MASTER

Understanding complex systems through executable models
the Tidal Flow scenario

van Thiel, K.H.J.

Award date:
2013

Link to publication

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
Understanding complex systems through executable models: The Tidal Flow scenario

by

K.H.J. van Thiel

Beng Human Mechanical Engineering — 2009
Student identity number 0709334

in partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

Supervisors:
Dr. M. Comuzzi, TU/e, IS
Dr. P.M.E. Van Gorp, TU/e, IS
Abstract

In this master thesis project the possibilities to enhance the understanding of complex systems during the development of the system design. The project is conducted at the advisory group Intelligent Transport Services in the business unit Transport of RoyalHaskoningDHV Nijmegen, the Netherlands. The main objective of the research is to identify a system engineering tooling to merge the system behavior information, stored in static SysML diagrams, with 3D CAD models to create an executable model. This new engineering tooling has to be integrated in the current RHDHV software environment. To test the new tooling a new system engineering approach is followed to create an executable model. The delivered scenario to apply this new approach on is the tidal flow scenario of the Coentunnel. A sub objective is to determine what the throughput of this unique new traffic system is and give an indication of how the system will behave when failures occur in sub-systems.
Management summary

RHDHV initiated a project to enhance their current system engineering approach with the use of executable models to make the development of a system design more understandable. The currently developed SE approach is already capable of generating stakeholder specific documents which are supported by static SysML diagrams. These diagrams have to increase transparency and show the consistency between various installations. Although, not all stakeholders have experience with SysML so the diagrams can be difficult to be interpreted by less experienced SysML stakeholders. To resolve this issue and to make validation of the system design possible in the early development phase by executable models are the basis of this graduation assignment. To improve the understanding and make it possible to work with executable models in the system engineering approach the following research question is formulated:

“Can a dynamic 3D simulation be developed that merges the SysML system specifications with 3D CAD models to improve the understanding to less experienced SysML stakeholders?”

To answer this question two objectives are accomplished. First, a suitable software program is selected using a software selection tool. Second, an executable model is developed of the Tidal Flow scenario to investigate the working of this tooling and to analyze the Tidal flow scenario.

The software selection tool is used defined criteria from the literature as well as practical criteria like the current software environment of RHDHV. Main criteria for the selection are:

- General purpose;
- Analysis possibilities;
- Visualization;
- Compatibility.

Based on these four criteria Flexsim is chosen to be the most suitable software program to merge SysML system specifications, defined in the software program Enterprise Architect, with 3D CAD models, focused on Autodesk 3DS Max.

To introduce Flexsim in the new software environment cooperation with the other software programs as a new System Engineering approach a framework of several steps is developed. To leverage more from this new approach some suggested improvements of the steps are given:

- use Solvea Intercax as plug-in from EA to import and export all parameters from the SysML diagrams to and from excel or perhaps directly to Flexsim.
- develop the SysML diagram information taken into account the structure of Flexsim used for developing all objects and in the end the complete executable model.

As a case study and to get acquainted with Flexsim the opening and closing of the Tidal flow from the Coentunnel is developed as the first executable model. For this executable model allot of data is required both to simulate the system behavior and to visualize this behavior by 3D objects. The results of the analysis by simulating the tidal flow for a year with a switchover once a day are:

- The average throughput time of the complete cycle per day is 6017 seconds.
- The average availability is calculated on 97.36%.
- The height detection is discovered as the bottleneck of the system.

An improvement of the height detection of 5% on the mean time before failure has a positive effect on both the availability and the maximum throughput time. It has no or low effect on the average throughput time. The specification on penalty costs is not possible because the values do not exceed the stated requirements, so no costs could be acquired.
Preface
This master thesis is the result of a graduation project executed at ‘RoyalHaskoningDHV’. It is the concluding work of the master study Operation Management & Logistics at the sub department of Information Systems at the Eindhoven University of Technology. During the past months I had the opportunity to get familiar with system engineering in the traffic and infrastructure sector. I gained numerous new insights and knowledge about the system development. The time at RHDHV in both Nijmegen and Rotterdam, the visitation by Croon, Soltegro and especially the Coentunnel was very enjoyable for me.

I would like to thank Marco Comuzzi, my first university supervisor, for the regular meetings and motivation and support to keep me on the right track. I wish you good luck with your new job. I also would like to thank Pieter Van Gorp, my second university supervisor, for the few meetings we had and the times when Marco was attended and not able to help me.

I would like to thank my company supervisor Twan Daverveld from RHDHV, for the meetings and discussions we had about the project and for some more experienced insights about the Coentunnel project. Another person to thank is Marcel Boender with supporting and actually investigating the visual possibilities of Flexsim. Other thanks go to Rene Krouwel for the explanation of the Diamond model and the suggestions to enhance the model, which created this assignment. And I would to thank Dirk-Jan Moens from the company Talumis for the retrieved student license for Flexsim. Another special thank goes to Leen van Gelder who give me the opportunity to conduct a graduation project at RHDHV even when the assignment was unknown.

To conclude this preface I would like to thank the students of the N-corridor and the other OML’ers who supported me during my master study. Also I would like to thank my family and my friends of the “Ridderworstenbrood” group for their support during my study.

Koen van Thiel
Eindhoven, April 2013
# Table of Contents

Abstract ......................................................................................................................... iii

Management summary .................................................................................................... iv

Preface ......................................................................................................................... v

1. Introduction ................................................................................................................ 1
   1.1 The Coentunnel project ...................................................................................... 1
   1.2 A service-level agreement ................................................................................. 1
   1.3 The “Tunnelstandaard” ..................................................................................... 1
   1.4 Current State of collaboration .......................................................................... 2

2. Research Project ........................................................................................................ 3
   2.1 Project description ............................................................................................ 3
   2.2 Problem definition ............................................................................................ 4
   2.3 Research question ............................................................................................ 4
   2.4 Research Scope ................................................................................................ 6
      2.4.1 The Tidal Flow ........................................................................................... 6
   2.5 Research Model ................................................................................................ 7

3. Literature review ...................................................................................................... 12
   3.1 Model Based System Engineering ................................................................... 12
      3.1.1 SysML ..................................................................................................... 13
      3.1.2 Model Drive Architecture ......................................................................... 14
   3.2 Software Selection ............................................................................................ 15
      3.2.1 Selection criteria ....................................................................................... 16
      3.2.2 Selection technique .................................................................................. 16
   3.3 Develop an Executable Model .......................................................................... 18
      3.3.1 Conceptual modeling ................................................................................ 18
      3.3.2 Construct a computer program .................................................................. 19
      3.3.3 Experimentation ........................................................................................ 19
      3.3.4 Implementation ......................................................................................... 19

4. Conceptualization .................................................................................................... 20
   4.1 Conceptual model ............................................................................................. 20
      4.1.1 Simulation requirements .......................................................................... 21
      4.1.2 Data collection .......................................................................................... 21
   4.2 Black box representation .................................................................................... 22
      4.2.1 Environmental variables .......................................................................... 23
4.2.2 Control variables ........................................................................................................ 24
4.2.3 Output variables ........................................................................................................... 24
5. Identify a suitable modeling tool .................................................................................. 25
  5.1 Potential Software programs ....................................................................................... 25
    5.1.1 Enterprise Architect ............................................................................................... 26
    5.1.2 Autodesk 3DS Max ................................................................................................. 27
    5.1.3 Software environment at RHDHV ......................................................................... 28
    5.1.4 Market ................................................................................................................... 28
  5.2 Selection Criteria ......................................................................................................... 29
    5.2.1 Defining selection criteria ...................................................................................... 29
  5.3 Software Selection Tool ............................................................................................... 30
    5.3.1 Software evaluation ............................................................................................... 30
    5.3.2 Software evaluation ............................................................................................... 30
6. A new MBSE approach: SysML, 3D CAD models, Flexsim ........................................ 34
  6.1 The integration of Flexsim in the RHDHV software environment ............................. 34
  6.2 Possible improvements: to connect SysML and 3D CAD models to Flexsim ............. 36
7. The executable model .................................................................................................... 38
  7.1 Assumption document ............................................................................................... 38
    7.1.1 Scope of the simulation model .............................................................................. 38
  7.2 Describing the essential parts .................................................................................... 39
    7.2.1 Main flow .............................................................................................................. 39
    7.2.2 Breakdown ............................................................................................................ 40
    7.2.3 The video wall .................................................................................................... 41
    7.2.4 The Coentunnel ................................................................................................ 41
  7.3 Model verification and validation .............................................................................. 42
8. Analyses ........................................................................................................................ 44
  8.1 Simulation parameters ............................................................................................... 44
    8.1.1 Warm up period .................................................................................................. 44
    8.1.2 Replication length .............................................................................................. 44
    8.1.3 Number of replications ...................................................................................... 44
  8.2 Result of the Tidal flow scenario ................................................................................ 45
    8.2.1 Throughput Time ............................................................................................... 45
    8.2.2 System availability .............................................................................................. 45
    8.2.3 System reliability ............................................................................................... 46
1. Introduction

This master thesis is executed at the advisory group Intelligent Transport Services in the business unit Transport of RoyalHaskoningDHV (RHDHV) Nijmegen which has started a project to enhance their system engineering (SE) approach with the use of an executable model. Currently their SE approach is evolved from a document centric approach to a model based approach which is making use of the by RHDHV and Soltegro developed Diamond Model. More information about the Diamond Model is given in the project description sub-chapter 2.1. To specify why the SE approach has to be enhanced an introduction is given concerning the Coentunnel II and a concise part of the state of collaboration is discussed.

1.1 The Coentunnel project

Everyday more than hundred thousand motorists make use of the Coentunnel, a tunnel located in the north west of Amsterdam (figure 34, Appendix 1). After the node Coenplein the road changes from three driving lanes to two driving lanes resulting in an overcapacity on the road. This track of the A10, from and to the Coentunnel, is ranked in the Dutch top ten of traffic jams for several years (Table 24, Appendix 1). When nothing will be done to this traffic congestion point, the congestion will expand to all entrance roads and the complete high way around Amsterdam. The solution is to create capacity by supplementing the Coentunnel with a second tunnel, the Coentunnel II. This expansion will increase the fixed driving lanes from two to three (Figure 33, Appendix 2). In addition two extra flexible driving lanes are developed, which are able to switch the driving direction to prevent congestion on the three fixed driving lanes. The scenario of switching these driving lanes in the other direction is called the Tidal Flow which will be elaborated in the Research Scope.

1.2 A service-level agreement

As promoter of the Coentunnel project the ministry of Environment and Infrastructure created one assignment including the design, build, finance and maintenance of the capacity expansion road section Coentunnel. The contract of this assignment is based on a service-level agreement with the contractor where the availability of involved road section is the most important parameter.

The large responsibility and dimension of this project resulted in consortiums of collaborating companies to assign to this project. Eventually the “Coentunnel Company” consortium (figure 31, Appendix 1) signed the contract, holding a thirty year service agreement, at the end of April 2008. At the first of July 2008 the project with a possible gain of € 500 million is started. This amount of money can decrease according to penalty costs depending on the non-availability of the road, including the tunnel. Some of these penalty costs will be elaborated in sub-chapter 8.4.

To fulfill the responsibility role some maintenance parts are subcontracted by the Coentunnel Company, as is the maintenance of the traffic tunnel technical Installations (TTTI) which is subcontracted to Croon Elektronica B.V. During the development phase of the Coentunnel II Croon, Soltegro, RHDHV and the ministry of Environment and Infrastructure (Appendix 3) joined forces to develop the TTTI.

1.3 The “Tunnelstandaard”

In parallel with the collaboration of RH DVH in developing the TTTI, the government initiated the development of the “Tunnelstandaard”, a huge text document which describes the safety norms for all future tunnels. Next to these instructions standard equipment for safe tunnels is prescribed. Similar as in the Coentunnel project the government will use this document to place the responsibility of the tunnel safety to the companies who develop or maintain it.
Due to complexity of the systems involving the safety of the tunnel described in the “Tunnelstandard”, it is hard to see the overall connection and behavior of these systems from the document by stakeholders. As a possible solution for future TTTI designs, RHDHV and Soltegro acted together to develop the “Diamond model”, a model to enhance the understandability of text documents with system requirements and scenario’s to model-based SysML diagrams containing system behavior. This has to prevent miscommunication to stakeholders, which eventually decrease delays of opening safe tunnels.

