions of NO_x and CO_2 for the general, worst- and best-case scenarios and their comparisons for project Zwolle Breezicht.

	General	Worst	Best	General – Worst	General – Best	Worst – Best
Emission of NO_x	176.9	865.2	38.2	-688.4	138.7	827.0
Emission of CO_2	*24047.2*	*16850.9*	*10255.7*	*7196.3*	*13791.6*	*6595.2*

What becomes clear from this table is that the three scenarios differ substantially in the amount of emissions forecasted. The best scenario has a 78% lower forecast of NO_x than the general case. The worst has a 289% higher forecast of NO_x than the general case. This means that a worst case scenario has a forecast which is almost four times as high as a general case. A sensitivity factor of 4 is very high, which means the current model is not usable by construction companies yet.

The forecasts of CO_2 are regarded less relevant, however the calculation errors are not that different in the different scenarios. It can be derived that the cleaner machines in the best scenarios have a higher influence on NO_x reduction than on CO_2 reduction.

The maximum width of error of the NO_x forecasts derived from these scenarios lies between [22%,389%] of a general example. An example from a maximum error mentioned in the interviews is [70%,130%] (deviation of 30%) or even [80%,120%] (deviation of 20%). From this we can derive that the current emission forecasting model does not make forecasts with a good accuracy. On the other hand, some other interviewees mentioned that the accuracy is not something binding in the first version of the model.

4.2.2 Important input variables

Since the previous validation gave the most complete results for the emission forecasts of NO_x, the sensitivity analysis for important input variables is also only made for NO_x. It can also be done for CO_2, however this is regarded less relevant. To validate the influence of all different variables is regarded outside the scope of this research due to time constraints.

We first take a look at all the different input variables of the formula for the emission of NO_x (same formula as in Chapter 3.5).

$$OT_t * PWR * LD * EMF * \frac{1}{1000} = EMNO_x \quad (AERIUS, 2020)$$

With:

- OT_t = Total operating time per machine for related work package in hours
- PWR = Power of machine in kilowatt
- LD = Load of machine in percentage
- EMF = Emission factor in gram NO_x per kilowatt-hour
- $EMNO_x$ = Total emission of NO_x of a machine for that related work package in kilogram

If we take a look at the formula, we see that all variables have the same order of influence on the emission of NO_x, i.e., a percentual difference in one of the values has the same influence on the total emissions of NO_x for alle variables. That is why this sensitivity analysis focusses on the determination of which changes in variables can be of biggest influence for emission reduction in practice.

The OT_t per machine is something that could be optimized to a certain extent. In Chapter 4.2 we assumed that the boundaries for worst case and best case are about 30% lower or higher than an average value. This means that a reduction from worst case to best case scenario can mean a reduction of $\frac{70\%-130\%}{130\%} = -46\%$. This is a very rough estimation, since we do not exactly know how much the OT_t can really be reduced. However, we can assume that it could be a significant difference, however a reduction of more than 50% would be very (probably unrealistically) high.

The PWR of a machine can very a lot. For example, according to the AERIUS (2020) database there are excavators with 28 kW and excavators with 375 kWh. The reduction from highest to lowest value can be $\frac{28\%-375\%}{375\%} = -93\%$. This is a lot; however, this is not possible in practice for emission reduction. The PWR of a machine is often a prerequisite for a certain construction task, which is why it is not possible to change the emissions by taking machines with lower kW. Machines with unnecessary high PWR are often not chosen because they are more expensive.

The LD is a given value for a certain type of equipment, e.g., it is 50% for a crane (AERIUS, 2020). Because most tasks cannot be carried out by other type of equipment than usual, this is not suitable for emission reduction as well.

The EMF of a machine depends on the type of motor a machine has and how 'clean' this type is. In practices how 'clean' the motor is only depended on the year the machine is built (and the regulations for motors after that year). This in combination with the kind of machine gives the EMF. According to the AERIUS (2020) database the EMF of a crane can differ between 8.9 (constructed after 2001) and 0.4 (constructed after 2015). This means that a newer crane can reduce the emission of NO_x by $\frac{0.4-8.9}{8.9} = -96\%$. Since this EMF has nothing to do with the construction performance of a machine, it means focussing emission reduction of NO_x on reducing the EMF is very suitable.

Conclusion of important variable sensitivity analysis

The most important input variable for emission calculation of NO_x is the EMF. To reduce emissions significantly, it is very effective to use newer machines with cleaner motors. It can reduce emissions of NO_x with 96%.

Another interesting factor to take into account is the OT_t of a machine, which can in practice also be reduced significantly up to an estimation of 50%. For the other variables for emissions calculations of NO_x it is in practise harder to make changes.

5. Discussion & Conclusion

This chapter contains the discussion, conclusion and recommendations for further research. Chapter 5.1 places the results, limitations and other findings into context. Chapter 5.2 summarizes the research and concludes the main observations. Finally, Chapter 5.3 gives some recommendations for further research.

5.1 Discussion

Emissions at the construction site are a large problem for the environment surrounded. Dura Vermeer is a progressive construction company that wants to reduce the negative environmental impact of their projects and wants to be ahead on the level of emission regulations. To reach their environmental goals, Dura Vermeer need to be able to forecast their emissions on a more detailed level.

The goal of this research became to design an emission forecasting tool that satisfies the requirements of the construction companies so that they can investigate where emissions can be reduced and show they meet regulations for emissions at construction projects.