1.4 Current State of collaboration

As in the consortium of the “Coentunnel Company” allot of companies are collaborating to leverage from each other’s knowledge. To cooperate effectively across these boundaries and realize the potential benefits from inter-organizational collaboration there need to be common understanding. From the past this understanding has been served as paper drawings or 2D computer-aided designs. More recently most of the 2D CAD designs are replaced with 3D CAD models which are used as boundary objects. Gal, Lyytinen, & Yoo (2008) describe these objects as conceptual or physical artifacts which can serve as a common reference point to members of multiple organizations.
2. Research Project
This master thesis project focuses on improving the system engineering approach of an independent project management, engineering and consultancy service provider. This chapter elaborates on the project context, including the research question. As a starting point the project description will be explained.

2.1 Project description
An important concern in an advisory group is clear communication, especially when dealing with interdisciplinary projects like developing a traffic tunnel. One major and complex part to create, next to the civil structure is the system design of the traffic tunnel connecting all technical installations. During the design phase a system engineering team has to decide what the requirements of all involved stakeholders are. The background of these stakeholders can be technical (like system engineers, mechanical engineers, software engineers, civil engineers, etc) but also less technical (managers, government representatives, emergency personal, etc.).

A good theoretical example to explain the working of System Engineers is Forsberg & Mooz (1994) Vee Model (1). The system engineers have to understand the top level user requirements stated by the Ministry of Environment and Infrastructure. Usually these less technical requirements are a bit vague and have to be translated to specific technical requirements. After the specific requirements on the lowest unit level are defined the start of building or purchasing units can begin. During this phase the unit will be tested to verify the defined requirements. This process will continue till the system engineers have verified the completely installed system with the top requirements.

Figure 1 Forsberg & Mooz Vee Model

The traditional procedure is to record all requirements on paper. Each of the stakeholders would receive this large pile of text documents, due to the risk of omitting important connections with other parts of the system. The time consuming and sometimes confusing task, to read everything, understand the behavior of the system, find out if there were made adjustments, discussing interpretations, etc. made RHDHV decide to renovate the traditional procedure. In cooperation with Soltegro they are developing the Diamond Model in a software program, which can generate stakeholder specific documents. Instead of full text documents these can be partially supported with
model based diagrams or even completely model based documents. The diagrams have to increase transparency and show the consistency between various installations. The stated system engineering language, SysML, is used to create the structure of these diagrams.

To summarize RHDHV is renovating the SE procedure to make it more understandable which will lead to a faster throughput time of the complete System Engineering development.

2.2 Problem definition
Followed from the previous section RHDHV wants to speed up the System Engineering development process. There are some issues that have to be resolved to retrieve the wanted result. The first issue is about the expired time to validate the completed system when all installations are assembled.

The Diamond model will eventually lead to faster communication. Although, it is still difficult to explain how the system works to stakeholders that do not understand the SysML language (e.g. some managers, fireman, etc.).

Both these issues can result in major complaints when the actual tunnel is already created and the adjustments cannot be resolved any more. To avoid these issues and to give a clear overview of how the sub-systems behave in the total system, RoyalHaskoningDHV wants an executable model that will be automatically connected to their static SysML diagrams as well as their CAD models to create full dynamic 3D simulations. This has to improve the communication and clarify the design in the development phase of the project to the less experienced SysML stakeholders.

A possible threat that occurs with modeling is that changes made during the modeling are not synchronically changed in the requirements stated in the text documents. Although, this is out of the scope of this research, it has to be taken into account and will be set as potential future work.

Due to the unknown requirements no trivial simulation software program is allocated, but has to be selected based on gathered information during the research.

2.3 Research question
The title of this graduation project “Understanding complex systems through executable models” has to have a supporting main research question that covers the complete master graduation project. The main research question for this master thesis is;

“Can a dynamic 3D simulation be developed that merges the SysML system specifications with 3D CAD models to improve the understanding to less experienced SysML stakeholders?”

To answer this main question and make the project more manageable, it is divided into the several sub-questions. These sub-questions will be answered in different stages of this master thesis graduation project, both the stages and the sub-questions are stated in figure 2.
Figure 2 Project outline in stages

Stage 1: Conceptualization
The sub-questions that have to be answered during this stage:

- What are the requirements for the executable model?
- What are the most important analyses that the executable model has to support?
- What data has to be collected for the executable model?

Make appointments with the supervisors in the project to discuss which analysis will be the most important. Discuss what the input and output variables have to be and what data has to be collected?

Stage 2: Identify a suitable modeling tool
The sub-questions that have to be answered during this stage:

- What is the current SE software environment of RHDHV?
- Which selection criteria can be used, theoretical and practical?
- What can be a potential software simulation program?
- What is the most suitable software program (tool) to build the executable model in?

Use the model requirements in combination with the current architecture to specify selection criteria. Search for a link between the executable model created from the tunnel specifications in SysML and the 3D CAD models.
Use these selection criteria as input of the software selection tool in combination with the potential software simulation programs. Select a suitable modeling tool.

Stage 3: A New MBSE approach: SysML, 3D CAD model, Flexsim
The sub-questions that have to be answered during this stage:

- What will be the role of the new modeling tool in the model based system engineering approach and how can it be executed?
- How can the SysML diagrams and the 3D CAD Models be connected to Flexsim?
- What are the leverages of this new approach?

Specify the role of Flexsim in the new model based system engineering approach of RHDHV. Describe stepwise how the new approach has to be conducted. Describe the value of using this approach over the old approach.

**Stage 4: The executable model**

The sub-questions that have to be answered during this stage:

- What will be the boundaries of the simulation?
- Which assumptions have to be made?
- How is the executable model made understandable?
- What kind of verification is used to verify if the model is working as it has to?
- What kind of validation is used to check if the executable model suits the real world scenario of the “Tidal Flow”?

Create the tidal flow scenario in the executable model. The executable model must be clear to the less or none experienced SysML stakeholders (e.g. some managers, policymakers). Apply theory to validate and verify the executable models with the actual situation and the stated SysML models.

**Stage 5: Analysis**

The sub-questions that have to be answered during this stage:

- How do you create a setup plan to conduct a reliable simulation?
- What is the throughput time of the tidal flow scenario?
- What is the availability of the tidal flow?

Create a setup to simulate the executable model for retrieving reliable output. Simulate the analyses selected in step 1 and make an understandable analysis report of all the analyses.

**2.4 Research Scope**

The scope of this research contains the enhancement of the current SE approach and the development of an executable model. The former can be reached by finding a suitable solution to integrate an existing or new software simulation program which is capable of merging SysML system specification with 3D CAD models. If a suitable solution is found clear steps have to define the “new SE approach”. With the real case description about the ‘Tidal flow’ in a traffic tunnel the “new SE approach” will be tested with an executable model as result.

**2.4.1 The Tidal Flow**

The Tidal flow consists of a flexible driving lane next to driving lanes with a fixed driving direction (see figure 32, appendix 2). When the utilization of a driving lane in a fixed direction is too high, the flexible driving lane has to decrease this utilization to prevent congestions.
Some applications of a tidal flow, or in most research papers contra flow, appear in evacuations during hurricane attack (Theodoulou & Wolshon, 2004) or planned events to tackle recurring congestions on busy roadways (Zhou et al., 1993). Wolshon, Catarella-Michel, & Lambert (2006) examined the variation in time to execute a contraflow between planned and unplanned events. For the unplanned event as a hurricane it took 2 to 3 days and for planned events like a football game it took 2 to 3 hours. To optimize the throughput of George Massey Tunnel in Vancouver Zhou et al. (1993) tried to compute an optimal schedule with online traffic data, though the solution was unable to predict traffic demand accurately. Xue & Dong (2000) made improvements on this computation and removed the random noise. Next to the scheduling of contraflow, another research stream investigated the determination of the number of lanes that need to be reversed during the implementation (Tuydes & Ziliaskopoulos, 2006).

The major difference to the above mentioned Tidal Flows is the implantation of this design in combination with a traffic tunnel, the ‘Coentunnel 2’. These tunnel is located in the north west of Amsterdam under the channel, ‘het Noordzeekanaal’ (see figure 34, appendix 2) near the existing Coentunnel. The ‘Coentunnel 2’ will be built in combination with a new motorway connection, de Westrandweg, between the Coentunnel and the traffic node Raasdorp, which will be the extension of the motorway A5.

The final situation will be a ‘Coentunnel 1’ with three fixed driving lanes to Amsterdam and the ‘Coentunnel 2’ consisting of three fixed driving lanes in the direction to the north (Zaanstad) and two flexible driving lanes who will be available in the direction with the highest utilization (see figure 33, Appendix 2). The purpose of this final solution is to decrease the daily congestions in front of the Coentunnel on the motorway A8, in the morning rush-hours, and the motorway A10-west, in the evening rush-hours. This must increase the reachability of Amsterdam from the north.

<table>
<thead>
<tr>
<th>Sub-systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel entrance lights</td>
</tr>
<tr>
<td>CCTV</td>
</tr>
<tr>
<td>Tunnel Ventilation</td>
</tr>
<tr>
<td>Traffic routing lights</td>
</tr>
<tr>
<td>Height detection</td>
</tr>
<tr>
<td>Moveable barrier</td>
</tr>
<tr>
<td>Crossing gate</td>
</tr>
</tbody>
</table>

Table 1 Sub-systems of the TTTI

To design a tunnel with the tidal flow functionality the integrated Technical Traffic and Tunnel Installations (TTTI) have to be compatible to support this. During the scenario to switch from driving direction, the TTTI sub-systems (table 1) will be set in the proper driving direction. Some of the functions that have to be adjusted according to the document “Project: Infra Provider Coentunnel – Tracé”.

More information about the simulation scope is stated in sub-chapter 7.1 the executable model.

2.5 Research Model

In the field of Information Systems (IS) two paradigms characterize the research discipline: behavioral science and design science (Hevner, March, Park, & Ram, 2004). In other papers a synonym of behavioral science, explanatory science is used. The mainstream research of the behavioral science is description-driven whereas the mainstream research of design science is prescription-driven. The main differences – more or less in black and white – about the two research programs are shown in (Aken, 2004).
Van Aken (2004) makes a distinction between Organization theory and Management theory. The former results from description-driven research, having an explanatory nature and is used largely in a conceptual way. The latter results from prescription-driven research and is used largely in an instrumental way to design solutions for management problems.

Van Aken (2004) concluded that both the descriptive and prescriptive research programs can operate in a profitable partnership. The organization theory from the behavioral science could explain the problem as a basis for creating technological rules and insight in causal mechanisms to uncover generative mechanisms, while management theory could provide more insight into the nature of managerial processes and generating new research questions. This meets the sentence stated by Nystrom & Starbuck (1981), 'If you want to understand a system, try to change it'.

The behavioral science has its roots in natural science and investigates to develop and verify theories that explain or predict human organizational behavior, like physics and sociology. The design science is a fundamental problem solving paradigm with its roots in engineering and the science of the artificial (Simon, 1981). It explores the boundaries of human and organizational capabilities by developing new and innovative artifacts, like in the fields of engineering and medicine.

**The applied theory and models**
The nature of my graduation assignment is more focused on design research to come to a relevant model and simulation for the company. Although, from the previous section can be obtained that some rigor theoretical behavioral science could be needed to conduct this research. *Fout! Verwijzingsbron niet gevonden.* (Hevner et al., 2004) will give a framework with both the rigor and relevance side applied in an IS research.
The framework will be the main structure of the research during this master thesis. As explained in the previous chapter (chapter 2.3) the graduation project is split up in several stages. In total two artifacts need to be created, from theory that can be connected to the relevant goals. These artifacts consist are broadly defined as constructs (vocabulary and symbols), models (abstractions and representations), methods (algorithms and practices), and instantiations (implemented and prototype systems).

The process to accomplish the several stages will correspond with the seven guidelines stated by (Hevner et al., 2004):

1. **Design as an Artifact**: Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.

2. **Problem Relevance**:
The objective of design-science research is to develop technology-based solutions to important and relevant business problems.

3. **Design Evaluation**:
The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.

4. **Research Contributions**:
Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.

5. **Research Rigor**:
Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.
6. **Design as a Search Process:**
   The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.

7. **Communication of Research:**
   Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

**Artifact 1: Software selection model**
To develop a software selection model applicable knowledge is needed. To gain this knowledge part of the literature study has to support this subject. What theories, frameworks or models are used in similar situations for selecting a software program?

To support the company’s need for developing the executable model in a software program, the first priority is to know where I need the software for. What are the functional requirements of the executable model? Which programs support these requirements? This information has to be conducted through interviews with the supervisors of the company.

When both parts are known the selection model can be developed and one or two software programs can be selected with it. Some general criteria to select the software could be; is it possible to become competent enough in a relative short time? Is there a manual or tutorial available? If there is a problem to get acquainted with the software program, the model will be evaluated and this iteration will give the next possible software program.

**Artifact 2: Executable model**
The applicable knowledge to create a complex executable model is required. With literature and knowledge from previous courses this knowledge has to be obtained. What are the most appropriate methods and strategies to develop such complex model? Will the model be divided in to sub-models to make it more applicable to develop the complex model? How can be verified if the model is implemented correctly?

For the development of the Tidal Flow scenario in the executable model, all the available data and documents from the company have to be requested. The company has to prefer which part of the Tidal Flow scenario is the most important, due to the probability of the division of the complete scenario. If some specifications or data from stakeholders are still lacking it has to be retrieved with interviews or documents from those stakeholders.

With this information it must be able to create the first executable model. This model will be evaluated by interviews with stakeholders to validate if the model is useful. When the stakeholder has suggestions to refine the model an iteration process is started to adjust the model till all the requirements are met.
With the validated model all agreed analyses can be conducted to improve the understanding of the complex model.

With an executable model the RHDHV can change parameters of the system in the early development phase and get knowledge about what the reaction of the system is. With this pre knowledge the system design can be adjusted with relative low costs. When development companies like RHDHV can leverage from this executable model all other companies that are involved with the creation and the maintenance of the system will have an advantage of a pre tested design before the
actual design is finished. In the end it has to result in a faster development with less physical adjustments.
In other industries, such as automotive industries, executable models are already used to speed up the problem solving cycles and to solve these problems in an earlier stage of development (Thomke & Fujimoto, 2000).
Another perspective to use such executable models could be as input for research for predicting traffic congestion and to enhance the throughput on highways (Tong & Wong, 2000).
3. Literature review

This chapter elaborates on the theory mainly from the earlier made literature review which is a deliverable of the pre-phase of this graduation project. The three key subjects stated in this review are the same as the three subchapters in this chapter, respectively Model Based System Engineering (MBSE), Software selection and Development of an Executable model.

3.1 Model Based System Engineering

MBSE is rooted from the developments of complex systems by the U.S. Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA). They introduced a lifecycle framework based on rigid acquisition guidelines including key life cycle phases, gate reviews and decision milestones, due to responsibility for managing billions of tax payer dollars. Balmelli, Brown, Cantor, & Mott (2006) stated that traditionally, these acquisition program reviews have relied on paper documents, because that was the cutting edge when government acquisition lifecycle models were first initiated.

In the past the document-centric approach solved system engineering problems, but with increasing complexity and globalization of the systems it would be difficult to maintain this approach. Another disadvantage of the document-centric approach is the error prone task (Johnson, 2008) in communicating the necessary information and knowledge. To transfer knowledge and information between the design team members, engineers must navigate the relevant documents, extract the necessary knowledge and translate the content into discipline-specific formats. MBSE (Estefan, 2007) encourages engineers to change from the document-centric approach to a more computer-based, interactive modeling approach. With MBSE engineers solve the system engineering problems through the formal collaboration of models that transform stakeholder requirements and objectives into a full system description.

Estefan (2007) stated a definition of MBSE:
“A model-based system engineering methodology can be characterized as the collection of related processes, methods, and tools used to support the discipline of system engineering in a model-based or model driven context.”

During the literature review six leading methodologies where investigated. Two methodologies were based on the “Vee” model. One of them could be an reference model of RHDHV future MBSE approach. The IBM telelogic Harmony-SE (figure 4) has a Vee-model process with a model repository in the center and modeling approach which is described by means of SysML (Section 3.1.1) diagrams. The explanation of the Vee-model is already elaborated in chapter 2.1.

The IBM Telelogic Harmony process mirrors the Vee lifecycle of system design. The process assumes that model and requirements artifacts are maintained in a centralized model/requirements repository. In addition to use the model/requirement repository the Harmony process uses a test data repository to capture case scenarios.
3.1.1 SysML
SysML is the potential leading language through a complete system engineering process. This language has to connect all different specialisms (e.g. electro engineers, software engineers, mechanical engineers) to communicate with each other.
It will be useful to understand each diagram of the SysML language during my graduation assignment, due to the fact that the System Engineering department of RHDEV, in corporation with Soltegro, is developing these diagrams for their traffic tunnel system project.

This section will explain what the main components of the SysML language are and the various kind of functions the SysML diagrams support. OMG SysML™ (2012). This subchapter explains SysML in a concise way, an extended version of this subject is stated in the complete literature review. The concise version describes the structure diagrams followed by the main components of SysML, requirement diagrams and ends with the behavior diagrams.

The structure diagram
The structure diagram in SysML consists of three other diagrams, the Package Diagram, the Block Definition Diagram and the Internal Block Diagram. The latter could be supported by another diagram, the Parametric Diagram. The use of these diagrams could be seen in a sense of hierarchical structure.

The package diagram
The package diagram is usually the top level of the structure and is used to organize the model by partitioning model elements into workable elements and establishing dependencies between the packages and/or model elements within the package. Each package defines a namespace for the workable elements, which can also be shown on other diagrams such as block definition diagrams, requirement diagrams and behavior diagrams. One of the packages could be the structure of a particular product this can be further defined in a block diagram.

The block definition diagram
The block definition diagram consists especially of blocks and lines. The block is a modular unit of a system description and can describe both structural and behavioral features, such as properties and operations to represent the state of the system and behavior that the system may exhibit. OMG
SysML™ (2012). SysML blocks can be convenient throughout all phases of system specification and design, and can be applied to many different kinds of systems. It can be applicable for modeling logical or physical decomposition of a system, and the specification of software, hardware, or human elements. The lines capture the relationships between blocks such as associations, generalizations and dependencies.

To stress the consistency of generalization, the internal block diagram shows the internal structure of a block in terms of properties and connectors between properties. There are four general category properties of blocks recognized in SysML are: parts, references, value properties and constraint properties. The latter properties are also depicted in parametric diagrams. These diagrams are restricted from the internal block diagram and shows only the use of constraint blocks along the properties they constraint within a context. This new SysML diagram type is used to integrate behavior and structure models with engineering analysis models such as performance, reliability, and mass property models.

The requirement diagram

The requirement diagram is a new SysML diagram type. A requirement diagram provides a modeling construct for text-based requirements, and the relationship between requirements and other model elements that satisfy or verify them.

The behavior diagram

The behavior diagram in SysML consists of four other diagrams;

- The Activity Diagram: describe the flow of control and flow of inputs and outputs among actions. This includes both discrete and continuous flows, either of material, energy, or information;
- The Sequence Diagram: describes the flow of control between actors and systems (blocks) or between parts of a system;
- The State Machine Diagram: represents behavior as the state history of an object in terms of its transitions and states;
- The Use Case Diagram: shows actors (environment) and systems (subjects) to achieve a goal, which is realized by the subject providing through the interaction between subject and its actors.

An elaboration of the SysML diagrams with the use of an example is stated in appendix ...

3.1.2 Model Drive Architecture

In 2001, when UML was the OMG’s standard, OMG launched the Model Driven Architecture (MDA) as a framework of Model Driven Engineering (MDE) standards (France & Rumpe, 2007). MDA reflects the OMG’s approach to using models in software development to help achieve the vision of integrated systems and applications that can be deployed, maintained and integrated with far less cost and overhead than traditional approaches.

MDA specifies modeling systems from three viewpoints:
- Computation Independent Model (CIM) sometimes called domain model: focus on the environment in which the system of interest will operate in and on the requirement features of the systems;
- Platform Independent Model (PIM): OMG defines a platform as “a set of subsystems and technologies that provide a coherent set of functionality through interfaces and specified usage patterns.
- Platform Specific Model (PSM): a view of a system in which platform specific details are integrated with the elements in a PIM.

The pillars of MDA are the Meta Object Facility (MOF), a language for defining the abstract syntax of a modeling languages (e.g. CIM to PIM), the UML, and the Query, View, Transformation standard (QVT), a standard for specifying and implementing model transformations (e.g., PIM to PSM transformations).

Johnson (2008) To transfer between model languages two possibilities are introduced, OMG’s QVT and Triple Graph Grammar (TGG). When comparing both languages QVT’s imperative nature of the Operational Mappings seems to hamper bidirectional transformation. Another advantage of TGG is the use of a correspondence metamodel which is essential for defining the graph transformation rules and maintains the traceability links between the two models.

3.2 Software Selection

In the development of software systems a lot is changed during the last three decades. The traditional approach to design software systems was to identify requirements with a development team, define architecture and then undertake (custom) implementation, shown on the left in figure 5 (Brownsword, Oberndorf, & Sledge, 2000).

Figure 5 The difference between traditional development approach and the COTS approach

The more current approach is to use pre-existing software products to lower development costs, short development time, and keep pace with the changing software market. With this Commercial Off-The-Shelf (COTS) approach the system developer focusses on requirements, architecture and the marketplace simultaneously to search for the best fit of the needed software as shown in the figure above. To discover the most suitable software program first selection criteria (chap 3.2.1) have to be defined to eventually rank the programs with a specified selection technique (chap 3.2.2).
### 3.2.1 Selection criteria

Several authors focused their research on software selection. From four selected papers the selection criteria are categorized into three main subjects, respectively Simulation, Model Transformation and Visualization. These criteria are chosen from a theoretical point of view to develop an executable model, where transformation of models is perhaps necessary to make the models executable.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Simulation</th>
<th>Model Transformation</th>
<th>Visualization</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Comella-Dorda, Dean, Morris, Oberndorf, &amp; others, 2002)</td>
<td>Programmatic Constraints</td>
<td>Architecture/Interface constraints (middleware)</td>
<td>Programmatic Constraints</td>
</tr>
<tr>
<td></td>
<td>Operational and Support Environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Kontio, 1995)</td>
<td>Functional criteria</td>
<td>Domain and architecture criteria</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Product quality criteria</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strategic criteria</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Domain and architecture criteria</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Verma, Gupta, &amp; Singh, 2008)</td>
<td>Hardware and software consideration</td>
<td>Hardware and software consideration</td>
<td>simulation capabilities: visual aspects</td>
</tr>
<tr>
<td></td>
<td>Modeling capabilities</td>
<td>Input/Output issues</td>
<td></td>
</tr>
<tr>
<td></td>
<td>simulation capabilities</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Input/Output Issues</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Wenzel, Bernhard, &amp; Jessen, 2003)</td>
<td></td>
<td></td>
<td>Graphical point of view</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Information-Related point of view</td>
</tr>
</tbody>
</table>

Table 3 Criteria from several writers divided in Simulation, Model transformation and Visualization criteria

Concluding Table 3 the criteria’s stated by Verma, Gupta, & Singh (2008) cover all main subjects which initiated these criteria to be prior to the other ones with the exception of the criteria’s stated by Wenzel, Bernhard, & Jessen (2003). Both lists of criteria are attached in the literature review.