In literature, most environmental assessments of construction projects were made from an external perspective (so outside the construction company). These assessments were often used as a form of judgement instead of possibility for optimization and reducing negative environmental impact. These environmental assessments were not exactly in line with the goals of construction companies as stakeholders.

This research answers the question which kind of requirements an emission forecasting tool should meet to fulfill the construction companies' goals. In six semi-structured interviews, these requirements are derived and assessed on importance. The requirements that are addressed during the interviews as important often and by people who are regarded having a relative high level of expertise are important requirements.

The second question this research answers is where the focus of emission forecasts should be placed. Emissions are generated in a lot of ways on a lot of places and it is impossible to forecast everything at once. Stakeholders indicate that the most important cause of emissions at construction projects is the construction equipment. Furthermore, this is most unknown by construction companies, which means a lot of improvement can be done.

The findings from the six interviewees are accepted as general construction company stakeholder requirements. It is hard to say with certainty that this is true, since all interviewees are approached the same way and from the same perspective. However, the interviewees have different points of view and differences in answers were noticed often and only repeating answers are generalized as important for the stakeholders.

The main findings of the stakeholders are combined with relevant literature and databases to generate an emission forecasting model for construction equipment at construction sites. This model gives the construction companies new insights in the more detailed way how these emissions are created.

On the other hand, the emission forecasting model needs a lot of data, which is often unavailable or really hard to get. This is why the new forecasting model is not functioning very good. Its accuracy is very low. The maximum width of the error of a forecast of NO_x is [22%,389%] of a general case. This implies a sensitivity factor of 4. This is not usable for a construction company, since the deviation can be very high and there is no way of knowing the exact emissions.

Improvements in accuracy will trade-off against other important requirements such as 'ease of use', 'future-proof' and 'simulation possibility', where these other requirements also have trade-offs to each other.

This research is limited to a first version of the emission forecasting tool. To see if the model can eventually make accurate forecasts and help the construction companies be more sustainable, more research is needed. More efficient ways should be determined to get the input data for the model and the model should be improved by trial and error in real-life context more often.

However, this does not mean the emission forecasting model does not provide interesting insight. Now the construction companies now in more detail were what kind of extent of emissions are created. Furthermore, they know which data they should collect, to make accurate forecasts of this. Next to this, the first emission forecasting model already provides a framework to build on and improve the forecasting.

5.2 Conclusion

Construction companies like Dura Vermeer need to develop in the area of emission forecasting to achieve sustainability goals. This research provides insight in what the construction companies as stakeholders want and what they need to get this. It provides a first version of an emission forecasting tool that could be used as a framework to build future forecasting tools on.

What construction companies want is an easy to use, accurate, future-proof emission forecasting tool with simulation possibilities for optimization. These are the requirements that are regarded important by themselves. In the future they want to broaden these requirements, however they also see that they need to start small.

What construction companies need to get this, is more data about their current emissions. The focus should more be on construction equipment at the construction site, which are big polluters. Data about these machines that influence emissions like the year on construction, power and operating hours should be easier accessible and with that better predictable.

An emission forecasting tool is a complicated tool. This research provides insights in a possible setup and what data is needed. However, a lot of improvement is needed before such a model can be used to make easy, accurate forecasts.

5.3 Recommendations for further research

There are many possible ways to improve the emission forecasting tool proposed in this research. There are some general important recommendations. Next to this, a extensive recommendation for a user validation is given, since this is regarded important for the implementation of newer versions of the tool.

5.3.1 General Recommendations for further research

This Section provides some general recommendations for further research. These extensions mostly focus on increasing the accuracy or extent of the emission forecasting model. These recommendations are not carried out in this research due to the specific focus explained in Chapter 3 and time constraints.

- There should be closer contact with subcontractors about the exact machines they have used and will use in the future for construction projects. This is necessary for more accurate forecasting.
- The operating hours of machines should be registered. From this data more accurate forecasts of future number of operating hours can be made.

- Board computers of construction equipment can be linked to the emission forecasting tool so data is automatically registered and forecasts can automatically be improved.
- The emission forecasting tool should be upgraded with financial aspects. This way mutual improvements can be spotted for both environmental and financial reasons. Also considered trade-offs can be made.
- The emission forecasting tool should be linked with BIM-models. This is the way of working withing Dura Vermeer and data is registered more structured in BIM-modelling.

There are many possible ways to improve the emission forecasting tool proposed in this research. There are some general important recommendations. Next to this, a extensive recommendation for a user validation is given, since this is regarded important for the implementation of newer versions of the tool.

5.3.2 Recommendation for user validation

The user validation would in a general way add value to the validation of the emissions forecasting model. This is because one of the foundations of the model is the (user) requirements determined in Chapter 3.2 derived from the interviews. Testing the model on these requirements by users within Dura Vermeer could give a good assessment of the model key-points. Furthermore, Chapter 1.3 shows that one of the things lacking in current literature is that emission forecasting models for construction companies are often not made from the point of view of a construction company (employee) as user. They are often made for external users. This is why the model could be tested by one or multiple users within Dura Vermeer.

During the user validation, the users can give their opinion on all the requirements mentioned in Chapter 3.2. They are asked to give their opinions on every requirement (no matter how important the requirement), to see if requirements that are regarded more important also score higher than requirements that are regarded less important.

They asses the model for eight requirements and they are asked to which extent the model meets the set requirements. Every requirement is shortly explained in key words, so the user knows what is meant by them. They asses each requirement on a scale from 1 to 5. This gives sufficient freedom to give a good assessment, however is not so specific, since the questions are somewhat subjective. Appendix G shows the complete user validation form.

The user validation forms could be used to give a good view of the functioning of the model and to which extent it meets the set requirements. Next to a numerical assessment, the users are asked for an explanation, which could serve as extra justification for the assessment. The user validation can in the future also potentially be used to improve the emissions forecasting model.

Although the user validation would have general added value to this type of research, it is not done for this specific research. The reason that this is not carried out, is because the lack of connection between the results of the first final version of the model and the actual goals of the users.

The research and the model give some new insights in interesting requirements, input variables and calculations. However, the first version of the final model is not yet in a phase to be used with the goals it is meant for on the longer term. As explained in previous validations, there are still a lot of complications and to big trade-offs between certain requirements, which makes the model not very good functioning.

The user validation would be of higher value after further development of the model. However, this is regarded outside the scope of this research due to time constraints.

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Appendix A: Systematic Literature Review

This appendix contains all the steps of my systematic literature review used for section 1.3.

1. **Research question**

The research question is about already used models and theories for designing a solution for the same problem I am facing: designing a tool that can forecast emissions for construction projects. It is useful for providing a conceptual problem framework to my research. The research question is:

"Which models and theories are used in literature for designing an emission forecasting tool for construction projects?"

2. **The inclusion and exclusion criteria**

This section is about the inclusion and exclusion criteria for articles that are used in this systematic literature review. According to information specialist Peter Noort (2019), inclusion criteria are must-haves for an article to be included in the review and exclusion criteria are factors that make an article ineligible to be included. Table 6 shows the selected criteria.

Table 6 Inclusion and exclusion criteria

Number	**Exclusion criteria**	**Reason for exclusion**
1	Pre 2010-articles	Emission forecasting at construction projects is a relatively new and fast developing scientific area. It is expected that articles before 2010 are significantly less valuable then more recent papers on this topic.
2	Articles about air quality inside buildings	This does not regard the topic of emission forecasting of construction projects.
Number	**Inclusion criteria**	**Reason for inclusion**
1	Article must regard construction project during construction phase	The goal of the overall research is to develop an emission forecasting tool with the main focus on the construction phase. If this is not included, the article is considered not relevant.

3. **The used databases**

For this systematic literature review, I used the databases of Scopus and Web of Science. According to Peter Noort (2019), these are both multidisciplinary scientific databases with tens of millions of reports. This gives a broad supply of potentially useful papers.

4. **The search terms and the used strategy**

The search terms are based on the main concepts of the research question. The main concepts are:

1. Models and theories
2. Emission
3. Forecasting
4. Construction projects

The search terms are distinguished in the four categories of the main constructs. The terms used are:

1. Model*, theor*, artifact, artefact, prototype, tool
2. Emission*, environment, "greenhouse gas*", CO2, NOx

3. Forecast*, predict*, estimate*, calculate*, expect*, prognos*
4. Construction, building

The strategy is to first search in a broad way and to narrow it down to more focused search. For Scopus, this means I check how many articles there are with a search term of each four of the main constructs in the Article title, Abstract or Keywords. This probably are a lot, so I have to narrow down the scope of the search to find the most relevant articles. For Web of Science this goes about the same way.

5. **Search-documentation – From number of entries to the final set of articles**

Table 7 shows in which way, which number of the articles are found in the databases and eventually selected.

Table 7 Search documentation

Search string	**Scope**	**Date of search**	**Data range**	**Number of entries**
Search protocol for Scopus				
(model* OR theor* OR artifact OR artefact OR prototype OR tool) AND (emission OR environment OR “greenhouse gas*” OR CO2 OR NOx) AND (forecast* OR predict* OR estimate* OR calculate* OR expect* OR prognos*) AND (construction OR building)	Article title, Abstract or Keywords	16-04-2020	2010 - 2020	17,281 (too much / not useful)
(model* OR theor* OR artifact OR artefact OR prototype OR tool) AND (emission OR environment OR “greenhouse gas*” OR CO2 OR NOx) AND (forecast* OR predict* OR estimate* OR calculate* OR expect* OR prognos*) AND (construction OR building)	Article title	16-04-2020	2010 - 2020	33
Search protocol for Web of Science				
(model* OR theor* OR artifact OR artefact OR prototype OR tool) AND (emission OR environment OR “greenhouse gas*” OR CO2 OR NOx) AND (forecast* OR predict* OR estimate* OR calculate* OR expect* OR prognos*) AND (construction OR building)	Topic	16-04-2020	2010 - 2020	27,138 (too much / not useful)
(model* OR theor* OR artifact OR artefact OR prototype OR tool) AND (emission OR environment OR “greenhouse gas*” OR CO2 OR NOx) AND (forecast* OR predict* OR estimate* OR calculate* OR expect* OR prognos*) AND (construction OR building)	Title	16-04-2020	2010 - 2020	37
Total				**70**
Removing duplicates				-23
Selecting based on exclusion / inclusion criteria				-32
Removed after reading				-6
Total selected for review				**9**

6. Conceptual matrix with articles and summary of the main findings

Table 8 provides an overview of the articles selected for the review. It contains the basic reference information about the article, as well as the research method and the key findings regarding the main constructs of the research question. The number in the first column is used for referencing in step 7.