Supported influence from the other two papers is the division of criteria into functional and non-functional requirements. Where Kontio (1995) stated that functional criteria from functional requirements are identifiable functional features or characteristics for the application that are derived from the requirements of design specification. A non-functional requirement is an identified evaluation criteria or requirement that is not always addressed by system requirements (Comella-Dorda, Dean, Morris, Oberndorf, & others, 2002).

### 3.2.2 Selection technique

The several COTS approaches during the years informs about possible problems that can occur during a selection process and illustrates the used selection techniques (Table 4). From the mentioned COTS approaches the AHP is the most commonly used technique, while the fuzzy AHP is the newest. Due to the complexity of the fuzzy AHP approach and the minimal advantage over the normal AHP (Azadeh, Shirkouhi, & Rezaie 2010) the normal AHP seems more practical to use.
AHP

Kontio (1996) stated that the analytic hierarchy process (AHP) is based on the idea of decomposing a multiple criteria decision making problem into a criteria hierarchy. The AHP has the advantage over the WSM to cope with the dependency among criteria. One similarity is that the AHP makes use of nominal scores like the WSM method in assigning weights. At each level in the hierarchy the relative importance of factors is assessed by comparing them in pairs. Finally, the alternatives are compared in pairs with respect to the criteria as shown in figure 6 and calculated in with the following equation (Azadeh et al., 2010):

\[
A = \begin{bmatrix}
c_1 & 1 & a_{12} & \cdots & a_{1n} \\
c_2 & 1/a_{21} & 1 & \cdots & a_{2n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
c_n & 1/a_{n1} & 1/a_{n2} & \cdots & 1 \\
\end{bmatrix}
\]

Where the number \(a_{ij}\) is the relative importance of criterion \(i\) \((c_i)\) in comparison with criterion \(j\) \((c_j)\) in the scale of Saaty.

The scale of Saaty and an example in apply AHP is given in appendix 4.

The main steps in applying AHP are: (Kontio, 1996)

1) Define a hierarchy of factors that influence the decision, resulting in a hierarchical structure of factors that have alternatives as the leaf nodes in the hierarchy
2) Define the importance of factors on each level
3) Define the preferences of alternatives
4) Check the consistency of rankings and revise the ranking if rankings are too inconsistent
5) Present the results of the evaluation, the alternative with the highest priority being the one that is recommended as the best alternative.

One of the important critics on Saaty’s initiated AHP approach is the use of normalization. In this paper (Saaty, 1990) Professor Dyer implicates that AHP deals with decision problems, due to the use of normalization. He assumed that there is a unique way to deal with decision problems, more or less along the traditional lines of utility theory largely reflected in his own work.
One disadvantage in using normalization is, when conducting normalization and there is a great
dominance of alternatives, the priority value of each criterion becomes smaller. Conversely, when
for example, the dominance of the alternatives is smallest and hence all the alternatives are alike,
the proportion of the criterion priority assigned to each is larger (if a>b then a+c>a+b and c does not
reverse order). To provide this situation Dyer proposes to transform ratio scales to interval scales.

3.3 Develop an Executable Model

In previous subchapter a theory and method of software selection is described. The software
selection process is a pre-process in the executable development process described by Robinson
8) is described. Another way of describing the process of doing a sound simulation study (figure 7) is
given by (Banks, 1999) and Law (2003). Both approaches are similar in structuring the simulation
study. The steps described by Law can be mapped to the processes and stages defined by Landry.

Figure 8 Simulation Studies: Key Stages and Processes.

Steps 1, 2 and 3 are the steps to develop a conceptual model, a
description of the model that has to be developed.
steps 4, 5 and 6 are the steps to create the computer model.
step 7,8, and 9 can be mapped to the experimentation process
and finally step 10 can be mapped to documenting the results and
use these results for implementation.

To give a brief overview some of these steps will be elaborated
others are described in the literature or the literature review.

3.3.1 Conceptual modeling

The conceptual model is a non-software specific description of the simulation model that is to be
developed, describing the objectives, inputs, outputs, content, assumptions and simplifications of the
model. (Pidd, 1999)

Based on qualities of an effective model and performance criteria (Brooks & Tobias, 1996) four main
requirements of conceptual model are defined:

- Validity; a perception, on behalf of the modeler, that the conceptual model will lead to a
  computer model that is sufficient accurate for the purpose at hand
- Credibility; a perception, on behalf of the clients, that the conceptual model will lead to a computer model that is sufficiently accurate for the purpose at hand.
- Utility; a perception, on behalf of the modeler and the clients that the conceptual model will lead to a computer model that is useful as an aid to decision-making within the specified context
- Feasibility; a perception, on behalf of the modeler and the clients, that the conceptual model can be developed into a computer model.

One of the tools used in conceptual modeling is the black box method. This will be elaborated in subchapter 4.2.

### 3.3.2 Construct a computer program

The conceptual model has to be converted into an executable model using a spreadsheet, specialist simulation software or a programming language. This mapping must be done in a systematic way, such that the explanatory power of the conceptual model is carried to the executable model. After the executable model has been designed, it should be verified for having the correct behavior. The verification should include checking the code, inspecting output reports and checking that the modeled elements work the way the real world elements do (Mehta, 2000). Some verification and validation techniques will be elaborated in subchapter 7.3.

In designing the model structure the modeler should have to take into account four aspects:

- Speed of coding: the speed with which the code can be written.
- Transparency: the ease with which the code can be understood.
- Flexibility: the ease with which the code can be changed.
- Run-speed: the speed with which the code will execute.

### 3.3.3 Experimentation

Once the executable model is developed, experiments can be performed in order to obtain a better understanding of the real world and/or find solutions to real world problems. This is a process of “what-if” analysis, making changes to the model’s input, running the model, inspecting the results, learning from the results, making changes to the input in a iterative way. The key issues when performing simulation experiments are:

- Obtaining sufficiently accurate results
- Performing a thorough search of potential solutions
- Testing the robustness of the solution

### 3.3.4 Implementation

Implementation can be thought of in three ways, implementing the findings into the real world, implementing the model rather than the findings or use the findings to learn and improve understanding.
4. Conceptualization

Based on previous chapters, there is insufficient information to start developing an executable model. To start building an executable model all requirements have to be clear and the developer needs to have a software program to begin. The latter will be elaborated in the next chapter. This chapter contains the analysis of the required data for the executable model supported by modeling a conceptual model and the preparing the data to be input for the executable model (see figure 9).

4.1 Conceptual model

As mentioned in theory (Pidd, 2007) it would be important to start with building a conceptual model as early in the project phase as possible, due to the raising questions while developing it. With these questions it become more clear what the nature of the problem is, what the modeling objective has to be, what the inputs, outputs and model content has to be and to analyze and collect the required data to develop the final executable model.

With the use of received information about the scenario of opening and closing the tidal flow, in text and in a flowchart (see figure 38, appendix 4), a first conceptual model is developed. The model is created in CPN tools which is a familiar software program used by the TU/e. In figure 10 the final conceptual model is shown (figure 39, appendix 5 contains a larger version). The blue lines show the similar process as the process in the flow chart, without any added assumptions. The blue transitions represent the human interactions.

To activate the two loops in the process, respectively the resolve failure loop and the remove objects on driving lane loop, two generators are designed. Both these generators can change conditions over time. Another addition to the main process is the black place “Camera stand”, holding the state of the camera view, due to the importance of the visual aspect in this project.

![Figure 9 stage 1: Conceptualization](image)

![Figure 10 the conceptual model in CPN tools](image)
4.1.1 Simulation requirements
To specify what the analytic aspect of the simulation has to be an interview was conducted with a manager of RHDHV. During this discussion the conceptual model gives a first impression of the main flow of the scenario. Summarizing the interview (Appendix 6) the main purpose is to develop a dynamic 3d simulation capable of simulating what-if scenario’s based on scenario information and failure information. With the analysis of this simulation the SE can gain knowledge about the availability of the tunnel tube containing the tidal flow. The visualization of the complete scenario has to improve the understanding of the interactions of human handlings and system handlings to less experienced SysML stakeholders.

4.1.2 Data collection
To develop a simulation to analyze the availability of the tidal flow tunnel tube it is necessary to have RAMS data and all process times of the installations and the handling of the traffic control manager. First the data collection of the RAMS data is described and secondly an elaboration is made about the retrieved time data.

RAMS data
The MTBF is the reciprocal of the failure rate. This latter is defined as the number of times an installation fails over a period of time with the equation:

\[
\text{Failure rate } (\lambda) = \frac{\text{number of failures}}{\text{Total life expectancy}}
\]  

(4.1)

Where \( \lambda \) is normally expressed in hours, i.e. number of failures per hour

The MTBF is \( \frac{1}{\lambda} \).

To calculate the availability of the tidal flow tunnel tube the next formula can be used:

\[
A = \frac{\text{Up time}}{\text{Total time}}
\]

(4.2)

\[
A = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}
\]

(4.3)

Where MTTR is the mean time to repair.

(Mehra.V ,2003,"Radio Engineering and Telemetry for Industry")

The available data at RHDHV are the fail ratios of the sub-systems shown in Table 5 both in failure rate per year (\( \lambda \)) and MTBF.

<table>
<thead>
<tr>
<th>Sub-installs</th>
<th>MTBF (hours)</th>
<th>MTTR (hours)</th>
<th>Process time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry lights</td>
<td>0,1</td>
<td>2</td>
<td>0,160</td>
</tr>
<tr>
<td>CCTV</td>
<td>0,22</td>
<td>3</td>
<td>0,160</td>
</tr>
<tr>
<td>Specific Cam view</td>
<td>0,042</td>
<td></td>
<td>0,017</td>
</tr>
<tr>
<td>Tunnel ventilation</td>
<td>2,6</td>
<td>3</td>
<td>0,160</td>
</tr>
<tr>
<td>Traffic support lights</td>
<td>0,3</td>
<td>2</td>
<td>0,017</td>
</tr>
<tr>
<td>Height detection</td>
<td>0,0096</td>
<td>8</td>
<td>0,080</td>
</tr>
<tr>
<td>VEVA</td>
<td>0,174</td>
<td>3</td>
<td>0,080</td>
</tr>
<tr>
<td>Traffic control gates</td>
<td>0,247</td>
<td>3</td>
<td>0,033</td>
</tr>
</tbody>
</table>

Table 5 RAMS data
Time data
To simulate and analyzing the throughput time of the scenario all durations of handlings in the system are required. In the process two type of handlings are important, respectively system/installation handlings and human handlings. The former handling times are estimated in the level 0 document, others have to be collected. The technical documentation does not include the human interaction times either. A suggestion during the interviews is to retrieve meta-data from the tidal flow on the A1 motorway.