Table 8 Conceptual matrix with key findings

Number	Article	Authors (year)	Method	Key findings
1	Integrated CO2, cost, and schedule management system for building construction projects using the earned value management theory	Kim, J., Koo, C., Kim, C.-J.b, Hong, T.a, Park, H.S.a (2015)	Developing an integrated CO2, cost, and schedule management (ICCSM) system	The ICCSM system allows a project manager to monitor and forecast CO2-emissions and costs, based on the construction schedule, simultaneously.
2	Life cycle assessment of the air emissions during building construction process: A case study in Hong Kong	Xiaoling Zhanga, Liyin Shen, Lei Zhangc (2013)	Inventory analysis approach + Case study	98% of the emissions of buildings are from the maintenance and the operating stage.
3	Importance of Operational Efficiency to Achieve Energy Efficiency and Exhaust Emission Reduction of Construction Operations	Changbum R. Ahn, and SangHyun Lee (2013)	Integrating Operating Equipment Efficiency into Quantification of Exhaust Emissions + Case studies	Considering environmental aspects in planning, helps construction managers identify options that will increase the project's integrated value. This includes schedule, cost, and environmental impact.
4	Prediction model for energy consumption and carbon emission of asphalt surface construction	Zhang, Z., Gao, X., Wang, J., Ji, X. (2019)	Design of a calculation theory for LCA + case study	It is important to use universal LCA values for calculations. A case study can set benchmark parameters.
5	Forecasting energy-related carbon dioxide emissions in Thailand's construction sector by enriching the LS-ARIMAXi-ECM model	Sutthichaimethee, J., Kubaha, K. (2018)	Design of a technical national emissions forecasting model	The results indicate that determining national sustainable development policies for the future, requires an appropriate forecasting model. This should be built upon causal factors in a context to relevant sectors, to serve as an important tool for future sustainable planning.
6	A prediction model for CO2 emission from manufacturing industry and construction in Malaysia	Ho, T.C., Keat, S.C., Jafri, M.Z.M., San, L.H. (2015)	Case forecasting analysis	The CO2 emissions from construction projects are rising if no new policies will be implemented.
7	Real-time emissions from construction equipment compared with model predictions	Heidari, B., Marr, L.C. (2015)	Real world measuring to check forecasted data.	Operating conditions cause considerable variability in emission factors. The results of the research will help researchers and practitioners with improving current emission estimation models, tools, frameworks, and databases.
8	Prediction Model of CO2 Emission for Residential Buildings in South Korea	Moon, HyunSeok; Hyun, ChangTaek; Hong, TaeHoon (2014)	Case-Based Reseaning + LCA + case validation	The results show that the developed model can facilitate the prediction and control of CO2 emission, in an early phase of construction projects, even before the design completion. "It is expected that the model developed in

				this study will be used in material-based decision making, designing, scheduling, and cost management of eco-friendly buildings."
9	Toward low-carbon construction processes: the visualisation of predicted emission via virtual prototyping technology	Wong, Johnny K. W.; Li, Heng; Wang, Haoran; et al. (2013)	Combining LCA with VP-simulation tool + case example	The tool helps construction companies or contractors to forecast the potential CO2 emission level from their activities. Besides it should encourage an idea of the holistic emission of the construction process. Furthermore it should help with finding ways to reduce excess emissions, for example, by improving or replacing old plant items prior to the commencement of projects.

7. Integration of the theory

This part of the systematic literature review is about integrating the important findings of the literature study. This is organized around the main constructs stated in the beginning, to answer the original research question:

"Which models and theories are used in literature for designing an emission forecasting tool for construction projects?"

From the literature it becomes clear that in the last decade, relevant research is done regarding the topic of emission forecasting for construction projects. Noticeable is that the methods often differ in approach and perspective. Some researchers take a descriptive approach, which often is uses a more zoomed-out view [2, 5, 6] with as a goal to describe the situation as it is. Other researchers take more of a more narrowed down approach to develop an artifact that is useful for improvement in emission forecasting [1, 3, 4, 8, 9]. This last group designs the tools with the goal to help the construction companies as stakeholders.

Nevertheless, all the researchers base their research on different theories, resulting in different methods and different goals. One research [1] integrates the emission with costs and scheduling in a management system, while others integrate the operating efficiency with the emission forecasts [3]. Some use extensive mathematical models [4], while others visualize the forecasts in a VP-simulation [9]. Research [8] founds its forecasts on material-based decisions making.

Interesting to notice is that almost all studies use case-studies to validate their models [1, 2, 3, 4, 8, 9]. It can be concluded that a case study in which the forecasted data is compared with real-world data is a useful method to test a theory or an artifact in this context. Research [7] provides useful reference values for the real-world emissions as well as important factors to take into consideration when measuring in the real-world.

Another useful theory in this context is the Life-Cycle Analysis theory, that is used in most of the literature [1, 2, 3, 4, 5, 7, 8, 9]. It provides relevant, scientifically proven data about emissions of material and objects in the construction context. This is often used as input for a model.

However the models are mostly scientifically founded and validated, it is often not tested how the models are used in practice by construction companies. Since knowledge is no wisdom yet, it is important that a created model is applicable by the stakeholders in practice. This is something that is not extensively researched and can be added with my research.

Appendix B: The interview

Interview – emissie voorspelling bouwprojecten

Dit semigestructureerde interview is onderdeel van het bachelor onderzoek "Het ontwikkelen van een emissie voorspellingsmodel voor bouwprojecten", uitgevoerd door Darryll Klein Koerkamp, student Technische Bedrijfskunde aan de Universiteit Twente.

De data gegenereerd in dit interview zal worden gebruikt voor het beantwoorden van deelvragen en het onderbouwen van keuzes in het onderzoek. Alle data wordt anoniem verwerkt.

Hieronder staan de belangrijkste vragen voor dit interview. Gedurende het interview zullen verdere vragen en uitleg volgen.

Introductie

1. Wat is jouw functie binnen Dura Vermeer?
2. Wat wordt er in de huidige situatie binnen Dura Vermeer al gedaan aan het meten en/of voorspellen van emissies bij bouwprojecten?
3. In hoeverre ben jij betrokken bij het meten en/of voorspellen van emissies bij bouwprojecten?

Emissies

4. Wat zijn de belangrijkste oorzaken van emissies bij bouwprojecten? (Bijv. transport)
5. Wat zijn de belangrijkste variabalen die deze emissies beïnvloeden? (Bijv. transport-afstand, soort brandstof etc.)

Het voorspellingmodel

6. Wat zijn de belangrijkste vereisten van een emissie voorspellingmodel voor bouwprojecten?
7. Op welk niveau moet het model voldoen aan deze vereisten?

Appendix C: The interview answers (complete)

This appendix contains the main findings of the six interviews that were conducted to answer research question 1 and 2. The interviews were conducted as explained in Chapter 2. For every interview, a description of the interviewee is given, followed by the found data structured per research question.

C.1 Main findings interview 1

The interviewee

The first interview is conducted with a BIM-engineer of Dura Vermeer. A BIM-engineer normally is responsible for the 3D model-based process that gives insights in the architecture, engineering and other aspects of construction projects. However, this person is at the moment active in as consultant in the preparation of construction projects. Every new project for DVBH passes by him and he checks if it complies with regulations, including the emission-regulations. He sees that right now the regulations are not that strict, but he sees the need for it in the future.

Requirements

The first requirement of the emission forecasting model he mentions is that it should be “realistic” to use. With this he means that it should not take long to fill in the input data of the model, “it would be nice to do it in half an hour”. If it is too complicated to work with the model, it will probably not be used.

Second, he says that there will be a consideration between the accuracy and the ease of use of the model. At this moment he thinks that the accuracy is not of the greatest importance. It is fine if the model is “very rough”, because there are too many different factors to take into account. To make it precise, the model would become too complicated. The most important thing is to recognize the biggest polluters and forecast their emissions.

Third, he says the model should provide different options, so the user can experiment with choices regarding the construction process. For example if we choose different materials of different suppliers, the model should show what would the effect on the emissions would be.

Fourth, the model should be expandable. It is acceptable if the first version of the model does not cover all the aspects of emission creation at construction projects. In a later phase, it should be easy to add aspects of emission creation so that the model becomes more complete.

In short, according to interviewee 1 the most important requirements are the ease of use, simulation possibilities and expandability. The accuracy in this phase is considered of fewer importance. From a general perspective, the set-up for the emission forecasting model should be clear and give options, while the level of detail is something that will come later.

Input variables

Interviewee 1 mentioned that the biggest cause of emission on the construction site is the construction equipment. This is because they have to perform heavy activities often run on fossil fuels. Especially heavy equipment like a mobile crane of excavators cause a lot of air pollution.

Second, he says that the transport to the construction site causes emissions. The trucks with materials and the transport of people to the construction site is a factor as well. This emission factor is regarded smaller than the emission factor of equipment.

The interviewee also mentioned that the NO_x-emissions of equipment and transport are already calculated for each project with the AERIUS calculator of the Dutch government. This is now only done for meeting regulations and there is no option for quick simulation. However, these calculations give insight into important variables of emission creation. For equipment these are the year of construction and the power. For transport vehicles this is the weight, however, the other factors are not shown in the calculation.

Third, the creation of the materials used for a building also causes emissions. This is calculated in the MPG-calculation (Environmental Performance Buildings), which gives the environmental impact of all the materials used for a building. The difference with previous emissions is that these emissions are not caused on or close to the construction site.

In short, the most important factor of emission creation is the heavy equipment on the construction site. This emission depends largely on the year of construction and the power of the equipment. Next to this, the transport also is a relevant factor. The creation of the materials for building is also a factor, but this is not created on the construction site.

C.2 Main findings interview 2

The interviewee

This interviewee has had several functions within Dura Vermeer. He worked in project preparations, as construction site manager and logistic construction site manager. At the moment he works at the business operations office (in Dutch "Bedrijfsbureau"), where he works partly on the budget for construction projects and the planning for parts of the equipment. He works on "everything you need on, but will not remain in the end", for example cranes, site offices, scaffoldings etc. Next to this, he worked on a project to estimate the CO2-footprint of construction projects, however never finished this. Because of his broad background at Dura Vermeer, he can give clear insights in what the relevant aspects are for emission forecasting.

The requirements

The interviewee said that the forecasts of the model should represent the reality. The requirement is to which extent this happens, so the accuracy of the forecasts. If the forecasts have a deviation of 30%, it would be quite big, however, he also mentioned that it still is a step forward, since are no forecasts at the moment. The accuracy is important, but not essential in the first version.

Second, the interviewee mentioned that it would be good if the model is linked to the BIM-models, because this is "the way of work" for Dura Vermeer. These BIM-models include a lot of data about the architecture and engineering of a building. The interviewee noticed that this models might be complicated for people without knowledge of BIM-modeling.