To collect data, the traffic control center managing the tidal flow on the A1 motor way is visited, a proposal to retrieve a data log of this meta-data is send to the DVM service desk and a request to search the lower level installation documents is send to Croon. Despite the multiple actions to retrieve acceptable and reliable time data, only one measurement of the process times during the opening of the tidal flow is retrieved and shown in Table 6

<table>
<thead>
<tr>
<th>Action</th>
<th>start</th>
<th>end</th>
<th>duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre-inspection driving lane</td>
<td>11:42</td>
<td>12:40</td>
<td>0:58</td>
</tr>
<tr>
<td>confirm pre-inspection</td>
<td>12:40</td>
<td>13:15</td>
<td>0:35</td>
</tr>
<tr>
<td>turn on green arrows</td>
<td>13:15</td>
<td>13:29</td>
<td>0:14</td>
</tr>
<tr>
<td>inspection driving lane</td>
<td>13:29</td>
<td>14:33</td>
<td>1:04</td>
</tr>
<tr>
<td>confirm inspection</td>
<td>14:33</td>
<td>15:08</td>
<td>0:35</td>
</tr>
<tr>
<td>remove red crosses</td>
<td>15:08</td>
<td>16:35</td>
<td>1:27</td>
</tr>
<tr>
<td>open Veva</td>
<td>16:35</td>
<td>17:56</td>
<td>1:21</td>
</tr>
<tr>
<td>confirm open Veva</td>
<td>17:56</td>
<td>18:31</td>
<td>0:35</td>
</tr>
<tr>
<td>open traffic control gate A</td>
<td>18:31</td>
<td>18:45</td>
<td>0:14</td>
</tr>
<tr>
<td>confirm open gate A</td>
<td>18:45</td>
<td>19:05</td>
<td>0:20</td>
</tr>
<tr>
<td>open traffic control gate B</td>
<td>19:05</td>
<td>19:19</td>
<td>0:14</td>
</tr>
<tr>
<td>confirm open gate B</td>
<td>19:19</td>
<td>19:39</td>
<td>0:20</td>
</tr>
<tr>
<td>turn on the sign open tidal flow</td>
<td>19:39</td>
<td>19:55</td>
<td>0:16</td>
</tr>
<tr>
<td>TOTAL DURATION</td>
<td></td>
<td></td>
<td>8:13</td>
</tr>
</tbody>
</table>

Table 6 Measurement process times opening Tidal flow A1

Additional to the measurements some points some key points from the conducted interviews (appendix 7) with the traffic control managers are:

- Road inspectors are on average within 15 minutes at the place they are required.
- The height sensors are sensitive and have to be replaced on a daily basis. On average a truck activates these sensors 20-25 times a day with a peak of 50 times.
- Setup times of the ventilation in the Velsen tunnel to 100% capacity is on average 3 minutes.

4.2 Black box representation
To decide what the specific role of the data will be in the executable model a black box representation is given in figure 11. It represents the executable model in an abstract way. The black box considers three types of variables which are:

- Environmental variables; variables which are a result of the environment of the system and will not be modified during simulation experiments.
- Control variables; variables which can be controlled and will be changed during the simulation experiments.
- Output variables; variables which contain important information depending on the previous two mentioned variables.

All the variables depicted in the black box representation will be described in the next sub section.
First the input variables will be explained followed by the environmental variables and finally the arguments for the output variables will be given.

4.2.1 Environmental variables

The data which is collected in sub-chapter 4.2 did not contain distributions. During a final interview with the RAMS expert the sub-installation data is validated and the distributions were discussed. As shown in table 7 the process times are fixed. These times of switching a (sub-) installation in the opposite direction have minor deviations. The MTBF is exponential, due to a constant failure rate that is stated in the overall tunnel requirements. The MTTR includes both the repair time and the logistic time for service engineers to arrive to a specific sub-installation. Both the repair time and the logistic time are normal distributed. The former of each installation will be considered with a mean and a standard deviation which will be 25% of the mean. The latter is has a fixed mean and standard deviation, respectively 1.5 hours and 0.41 hours. This illustrates the arrival time of 1.5 hours with plus or minus a half hour stated the overall tunnel requirements.

<table>
<thead>
<tr>
<th>Name</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-installation</td>
<td></td>
</tr>
<tr>
<td>Process times</td>
<td>Fixed</td>
</tr>
<tr>
<td>MTBF</td>
<td>Exponential</td>
</tr>
<tr>
<td>MTTR</td>
<td>Normal</td>
</tr>
<tr>
<td>Human</td>
<td></td>
</tr>
<tr>
<td>Handling times</td>
<td>Normal</td>
</tr>
<tr>
<td>Object on road</td>
<td>Exponential</td>
</tr>
<tr>
<td>Remove object</td>
<td>Normal</td>
</tr>
</tbody>
</table>

Table 7 Environmental variable distributions

The human handling information considers the handling times of the traffic control manager, the generating objects on the road and the removal of objects by the road inspector. The handling times of the traffic control manager are normal distributed. The actions are categorized in inspection and confirming. Table 8 shows the calculation of the mean and standard deviation of these actions, considering the obtained data at the traffic control center (sub-chapter 4.2).

<table>
<thead>
<tr>
<th>Human Handling</th>
<th>Time measurements</th>
<th>Total</th>
<th>Mean</th>
<th>( \sigma^2 )</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>inspection</td>
<td>1 2 3 4 5</td>
<td>122</td>
<td>61</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>confirming</td>
<td>35 35 20 20</td>
<td>145</td>
<td>29</td>
<td>54</td>
<td>7.35</td>
</tr>
</tbody>
</table>

Table 8 Calculation human handling

To generate objects on the road an exponential distribution is chosen, due its independency of time. The amount objects appearing on the road is based on Belgic traffic data, due to the unavailability of a document containing Dutch traffic data about object appearance on highways. As reference the
data of the ring road Antwerpen (table 9) is used and this information is divided by eight to receive an approximation about the length of the Coentunnel access roads. The calculated mean of 55,73 objects appearing in a year is used for the assumed amounts of objects appearing on the road influencing the tidal flow scenario.

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>46,5</td>
<td>55,25</td>
<td>48</td>
<td>55</td>
<td>69,75</td>
<td>59,88</td>
<td>55,73</td>
</tr>
</tbody>
</table>

Table 9 Calculation object appearance

The removal of an object by a road inspector includes an arrival time estimated on 15 min and remove time of 10 minutes.

4.2.2 Control variables

*Number of switchovers:* This input parameter of amounts of changing directions a day will be useful to give an indication what strategic opportunities are possible.

*MTBF:* The sub-system with the largest contribution of delay of the whole system will be replaced with a better version of the sub-system which results in a 5% improvement on the MTBF.

4.2.3 Output variables

*Throughput times:* This will be the result of the time started from closing direction A and opening direction B. This can be from North to South or the other way around. This PI will be the first indication of the actual working of the tidal flow. It is important for the company to get an impression for considering different opening and closing strategies.

*Bottleneck:* This will be the result of the component that has the largest down time which influence the throughput of the complete system. A useful PI for the company to consider replacements if a low availability or reliability of the complete system occur.

*System availability and reliability:* This will be computed by the average amount of failures and the average repair of the total system. The most important PI for the company, especially to give feedback on the tunnel requirements. In these tunnel requirements a maintenance contract is stated. For every 15 minutes of that the tunnel is unavailable tunnel a cost penalty of 14.000 euros is considered (appendix 19).
5. Identify a suitable modeling tool

For the selection of the software there are three main perspectives according to the COTS approach chapter 3.2, respectively “Requirements”, “Architecture and Design” and “Market”. The former is discussed in the previous chapter. This chapter will elaborate on the other two aspects to define selection criteria to finally identify a suitable modeling tool. The first two perspectives are used to form criteria where the last one is used to define a long list of potential modeling tools (figure 12).

5.1 Potential Software programs

From the perspective of architecture and design an initialization has been made of all commonly used in-house programs. To investigate which in-house programs are important for RHDHV Nijmegen according to this project, table 10 is composed with the amount of licenses available. One software program that has to be included in the software environment is Enterprise Architect, due to the containment of system specifications. Obtaining the other programs in this table it can be concluded that the Autodesk products are the most popular software programs containing 3D CAD models.

<table>
<thead>
<tr>
<th>In-house programs</th>
<th>Amount of licenses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allplan Architecture</td>
<td>2-3</td>
</tr>
<tr>
<td>Autocad 2012</td>
<td>1-2</td>
</tr>
<tr>
<td>Autodesk Navisworks</td>
<td>2-3</td>
</tr>
<tr>
<td>Autodesk Revit</td>
<td>5-10</td>
</tr>
<tr>
<td>Autodesk 3DS</td>
<td>5-10</td>
</tr>
<tr>
<td>Enterprise Architect</td>
<td>12*</td>
</tr>
<tr>
<td>Labview</td>
<td>2</td>
</tr>
<tr>
<td>Matlab/Simulink</td>
<td>2</td>
</tr>
<tr>
<td>VR4MAX</td>
<td>1</td>
</tr>
</tbody>
</table>

* including 10 employees of Soltegro

Table 10 Initialization of Inhouse software programs

The most obvious and suitable solution is to create the simulation model in one of the Autodesk products available. After gaining information about the product possibilities from an Autodesk reseller, none of the products were capable of simulating the required solution. Autodesk Revit is used to simulate structural building of constructions and simulate constructions in a sustainable way (e.g. energy consumption), where Autodesk Navisworks simulate construction schedules and logistics in 4D to visually communicate and analyze project activities. (Appendix 10 brochure Autodesk). The reseller eventually advised to focus on the compatibility with Autodesk 3DS Max 3D models, due to the capability of importing all kind of Autodesk files in this program.
Further research resulted in a software environment as shown in the figure 13 below. All this software is used during a system engineering process at RHDHV. Enterprise Architect (EA) in the center of the figure holds the Diamond model (Sub-chapter 2.1), consisting of SysML diagrams. The input for these diagrams are the system requirements stated in Relatics (Appendix 11) and the Reliability Availability Maintenance and Service (RAMS) analysis stated in the Reliability Workbench.

![Figure 13 The software environment at RHDHV](image)

In line of the main research question the SysML information from EA has to be merged with the 3D models from Autodesk 3DS Max. Table 11 contains the design alternatives. One assumption for this table is that EA and 3DS Max has to be involved in the combination of software programs this could be as input program, output program or both. Eventually the system behavior information has to be updated and a 3D visualization of the system has to be developed.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Used Programs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3DS Max</td>
<td>Send system information from EA to 3DS max to develop a dynamic 3D simulation.</td>
</tr>
<tr>
<td>2</td>
<td>EA</td>
<td>Use EA to conduct the dynamic simulation and do only the visualization in 3DS Max.</td>
</tr>
<tr>
<td>3</td>
<td>?</td>
<td>Use an intermediate executable model developed on the system information from EA to do the behavioral analysis and 3DS Max to do the visualization.</td>
</tr>
<tr>
<td>4</td>
<td>EA</td>
<td>Use EA to conduct the dynamic simulation and use an executable model to do the 3D visualization. 3D models has to be compatible with 3DS Max.</td>
</tr>
<tr>
<td>5</td>
<td>?</td>
<td>Use a software program to do the system behavior analysis with the system information from EA and a software program to do the visualizations. The 3D models has to be compatible with 3DS Max.</td>
</tr>
</tbody>
</table>

Table 11 design alternatives

After a desk research, tutorial modeling and interviewing the specialists within the company the following information about EA and 3DS max has been retrieved.

5.1.1 Enterprise Architect

Enterprise architect is a high performance modeling, visualization and design platform based on UML 2.4.1. standard including the SysML structure (Sub-chapter 3.1.1). To give an impression what kind of documents can be generated by the Diamond model in EA a flowchart is shown (figure 14) with the scenario text on the right. A complete flowchart for the opening of the tidal flow is shown in appendix 4.
Although, the development of the Diamond model is under construction and the current model does not reach the low level parametric diagrams. These diagrams contain values for performance and reliability, which are important input values to simulate the behavior of the system. A possible option proposed during the interview is to create an Excel file with all dependent values for the dynamic simulation which can be obtained in the parametric diagrams in a later stage of the Diamond model development. On this proposal a plug-in software program of EA is found, Solvea Intercax (Appendix 12), which has the opportunity to easily import/export data from or to Excel.

Another issue is the simulation possibility within EA which does not support timed events and stochastic distributions.

5.1.2 Autodesk 3DS Max

Autodesk 3DS Max is a software program to model and animate 3D-objects with the ability to render pictures from this 3D environment. The visualization model used by the visualization expert contains the complete Coentunnel 3D model (figure 15) with the road to and from the tunnel on high realistic scale. A minor point is the exclusion of some TTTI in the model e.g., Camera’s, Tunnel ventilation, Moveable bariers and height detections. Another problem of this software program is the non-dynamic possibility to run a what-if scenario. In cooperation with the 3D specialist a short scan is made to investigate the possibilities to connect Autodesk 3DS Max to a 2D simulation program like CPN tools. The result is that it would take allot of time to handle the complexity behind 3DS Max and the risk to fail finding a connection would be too high.
5.1.3 Software environment at RHDHV

Concluding the retrieved information from EA and 3DS Max the final alternative is alternative 5. It is necessary to search for a software simulation program on the market which can analyze the dynamic behavior of a system and which is compatible with both excel and Autodesk 3DS max. The software environment at RHDHV with the discovered possibilities described in this subchapter is shown in figure 16 colored black elements. The blue elements depicted in the figure above are the connection of a conceptual model in CPN to the software environment.