Third, the interviewee considers it important that the model is a "living model". This means that it should be updated with new data regularly, so the model will remain relevant and not lose its usefulness. This could be seen as an aspect of making the model future-proof.

Fourth, it should be possible to simulate with the model. Even better would it be if the model gives options for emission reduction. This gives better insights to Dura Vermeer in what choices influence the emission and how they can reduce them.

Fifth, the financial aspect of different choices in construction projects is mentioned. However, the interviewee believes that the issue of money will negatively influence the research to insights in emission reduction. This is why the link to financial aspects is regarded less of value at the moment.

Sixth, the interviewee talked about the ease of use of the model. Since the model will be an extension of the currently used volume-prediction model, they could be worked out together. In total it should not take more than about two hours.

All in all, the interviewee mentioned six different requirements that could be taken into account for the quality of the emission forecasting model. The most relevant requirements at this moment are that it should be future proof, possible to simulate and easy to work with. The accuracy will be more relevant in later versions of the model. The link to BIM-models is important, however does not fit good in the scope of this research. The financial aspect will probably hold back the goal of this research.

The input variables

Construction machines are the “biggest polluters by far”, according to the interviewee. Equipment such as mobile cranes, excavators, pile drivers and drilling racks often all use diesel and create lots of emissions. All these emissions are created on the construction site.

The interviewee also mentioned the variables that influence the emissions of construction equipment. These are: the kind of equipment, the kind of fuel they use, stage of emission (which is linked to the construction year) and the power. These are the standard variables, but per machine the emission depends on the variables it has to work with in practice. For example the loading weight a crane has to carry or the length of piles for the pile drivers. The emissions of construction equipment could be forecasted by the standard emission variables plus the relevant variables per machine.

Next to the construction machines, the transport of material to the construction site is a cause of emissions. For this, the most relevant variables are the transport distance, the loading weight of the trucks and their stage of emission (which is linked to the year of construction). The transport of people also is a factor, however regarded less relevant.

The interviewee mentioned that it could be hard to gather all the data for the input variables. This is due to the fact that a lot of data should come from subcontractors or suppliers and they often have no idea about their emission creation. This could be a challenge for the research to a functioning model.

In short, the interviewee gave a lot of relevant information about input variables for the model, however gathering the exact data is a challenge. The most important polluters are construction machines. After this the emission of the transport of materials are also important. The interviewee did not have a lot of knowledge about the materials used and their influence on emissions.

C.3 Main findings interview 3

The interviewee

The third interviewee is a BIM-engineer of Dura Vermeer, who is working on an innovative emission reduction project. The goal of the project is to use logistic improvements to reduce the emissions on construction sites. He also is familiar with the currently used volume-prediction model and he sees the possibilities to include more logistic operations in the model, so emissions can be forecasted.

The requirements

The first requirement the interviewee mentioned is the accuracy of the model. The value of the model will eventually be the accuracy, so it is of importance. On the other side he sees that this field of research is relatively new in the construction sector, so for the scope of my research it is not possible to limit myself to the importance of accuracy. For my research, finding the most important variables is relevant and the accuracy should later be improved by trial and error.

Second, it should be possible to simulate with my model to see how logistic improvements influence the emissions. If this is possible, the interviewee can simulate for his research without having to test everything in practice. This would reduce time and costs.

Third, the usability of the model is important. It should be easy to give input for the model in a clear and structured way. There might be over 100 variables that influence the emissions, but it is important to limit the input for the model to the most relevant variables, so it can be used efficiently. To make sure the usability of the model will remain, a key user within Dura Vermeer can be appointed, so the all the knowledge I put in the model is understood in the company.

The input variables

The interviewee noticed that an important variable that helps to forecast emissions, is the number of logistic actions per machine. This could follow from the kind of materials and the quantity of those materials linked with the kind of machine. If this is known, this can be linked to emission data of those machines and then the total emission per machine can be calculated.

Next to this the transport to the construction site is an important cause of emissions. All the trucks with fossil fuels cause emissions that become more per kilometer they have to drive. If the number of trucks to the construction site can be limited, the emissions can be limited as well.

In general the interviewee sees over 100 variables that influence the total emissions. To keep it simple he says that my model should focus on the most important one and leave the rest out of the scope for this research. This keeps the goals feasible and any forecasting is an improvement compared to the old situation.

C.4 Main findings interview 4

The interviewee

The fourth interviewee works as sustainability manager for Dura Vermeer. Since the start of 2019 he focusses on circularity, energy transition, emissions and green buildings company wide. His task includes stimulating all the sustainability of all the business units of Dura Vermeer company wide. He confirms that the topic of sustainability is relatively new for the construction sector and it is hard to get to data. His broad vision on sustainability in the construction sector gives interesting overview of relevant subjects.

The requirements

The interviewee thinks that a model that gives insight in emission creation should cause behavioral change among the employees of Dura Vermeer. Except only providing insight in more sustainable options, it would be better if people start thinking about more sustainable construction methodology. For example how different material choices could influence the necessity of certain machines.

Second, the interviewee thinks that the financial aspect should be taken into account. He thinks that about 80% of the people do not intrinsically feel the need for sustainability. That is why the financial aspect should also be included to see that certain choices could influence both the sustainable and financial aspect positively.

Third, the model should provide insight and grip on what alternative options than the regular choice are. This could be seen as a simulation ability of the model.

Fourth, the model should be easy to use. Sine the model is made for giving rough forecasts in an early stadium, the interviewee wants a quick insight. It should take about one hour to fill it in.