![Diagram of software environment at RHDHV](image)

**Figure 16 A schematic view of the software environment at RHDHV**

<table>
<thead>
<tr>
<th>Market</th>
<th>Description how the program is found.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arena</td>
<td>Used at the TU/e and stated in theory (Law).</td>
</tr>
<tr>
<td>Catia SE</td>
<td>The System engineering program of Dassault Systemes, the opponent of Autdesk.</td>
</tr>
<tr>
<td>CPN tools</td>
<td>Used at the TU/e.</td>
</tr>
<tr>
<td>Dymola</td>
<td>Stated in paper both with Modelica.</td>
</tr>
<tr>
<td>Enterprise Dynamics</td>
<td>Used at the TU/e.</td>
</tr>
<tr>
<td>Flexsim</td>
<td>Used by previous graduation students.</td>
</tr>
<tr>
<td>IDA Tunnel EQUA</td>
<td>Tunnel modeling program found on Modelica.</td>
</tr>
<tr>
<td>Simio</td>
<td>Found with keywords: 3D simulation.</td>
</tr>
<tr>
<td>VSTEP</td>
<td>Suggested during a meeting.</td>
</tr>
<tr>
<td>XVR</td>
<td>Suggested during a meeting.</td>
</tr>
</tbody>
</table>

**Table 12 Potential software programs on the market**

5.1.4 Market

Scanning the market with previous knowledge from the university, using keywords and receiving suggestions during the search of potential software programs resulted in a long list of software programs. All simulation software programs during the search are stated in table 12. After each
program name there is a short description how the program is found. This long list will be the input
of the software selection tool elaborated in the sub-chapter 5.3.

5.2 Selection Criteria
The selection criteria are evolved from two of the three perspectives, respectively “Requirements”
and “Architecture and design”. This practical information will be coupled to theoretical stated criteria
to form more general criteria. These general criteria will be used in the next subchapter to qualify the
most suitable modeling tool.

5.2.1 Defining selection criteria
The discovered practical information is translated in the following theoretical selection criteria.
(selection from criteria defined by Verma et al. (2008) and Wenzel et al. (2003).
- General information; purpose, ease of learning, financial information;
- Analysis possibilities; experimentation facilities, what-if analysis, statistical facilities;
- Visualization; dimension, representation;
- Compatibility; Input/Output issues;

**Purpose;** A short description of what the main purpose of the program is. The lower level criteria are
defined in: general purpose vs. Application Oriented and object oriented simulation package.
General-Purpose simulation package; can be used for many applications, but might have special
features for certain ones. (written code, more flexible, difficult to learn)
Application –oriented simulation package; is designed to be used for certain class of applications
such as manufacturing, health care, etc. (graphics, dialog boxes and pull-down menus, easy to learn,
only not flexible enough).
Object – oriented simulation package; a model consisting of objects that interact with each other as
the simulation evolves through time.

**Ease of learning;** Is it hard to learn to work with the simulation package? And what kind of support is
available. The lower level criteria are defined in availability of: Manual, tutorial, forum or training
courses.

**Financial information;** purchase prices and licensing prices.

**Experimentation facilities;** A software package with improving quality of simulation results and for
speeding up the process of designing experiments of the experimentation itself. The lower level
criteria are defined in: Warm-up period, Automatic batch run.

**Statistical facilities;** what is the range and quality of the statistical facilities available in the software
package. The lower level criteria are defined in availability of: statistical distributions, random
number streams.

**Dimensions;** the dimension of the software package during the modeling phase and when simulation
is running. The lower level criteria are defined in: 1D, 2D, 2.5D or 3D. 2.5D is modeling in 2D and the
possibility of running the simulation in 3D animation.

**Representation;** the abstraction level of the elements in the simulation package. The lower level
criteria are defined in: Symbolic/Letter, Symbolic/Abstract, Portrait/Simplified (P/S), Portrait/Real
(P/R) or Photo-Realistic (P-R).
Input/Output: what are the capabilities of data transfer in the defined architecture and design of the software environment of RHDHV. The lower level criteria are defined in compatibility with: Excel, Autodesk 3DS max, other CAD files.

5.3 Software Selection Tool
To specify the most suitable software program the long list of potential software programs has to be brought back to a shortlist as input for the selection framework. This shortlisting is done by evaluating the long list.

5.3.1 Software evaluation
To shortlist the long list all software packages are evaluated. The explanation of not selecting a specific package for the shortlist is given below. The software evaluation will be based on the main purpose of the software simulation packages as described in the additional information in appendix 13.

VSTEP and XVR
Both the software programs VSTEP and XVR have the main purpose to do simulations in virtual training environment for e.g. simulate emergencies with fireman. It is not a modeling environment to analyze and visualize the System Engineering design in.

IDA tunnel
This software program is a modeling and simulation program based on tunnel design. The issue about this product is the focus. It is developed to compute underground climate and to support ventilation and fire design task of tunnel systems.

CPN-Tools
This is the only software package without a connection to 3D.

Catia SE
Catia SE from Dassault Systemes is a program used in production companies to fully support system engineering with lifecycle management, from versioning to configuration, alternatives, and collaborative design as all objects are managed in a single PLM platform.

This complete package would need a full reconstruction of the current software environment taking all kind of Dassault systemes as foundation to make the perfect SE tooling. It is also a too specific tooling used in the aerospace and automotive industries to simulate behaviors on the level of bearings.

5.3.2 Software evaluation
The software selection tool is a framework which uses sub criteria to specify the differences between the packages on the shortlist, according to gained information from the software developer or reseller. Each sub criteria can be valued from a five point scale (see under table 14) from “very strong” to “very weak”. This qualitative ranking will give an indication which software program will be the most suitable.
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Arena</th>
<th>Dymola</th>
<th>Enterprise Dynamics</th>
<th>Flexsim</th>
<th>Simio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sub</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>General information</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purpose</td>
<td>±</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Ease of learning</td>
<td>+</td>
<td>-</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Financial</td>
<td>--</td>
<td>?</td>
<td>±</td>
<td>±</td>
<td>±</td>
</tr>
<tr>
<td><strong>Analysis possibilities</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimentation facilities</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Statistical facilities</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Visualization</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dimension</td>
<td>±</td>
<td>±</td>
<td>±</td>
<td>++</td>
<td>±</td>
</tr>
<tr>
<td>Representation</td>
<td>--</td>
<td>±</td>
<td>--</td>
<td>++</td>
<td>±</td>
</tr>
<tr>
<td><strong>Compatibility</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input/Output</td>
<td>±</td>
<td>++</td>
<td>±</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

Scale: (+++) – very strong, (+) – strong, (±) – intermediate, (-) – weak, (--) – very weak

Table 14 the software selection tool

**Purpose**
The purpose is to create a model in the domains of System engineering. If is preferred to be object-based to enhance the understanding of the model, especially the behavior of the sub-installations. Supporting the score:
- Weak: Not in the domain of System Engineering but a general modeling tool, which is not object based.
- Strong: Do not support an application of System Engineering directly but can also be more general modeling tools. These programs are object-based.
- Very strong: Supports the System Engineering domain and is object-based.

Ease of learning
Due to the limited time of the graduation project is a preference to learn the software package within a short time.
- Weak: There is enough supporting information available but due to complexity of the program the limited time can become a problem.
- Strong: There is enough supporting information available to get acquainted with the software in a reasonable time.
- Very Strong: There is already some experience with using this simulation package.

Financial
What are the annual commercial purchasing costs for the software packages dedicated to one licenses. These prices are based on given prices by the developer or reseller with taking in account the possibilities to adjust elements to customize the package for this particular use.
- Arena: € 27.500,- only received one price
- Dymola: none indication received.
- Enterprise dynamics: ED developer platform + Runtime = € 14.000 + € 4.500 = € 18.500,-
- FlexSim: received two options; € 21.500 one year contract, € 17.500 for a four year contract.
- Simio: Enterprise edition; €20200, -

Experimentation Facilities
A software package with the improving quality of simulation results and for speeding up the process of designing experiments of the experimentation itself. Automatic batch runs, warm-up period and running scenario’s.
- Arena: Run setup configuration option available.
- Dymola: Run setup configuration option available.
- Enterprise dynamics: Run setup configuration option available.
- FlexSim: Run setup configuration option available.
- Simio: Run setup configuration option available.

Statistical facilities
What is the range and quality of the statistical facilities available in the software package?
Statistical distribution and number of random streams available.
- Arena: Opt Quest, is an add-on option to analyze
- Dymola: can solve differential algebraic equations and has a design optimization option.
- Enterprise dynamics: has a flow analyzer which is capable of these statistical facilities.
- FlexSim: Has a data fitting tool, called Expertfit (which has a connection to averill-law) integrated.
- Simio: optional to work with Opt Quest.

Dimensions
For increasing the understanding of a model it is preferred to develop the executable model in 3D.
- Very weak: modeling in 2D
- Intermediate: modeling in 2D with visualization in 3D
- Very strong: modeling in 3D
Representation
The representation is the abstraction level of the elements in the simulation package. For some software packages there can be two abstraction levels, respectively the abstraction level in modeling and the abstraction level in the visualizing the simulation. The possible representations are Symbolic/Abstract, Portrait/Simplified (P/S), Portrait/Real (P/R) or Photo-Realistic (P-R).

- Arena; the modeling is Symbolic/Abstract and the visualization (P/S)
- Dymola; the modeling is Symbolic/Abstract and the visualization (P/R)
- ED; the modeling is Symbolic/Abstract and the visualization (P/S)
- FlexSim; both (P/R)
- Simio; the modeling is Symbolic/Abstract and the visualization (P/R)

Input/output
The input and output possibilities of the software package according to this specific assignment
- Arena; Excel
- Dymola; Excel and CAD models
- ED; Excel
- Flexsim; Excel and CAD models
- Simio; Excel and CAD models

As a result of the applied software selection tool, FlexSim is considered as the most suitable software program to develop the final executable model in. Chapter 6.2 will give an impression of the software simulation package, elaborating on the essential parts of the designed executable model.
6. A new MBSE approach: SysML, 3D CAD models, Flexsim

In this chapter the selected software program is placed into the software environment of RHDHV (see figure 17). This new environment needs a new approach to leverage from the possibility of using Flexsim. Sub-chapter 6.1 describes how the interaction of the software in the new environment is and describes the specific approach used in this research. Finally, sub-chapter 6.2 will give some improvements of the approach for the future.

6.1 The integration of Flexsim in the RHDHV software environment

With the selected suitable modeling tool from previous subchapter, the new software environment for RHDHV is developed. The software environment will become like the figure 18 below.

- Enterprise Architect: holding the SysML diagrams (including the requirements, parameters, etc.) explained in sub-chapter 3.1.1.
- Intercax Solvea (appendix): A software-plugin for EA capable of importing and exporting SysML parametrics to and from Excel.
- Microsoft Excel: as an intermediate software program to connect parameters from EA to Flexsim.
- AutoCad 3DS Max: to develop, change and contain 3D models (in .3ds format). These 3D contain input information of the objects in Flexsim;

- Flexsim: that merges the information of the software programs EA (through excel) and 3DS Max to an executable model.