Fifth, the interviewee mentioned that the model should provide a clear framework for emission forecasting, where it should not directly be focused on the proof of the concept. With this he means that not every part of the model can be accurate at the start of use, but it should be clear how this can be improved in the future. Based on his feeling, he says that the accuracy should at the start can be about 80%, where it later can be improved to 90% - 95%.

The input variables

The interviewee appointed the three main causes of emissions at construction projects. These causes are the construction machines, the transport and the creation of materials. These are confirmed by a rapport with a new method that is used to indicate the emissions of construction projects afterwards, the "PER-berekening".

The most important cause is the construction equipment. Especially the most heavy equipment like mobile cranes cause a lot of emissions. An important factor is the engine of the machine. If old engines are used, they cause significantly more emissions. A variable that could be used to forecast the emissions is the expected number operating hours of the equipment. The interviewee emphasized that the construction equipment is a very large factor.

Second, the interviewee mentioned the factors that influence the emission of transport to the construction site. One of them is the transport distance of the trucks. Next to this there is the kind of fuel and amount of fuel used. To reduce the number of transports to the site, the loading rate of these trucks should be full. This also can be a relevant variable.

For the interviewee, the embedded emissions in the used materials are very important. He says that the creation of materials like concrete and steel, a lot of energy is used. This is relevant if you look at emissions during the whole chain of a construction project, however it does not influence the emissions on site. The total emissions of the material creation is taken into account with the previous mentioned MPG-calculation.

Another environmental performance indicator is the EPC (Energy Performance Coefficient) of a new building. It indicates if the building is built environmentally friendly enough for energy use during the user phase of a building. This is relevant for the broad environmental picture, however it does not directly influence the emissions of construction projects.

C.5 Main findings interview 5

The interviewee

The fifth interview was with a director of preparations of Dura Vermeer. He works at Dura Vermeer for over seventeen years and has had several functions such as project manager and company director. At the moment he is responsible for the logistic schedules and calculations of direct costs in the preparation phase of new construction projects. Next to this, he is the director who is responsible for the topic of sustainability and the emission of nitrogen within DVBH. His focus is on how to measure emissions in practice. He sees the need for registrations, but also for forecasting and optimizing. The experience in different functions and the topic of sustainability in his portfolio makes him a relevant interviewee.

The requirements

The interviewee mentioned some sustainability KPI's (Key Performance Indicators) which Dura Vermeer uses to measure their sustainable performance. These are: waste reduction, the MPG-calculation, tons of CO_2 per million of revenue and percentage of wood from a sustainable source. For him, it would be relevant if the model calculates these KPI's in advance of a project.

To forecast all the KPI's would be an extensive job. However, the tons of CO2 is a relevant one, which fits in the scope of this research. Also the interviewee realizes the relevance of the NOx emission, so he sees the total tons of NOx as a relevant KPI as well.

As regards the accuracy of the model, the interviewee mentions that every forecast is an improvement in comparison with the previous situation. The first version of the model should not be bound by the focus on details, however should provide a framework which can be updated regularly.

The interviewee mentioned that he will probably not be working with the model, so the answers of other people are more relevant regarding the requirements of the model.

The input variables

The interviewee distinguished the three general causes of emissions: transport, construction equipment and material creation. For the equipment he mentioned that the type of equipment and the fuel are important variable. For transport he mentioned the different factors of material supply, material drain and employee transport. Next to this he mentioned that the MPG-calculation shows the environmental impact of material creation. Apart from this, he was not very specific about the influencing variables.

C.6 Main findings interview 6

The interviewee

The interviewee works at the department business operations office, where he is involved in construction projects in an early stage. He handles the construction site planning, the general construction site costs and logistic schedules. In his position he sees that the emission of nitrogen is becoming more and more relevant. Next to this he notices that reusing materials is becoming a thing, but he is not really involved in this. He has a clear look on the equipment used on construction sites.

The requirements

The interviewee does not have a strong opinion about what the model should provide. He is involved in good planning of construction equipment and gives advice how it influences emission, but he does not go into depth about goals of the model.

The one thing he mentions is that if the model shows improvements in the forecasting of equipment hours, this should also be used improved for the budget (financials).

The input variables

The interview noticed that a lot of the emission at construction sites come from the construction equipment. He stated an example at which he saw that 11,3 tons of nitrogen were created at the construction site, of which 11 tons was from construction equipment. People often think that a lot of emissions are caused by transport, however this is a misconception.

A part of the construction equipment is owned by Dura Vermeer and the rest comes from sub-contractors. The part of Dura Vermeer is mainly large tower cranes and small hand tools. These all run on electricity, so they do not cause emissions on site. The part of the sub-contractors on the other hand almost always run on diesel. These are the biggest polluters.

The different workloads that are the responsibility of the sub-contractors often are the demolition, digging, driving and the lifting of a lot of materials. For this machines like excavators, pile drivers, shovels, mobile cranes etc. are necessary. They cause about "99% of the nitrogen emission".

To forecast the emissions, the type of equipment used by the sub-contractors should be known. This should be combined with the expected number of operating hours of each machine. When that data is combined with emission data, the total emissions of the construction equipment can be forecasted. For this it is necessary to gather information of the sub-contractors.

To validate the emission forecasts, the real-world operating hours should be compared with the forecasted number of operating hours. For this again, the contact with sub-contractors is important. At the moment this data is not available, but in the future this data can be used to improve the forecasts.