Figure 19 The SysML diagrams

Taken into account the limitations of the current SysML models developed in EA (chapter 5.1.1), the following practical steps has been executed with Excel as input and output database for the system parameters. Improvements for the future suggesting that all the SysML diagrams will be available are stated in the next sub-chapter. The approach used in this research for developing the executable model in Flexsim, is:

1. The start point of the process is to read the scenario's in text or flowchart to define all involved objects. The flow chart can be the starting point although not all descriptions can be directly linked to an object, use the text to resolve this problem.
2. Create all routings according to the flowchart and define all conditions to the object triggers to create the main behavior of the scenario.
3. Create an Excel chart as intermediate database for the system parameters that dependents the system behavior.
   - a. Create an excel chart with all input parameters that have to be variable.
   - b. Load the chart in Flexsim and couple the table references with the parameters describing the system behavior to the concerning object triggers. (e.g. process times, MTBF, MTTR, etc.) and reserve table cells or another chart for all output variables.
4. Split the scenario into sub-scenarios and develop these essential sub models to verify and validate the behavior.
5. Develop or change 3D models with Autocad 3DS Max and load this objects shape in Flexsim to the corresponding objects with the system behavior parameters.
6. Define the movements of the 3D shape in Flexsim and specify on triggers when it has to move.
7. Assemble all sub-models into the scenario model and do final verification and validation iterations.
   - a. The model can be simulated in 3D to receive more comments to adjust the model from the less experienced SysML users.
b. To analyze, the model has to be simulated with the use of the experimenter and the results can be evaluated in Flexsim or in Excel.

c. Adjustments can be made according to the outcome of 7a or 7b.

8. When the right parameters set with the preferred outcome is received from the executable model these can stored into the reserved output table cells or chart in Excel.

The approximated time to design the Tidal Flow scenario in Flexsim, excluding the time to get acquainted to Flexsim, is about 200 man hours.

6.2 Possible improvements: to connect SysML and 3D CAD models to Flexsim.

To retrieve the maximum leverages from the connection of these software programs some improvements are suggested. Assuming that in the near future all static SysML diagrams (especially the lower level diagrams as the parametric diagrams) are available in Enterprise Architect.

The first improvement could be the use of Solvea Intercax as plug-in from EA to import and export all parameters from the SysML diagrams to and from excel or perhaps directly to Flexsim.

The second improvement could be the development of the SysML diagram information taken into account the structure of Flexsim (figure 20) used for developing all objects and in the end the complete executable model.

The blocks or some of the blocks in the activity and sequence diagrams could be used to describe objects and the connection of these objects in Flexsim. This would create the basis of the Executable model.

The behavior of the objects in certain conditions, explained in use case or state diagrams could be exported by parameters and connected to the object structure of Flexsim. Under the variable topic lots of possible triggers are defined to simulate the right behavior of the executable model in relation to the possible defined states and the defined cases of the object or objects in the systems.

To centralize the visual aspects of the objects in Flexsim a parameter in SysML has to hold information about which 3DS Max file is connected to the object. Other information could be the size and position.

With these improvements EA will hold and evolve all system behavior as a database, 3DS Max will support Flexsim with the development or adjustments on 3D CAD files and Flexsim will combine both strengths to make and test the executable model. On evaluation of these tests all inputs can be adjusted and the executable model will be changed as an iterative process.

The new additional possibilities which probably enhance the previous approach are:

- Testing SE designs in the early development phase with executable models.
- Creating a 3D model to increase understanding of the SE design, to other less experienced SysML stakeholders.

These enhancements have to decrease the time to validate the system design before it is physically created, which will reduce errors and resolve problems. In the end the probability of installing wrong
subsystems or changing the physical systems will be reduced, resulting in lower costs and faster throughput times of the SE projects.
7. The executable model

Based on the previous two chapters the start of developing the actual executable model can begin. Stage one provides most of the acquired data and the simulation requirements from RHDHV and stage two the software program (figure 21). With this information the scope of the simulation is defined in sub-chapter 7.1. Sub-chapter 7.2 contains the description of the model, more specifically the essential parts. Finally sub-chapter 7.3 describes the verification and validation of the model.

![Stage 4: the executable model](image)

7.1 Assumption document

This sub-chapter contains the description of the assumption document containing, a black box representation with the explanation of the variables, the scope of the simulation model, the assumptions and the simplifications. This document supports the simplified representation of the real world in the executable model. The black box representation with the explanation of the variables is already described in chapter 4.2.

7.1.1 Scope of the simulation model

Zooming in on the black box representation a schematic simulation model (figure 22) will appear. This schematic model, the made assumptions and simplifications form the scope of the actual simulation model.

![The schematic model](image)

The schematic model gives an overview of how the switching from driving direction will be translated to the simulation. To give an indication of the lower complexity of one block, the content of the block “Open access road A10” is discussed earlier in the conceptual model and is stated in appendix 4 and 5. The red arrows specify the time when the tunnel is open and is excluded from the simulation. It is not in the scenario and during this time other system behaviors occur. Remarkable is the difference in number of accesses from the North only A8 and from the South A5 and A10.
The level of detail:
- The level of detail is discussed and decided to be on the TTTI sub-system level. Some of the sub-systems have installations with visual importance to the scenario, e.g. the movement of crossing gates or the moveable barrier. These sub-systems have a level of detail on installation level.
- A hand is used as flow item to visualize the handlings of the traffic control manager
- A yellow sphere is used as flow item to visualize the system handlings.

Assumptions:
- The traffic flow is excluded from the model
- A Road inspector will remove objects from the road and can confirm an action on manual vision after a call is made by the Traffic control manager.
- The appearance of objects on the road is based on information of the Belgic Traffic data.
- A service engineer can be called to repair a failure and will fix it.
- TTTI’s are only checked when opening the tunnel as mentioned in the scenario.

Simplification:
- If sub-installation CCTV is repaired all malfunctioning cameras are up again.
- Installations which fail after the TTTI availability conformation stay down till the next TTTI availability in another “Opening scenario”.
- Changing times from one direction state to another are the same, e.g. the opening and closing of crossing gates.

7.2 Describing the essential parts
As stated in the previous chapter the executable model is designed in FlexSim. To not describe the complete model, some essential parts are highlighted in a concise way. These parts will give an impression of the behavior or visual issues that had to be investigated before the complete executable model could be assembled. The selections of parts to describe are the main flow, the breakdown, the video wall and the Coentunnel.

7.2.1 Main flow
The first part and the fundamental base of the simulation model is the main flow (figure 23), which is similar with the flow stated in the scenario and designed in the conceptual model. A remarkable difference between this model and the conceptual model is the use of two flows. The upper flow, with a hand as flow item, consists of the human handlings that have to be done by the traffic control manager. The human handlings are calling, inspecting the road and confirming system handlings. The flow below, with a yellow sphere as electric signal, illustrates the system handlings defined in the scenario. The system handlings are switching sub-installations in another state, e.g. cameras have to be set in the other direction when the driving direction changes, traffic beams have to be opened etc. Some other system handlings are the camera views that have to pop-up on the video wall, these are defined in the grey squares in the middle row. This layout with the actual tunnel site in the top of the figure is the heart of this executable model.

The issue of modeling such a scenario in Flexsim was the one item flow (in this case two, because of the two parallel flows). Usually Flexsim is used to simulate multiple flow items like production flows or stocking processes. To adjust Flexsim to a one item flow which follows the correct process similar to the scenario all objects had to be configured with opening/closing ports code.
7.2.2 Breakdown

To simulate a breakdown of an object, Flexsim has a standard solution to repair the object and continue the process. However, this solution is not in line with process of the scenario. The difference is the calling process that has to be simulated as a human handling of the traffic control manager. Another difficulty is the hierarchy of the top process of switching the TTTI in the main flow and the breakdowns that occur on sub-system level. Figure 24 below shows the situation of a breakdown in a sub-process which is a more detailed level of the main flow objects within the red circle of figure 23. To continue the main flow in this situation the following processes are done:

On breakdown (1)* the input of the call service engineer will be opened. After finishing the call (2)* by the traffic control manager a message is send to the sub-processor. On this message (3)* the sub-processor sends the task sequence of repairing the sub-processor to the service engineer. In this
particular case the service engineer travels to the sub-processor to repair it. After the reparation the main process continues.
*The numbers correspond with the modeling codes of this process which are stated in appendix 15.

7.2.3 The video wall
The final essential part to discuss is the popup of camera views on the video wall. The creation of the video wall is quite easy, due to the Graphical User Interface option in Flexsim. However, to change the view during a running simulation needed some research in the coding. The final solution to control the views of the video wall is shown in figure 25. The corresponding codes are stated below.

```plaintext
Figure 25 the essential part "video wall"

7.2.4 The Coentunnel
Besides all functional related objects described above the Coentunnel and environment is the main visual object (figure 26) of the executable model. On this model all other visual moveable parts are located to simulate the behavior in 3D when the installation is activated in the main flow. The movements of these parts will also be shown with the use of the camera function and the video wall.

Werkingsrichting veranderen – OnEntry:
/**Custom Code*/
treenode item = parnode(1);
treenode current = ownerobject(c);
int port = parval(0);
startanimation(current,"WR1");
{
    string viewpath = "MAIN:/project/model/Tools/GUIs/GUI 1";
    treenode viewnode = node(viewpath);
    set(spatialx(viewnode),0);
    set(spatialy(viewnode),100);
    set(spatialz(viewnode),400);
    set(viewpointx(viewnode),-15);
    set(viewpointy(viewnode),0);
    set(viewpointz(viewnode),0);
    set(viewpointrx(viewnode),315);
    set(viewpointry(viewnode),0);
    set(viewpointrz(viewnode),45);
    set(viewmagnification(viewnode),2);
    set(viewfield(viewnode),90);
    set(windowtitle(viewnode),2);
    createview(viewpath, 0,0);
```
7.3 Model verification and validation

Before assembling all the parts to a complete executable model all functional related parts have been verified and validated. Where verification is concerned with, determining whether the “assumptions document” has been correctly translated into a computer “program”, i.e., debugging the simulation computer program. And validation is the process of determining whether a simulation model is an accurate representation of the system, for the particular objectives of the study. concerned with determining whether the “assumptions document” has been correctly translated into a computer “program”, i.e., debugging the simulation computer program. (Law, 2007)

Essential parts
The approach of using subprograms, which are defined in this chapter as essential parts, to write and debug important parts of the complete executable model is already one technique to verify. Another applied technique on the essential parts is using a variety of input parameters and checking the output.

The essential parts are mainly validated on face validity, asking individuals’ knowledge about the system whether the essential parts and the behavior are reasonable. This validation is performed by talking to experts at RHDHV and by performing a presentation containing the demonstration of the working essential parts to experts on the tunnel construction side.

Complete model
Besides the techniques used to verify the essential parts, the trace technique is realized in verifying the complete model. First the inputs variables are changed into easily countable numbers. Secondly, a table in Flexsim is developed which stores the entrance data of each event and calculates the
throughput of the sub-scenarios (Appendix 18). The trace is verified by checking event after event if the model time was similar with the pre-calculated times. Some routings had to be adjusted to succeed the verification of the four sub-scenarios of the complete model. The validation of the complete model is only based on the face validity, due to the non-available historical data.
8. Analyses
In previous chapter the development, verification and validation of the executable model designed in Flexsim is described. In this chapter the performance of the model is reported, according to the defined parameters from sub-chapter 4.2. Primarily to explaining the performances in sub-chapter 8.2, the determination of the simulation parameters are discussed in 8.1. Sub-chapter 8.3 compares the main parameters of 7.2 with results from an improved design of the tidal flow system. Finally, Sub-chapter 8.4 map the results to the specified penalty costs of the level 0 documents.

8.1 Simulation parameters
Stated by Law (2007) there are two types of simulation, terminating and non-terminating. The former has a specified run length due to a natural event. The simulation experiment in this research is a non-terminating simulation with a final discrete event described by the scenario of opening or closing the tidal flow.

8.1.1 Warm up period
The warm up period is the time to bring the simulation in its long term “steady-state” behavior. To determine the warm-up period for the executable model some graphs of pilot runs are created. Appendix ... contains the final graph where the warm-up period is observed to be at approximately the amount of 200 scenarios. This corresponds with 1778000 seconds.
It should be mentioned that stochastic processes for most real systems do not have steady-state distributions, since the characteristics of the system change over time (Law, 2007).

8.1.2 Replication length
After the determination of the warm-up period, the replication length has to be decided. Due to the RAMS data based on annual ratio’s and the assumed practical use of the tidal flow on a daily bases, the replication length is considered to be at 365 complete switchovers. This means, a process that switch the driving direction from north to south and back.