Appendix D: Screenshots of the emission forecasting model

This appendix shows screenshots of the different parts of the emission forecasting model as explained in Chapter 3.5.

D.1 Part 1: Work packages and workload

Figure X shows the work the work packages and workload example for the emission forecasting model as explained in Chapter 3.5.

Table 9 Part 1: The work packages and workload of the emission forecasting model

[redacted]

D.2 Part 2: Work activities and equipment

Figure X shows the work activities and corresponding possible used equipment for every work package as explained in chapter 3.5.

Table 10 Part 2: The work activities and equipment of the emission forecasting model

[redacted]

D.3 Part 3: Companies and exact machines

Figure X shows the company choice and exact type of material used for every work activity and the corresponding emission factors as explained in Chapter 3.5. When emission factors are unknown, it shows two question marks ("??"). For this example, only simulated general example data is used because of privacy reasons.

Table 11 Part 3: The companies and exact machines of the emission forecasting model

[redacted]

D.4 Part 4: Operating hours

Figure X shows the operating hours calculation for method 1 and method 2 for every machine used as explained in Chapter 3.5.

Table 12 Part 4: The operating hours of the emission forecasting model

[redacted]

D.5 Part 5: Emission forecasts

Figure X shows the emission calculations of the emission forecasting model as explained in Chapter 3.5. When emission factors are unknown, it shows two question marks (“??”).

Table 13 Part 5: The emission forecasts of the emission forecasting model

[redacted]

D.6 Part 6: Evaluation

The evaluation part of the model is a copy of all elements as shown in Appendices B.1 until B.5. However the data filled in the model is different, since this is done with real world data. Next to this more columns are added to measure the difference in emissions factors, operating hours and the emissions itself. Figure X shows these extra columns needed for the evaluation.

Table 14 Part 6: The evaluation of the emission forecasting model

[redacted]

Appendix E: Screenshots of the demonstration of the model for project Zwolle Breezicht

Table 15 The demonstration of the model for project Zwolle Breezicht

[redacted]

Table 16 Second part of the demonstration of the model for project Zwolle Breezicht. Black cells are covered because of privacy reason s.

[redacted]

Table 17 Third part of the demonstration of the model for project Zwolle Breezicht

[redacted]

[redacted]

Table 18 Comparison of general case with worst case scenario

Table 19 Second part of comparison of general case with worst case scenario

[redacted]

Appendix F.2: Comparison general case with best case scenario

[redacted]

Table 20 Comparison of general case with best case scenario

Table 21 Second part of comparison of general case with best case scenario

[redacted]

Appendix G: User validation form

Validatie – emissie voorspellingsmodel

Inleiding

Deze gebruikersvalidatie is onderdeel van het bachelor onderzoek
"Het ontwikkelen van een emissie voorspellingsmodel voor bouwprojecten", uitgevoerd door Darryll Klein Koerkamp, student Technische Bedrijfskunde aan de Universiteit Twente.

De data gegenereerd in deze gebruikersvalidatie zal dienen als onderbouwing van het hoofdstuk validatie van de verslagging (thesis) van het bachelor onderzoek. Alle data zal anoniem worden verwerkt.

Validatie

In een eerdere fase van het onderzoek zijn acht vereisten opgesteld waar het emissie voorspellingsmodel in meer of mindere mate aan zou moeten voldoen. Het doel van deze gebruikersvalidatie is dat de gebruiker aangeeft in hoeverre deze vereisten vervuld worden. De gebruiker wordt gevraagd om elke vereiste op een schaal van 1 tot 5 te beoordelen.

- 1 betekent: het model voldoet niet tot zeer beperkt aan de vereiste
- 3 betekent: het model voldoet gemiddeld aan de vereiste
- 5 betekent: het model voldoet erg goed tot perfect aan de vereiste

Per beoordeling van de vereiste wordt nog om een korte toelichting gevraagd.

De vereisten

1. *Gebruiksgemak*
   Snelle invultijd – duidelijke structuur – niet te veel invoervariabelen

1	2	3	4	5
○	○	○	○	○

Toelichting: …….

………

………

2. *Nauwkeurigheid*
   Nauwkeurigheid van de resultaten

1	2	3	4	5
○	○	○	○	○

Toelichting: …….

………

……

3. *Simulatie mogelijkheden*
   Model laat opties zien – model laat verbeteringen zien – er kan geëxperimenteerd worden

1	2	3	4	5
○	○	○	○	○

Toelichting: ……

……

……

4. *Omvang*
   Brede aanpak onderwerp – veelomvattend model

1	2	3	4	5
○	○	○	○	○

Toelichting: ……

……

……

5. *Toekomstbestendig*
   Model is uit te breiden – levend model (is bij te werken) – biedt duidelijk kader

1	2	3	4	5
○	○	○	○	○

Toelichting: ……

……

……

6. *Link with BIM-model*
   De link van het model met BIM (Building Information Modelling)

1 2 3 4 5

○ ○ ○ ○ ○

Toelichting: ………

……

……

7. *Financiële aspect*
   Het model neemt financiën mee – kosten en/of omzet wordt duidelijk

1 2 3 4 5

○ ○ ○ ○ ○

Toelichting: ………

……

……

8. *Gedragsverandering*
   Veroorzaakt positieve gedragsverandering – zorgt voor duurzamere keuzes

1 2 3 4 5

○ ○ ○ ○ ○

Toelichting: ………

……

……