8.1.3 Number of replications
As a rule of thumb, a modeler should always perform at least three to five replications for each experiment. According this rule a number of five replications will be used to simulate the executable model.

Flexsim offers an experimenter option which can be used to setup the simulation with the discussed parameters. Another setting is the confidence level interval which will be set on 95%.
8.2 Result of the Tidal flow scenario

In this subchapter the results of the tidal flow scenario will be described. First the throughput time will be discussed the next section followed by the system availability. Finally a suggestion about the determination of the system reliability is made.

8.2.1 Throughput Time

In table 15 the mean throughput times of the different sub-scenarios of opening and closing the tidal flow are shown. As expected the opening scenarios are higher as the closing scenarios, due to the checking and switching the tunnel installations which not have to be done when closing the tunnel. Another obvious result is the higher throughput times for opening and closing the A5 and A10 sub-scenario, because of the double entrance roads with both two crossing gates and one moveable barrier. This mean is based on the average throughput time per sub-scenario, the minimum throughput and maximum throughput are stated in the appendix 18.

<table>
<thead>
<tr>
<th>Average Throughput</th>
<th>Mean( 95% Confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;</td>
</tr>
<tr>
<td>Opening A8</td>
<td>1471,95</td>
</tr>
<tr>
<td>Closing A8</td>
<td>886,59</td>
</tr>
<tr>
<td>Opening A5 + A10</td>
<td>2093,99</td>
</tr>
<tr>
<td>Closing A5+A10</td>
<td>1499,79</td>
</tr>
</tbody>
</table>

Table 15 Average throughput times per sub-scenario in seconds

8.2.2 System availability

As mentioned in the data collection the availability can be calculated with equation (4.2). Because not the up time but the downtime is the output from the simulation and the availability is requested to be stated in percentages the equation has been rewritten in:

\[ A = \left(1 - \frac{down\ time}{Total\ time}\right) \cdot 100\% \]

In this equation the down time is the sum of the cumulative downtimes of the sub-systems and the total time is one year defined in seconds (31.536.000) according to the simulated 365 switchovers. Based on the equation and the gathered cumulative breakdown output from Flexsims’ Experimenter the following system availability for each replication is calculated in table .... The overall average system availability as solution of this simulation is 97.36%.

<table>
<thead>
<tr>
<th>Availability per replication</th>
<th>Rep 1</th>
<th>Rep 2</th>
<th>Rep 3</th>
<th>Rep 4</th>
<th>Rep 5</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Down time per year (sec)</td>
<td>812165</td>
<td>645653,2</td>
<td>1464257,7</td>
<td>734433,85</td>
<td>509118,78</td>
<td>833125,71</td>
</tr>
<tr>
<td>Availability</td>
<td>97.42%</td>
<td>97.95%</td>
<td>95.36%</td>
<td>97.67%</td>
<td>98.39%</td>
<td>97.36%</td>
</tr>
</tbody>
</table>

Table 16 Calculated availability

The most remarkable output of the table is the down time of replication three. According to the pie chart (figure 28) below it can be concluded that the high down time of this replications is the result of failures in five sub-systems with high mean times to repair, respectively the entrance lights (IV), traffic guidance lights (VGV), height detection (HD), the moveable barrier (OV) and the crossing beam (OC). It is obvious to conclude that the sub-system Height Detection (HD) has the largest share of non-availability. Reflecting this result to the input parameters shows that the high MTTR and low
MTBF are the causes of this large percentage. From the defined sub-systems the HD is determined as the bottleneck of the system.

8.2.3 System reliability

To calculate the reliability only based on the down times is not an option, it could be that a breakdown of a sub-system does not or not completely influence the reliability of the whole system. To investigate and give an indication how breakdowns have influence on the complete system, the average stay times and maximum stay times of human handlings are recorded per replication (appendix 18). Each human handling is dependent on system handlings including breakdowns or unusual human handlings like calling the road inspector to remove and object or confirming on manual vision if crossing gates are opened or closed. The human handlings with stay times and there depending possible delay objects are stated in table 17.

<table>
<thead>
<tr>
<th>Human handling</th>
<th>Possible delay objects</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>IV, CCTV</td>
</tr>
<tr>
<td>BOV</td>
<td>BOV</td>
</tr>
<tr>
<td>BSS</td>
<td>OV, CCTV</td>
</tr>
<tr>
<td>BRV</td>
<td>BRV1, BRV2</td>
</tr>
<tr>
<td>BCO</td>
<td>BCO, OC</td>
</tr>
<tr>
<td>BAO</td>
<td>BAO, OA</td>
</tr>
<tr>
<td>MTM</td>
<td>MTM, ALB</td>
</tr>
<tr>
<td>MTM2</td>
<td>MTM, PPM</td>
</tr>
<tr>
<td>DRIPS</td>
<td>PD</td>
</tr>
</tbody>
</table>

Table 17 The human handlings with depending breakdown objects

Figure 29 shows the maximum stay time and average stay time of the human handling command open. From this figure can be obtained that runs two, three and four have high maximum stay times, were runs one and five have low ones. It can be concluded that in run one and five neither of the sub-systems Entrance lights, CCTV, Ventilation, Traffic guidance lights and Height detection had a breakdown with a high peak influencing the complete system. To give a more precise evaluation of the maximum stay times of 2, 3 and 4 more exact data is required. The measured maximum value obtains no information of the
amount of times that a specific value or other high values just below the maximum occur. Due to this missing information it is impossible to give an answer to the system reliability.

Concerning the time of the complete research only a possible option to receive the information is given. The option for further research could be to data log the event log of Flexsim to receive information about the flow items in the system and the breakdowns. In this way a more reliable conclusion can be made about the object with the highest delay which affects the system the most.

### 8.3 Comparison of a design improvement

To simulate the possibility of analyzing the complete system behavior in a designing process the discovered bottleneck from subchapter 8.2 is improved in the executable model. The MTBF of the height detection is increased with five percent. To give an illustration of the improvement, with the previous parameter it has an average of 104 failures a year, and with the improvement it has reduced to 99 failures a year.

#### 8.3.1 Throughput times

As shown in table 18 the throughput times of the normal system design is compared with the improved system design. The influence of the improvement is mainly visible on the maximum means which is reduced from almost fifteen hours to nine hours. This reduction has to be the result of fewer failures, taken into account that the reduction of one failure will reduce the total failure time with a mean of 9.5 hours. Another not expected improvement is on the highest measured maximums. The results of these measurements will be dependent on the random generator variables which are generated by Flexsim.

<table>
<thead>
<tr>
<th>Comparison Throughput times</th>
<th>Average mean Normal</th>
<th>Improved</th>
<th>Maximum Mean Normal</th>
<th>Improved</th>
<th>Maximum Max Normal</th>
<th>Improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening A8</td>
<td>1494</td>
<td>1507</td>
<td>21934</td>
<td>15671</td>
<td>53123</td>
<td>36628</td>
</tr>
<tr>
<td>Closing A8</td>
<td>893</td>
<td>886</td>
<td>4783</td>
<td>1610</td>
<td>15434</td>
<td>2262</td>
</tr>
<tr>
<td>Opening A5 + A10</td>
<td>2122</td>
<td>2098</td>
<td>21151</td>
<td>10522</td>
<td>40536</td>
<td>23676</td>
</tr>
<tr>
<td>Closing A5+A10</td>
<td>1509</td>
<td>1517</td>
<td>5958</td>
<td>5729</td>
<td>18956</td>
<td>18389</td>
</tr>
<tr>
<td>Total switchover</td>
<td>6018</td>
<td>6008</td>
<td>53826</td>
<td>33532</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 18 Comparison of throughput times*

#### 8.3.2 Availability

As stated in table 19 the availability on each replication is increased. The discussed replication three is again a point of discussion, where it was the most negative run in previous analyses it is the most positive one in the improved design analysis. The improvement of 1.18% will be reduced to a reduction of 0.52 % if run three should be excluded. The values for the normal availability and improved availability would be 97.86 % and 98.38%.

Whether the particular run is excluded or not the improvement of the height detection seems to have effect on the availability.

<table>
<thead>
<tr>
<th>Comparison availability</th>
<th>Rep 1</th>
<th>Rep 2</th>
<th>Rep 3</th>
<th>Rep 4</th>
<th>Rep 5</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability normal</td>
<td>97.42%</td>
<td>97.95%</td>
<td>95.36%</td>
<td>97.67%</td>
<td>98.39%</td>
<td>97.36%</td>
</tr>
</tbody>
</table>
improved  98.34%  98.24%  99.25%  98.40%  98.49%  98.54%
Table 19 Comparison of availability

Looking further into the cumulative breakdown time of the height detection (table 20) it can be concluded that on the total downtime of the height detection is decreased significantly, almost fifty percent. Like in the table of the availability in this table replication three shows the largest difference, with 971.665 seconds. Excluding this replication in analyzing the results show that on replications one, two and four improvements are made and in replication five a slightly increased breakdown time is discovered.

<p>| Cumulative breakdown time Height detection |</p>
<table>
<thead>
<tr>
<th>Rep 1</th>
<th>Rep 2</th>
<th>Rep 3</th>
<th>Rep 4</th>
<th>Rep 5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>normal</td>
<td>685297,1</td>
<td>611024,53</td>
<td>1130970,01</td>
<td>569989,88</td>
<td>436872,98</td>
</tr>
<tr>
<td>improved</td>
<td>422101,8</td>
<td>461825,74</td>
<td>159305,91</td>
<td>310821,16</td>
<td>458798,13</td>
</tr>
</tbody>
</table>

Table 20 Cumulative breakdown time Height detection

In relation to the other sub-installations during the complete analysis the improved design has decreased the percentage of downtime with three percent by the height detection. The more specific percentage of downtime per run can be found in appendix 17.d and 18.d.

Figure 30 Percentage of downtime per sub-system for both the Normal and Improved design
8.4 Evaluate results with penalty costs

This subchapter will evaluate the analysis results from the executable model with the penalty costs stated in the level-0 document. The costs construction depends on the availability discount and the performance discount. The former will cost money when the minimum safety level is not met. The latter will cost money when the performance of the system does not met the stated requirements. When a failure occurs the previous to discounts have to be taken into account. The availability discount requirements are stated in the upper bound of table 21. The average penalty costs for such availability discount is € 14,000 per fifteen minutes. The performance discount is based on the requirements on the lower bound of table 21. If these requirements are not met a penalty point will be given. Every time the maximum time to repair (TTR) is exceeded another penalty point will be given. Each penalty point can be calculated as an average cost of € 10,000.

### Availability discount

<table>
<thead>
<tr>
<th>Sub-system</th>
<th>Requirement</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossing gate (OC)</td>
<td>TTRmax &lt; 8 hour</td>
<td></td>
</tr>
<tr>
<td>Entrance lights (IV)</td>
<td>TTRmax &lt; 8 hour</td>
<td></td>
</tr>
<tr>
<td>Height detection (HD)</td>
<td>TTRmax &lt; 8 hour</td>
<td>Red phase</td>
</tr>
<tr>
<td></td>
<td>TTRmax &lt; 192 hour</td>
<td>Other phases</td>
</tr>
<tr>
<td>Dynamic traffic signs</td>
<td>TTRmax &lt; 8 hour</td>
<td></td>
</tr>
</tbody>
</table>

### Performance discount

<table>
<thead>
<tr>
<th>Sub-system</th>
<th>Requirement</th>
<th>Penalty points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moveable barrier (OV)</td>
<td>TTRmax &lt; 360 hour</td>
<td>1</td>
</tr>
<tr>
<td>Traffic guidance lights (VGV)</td>
<td>TTRmax &lt; 24 hour</td>
<td>1</td>
</tr>
<tr>
<td>Ventilation (VENT)</td>
<td>TTRmax &lt; 192 hour</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 21 The summarized Availability discount and Performance discount

### Average breakdown times per sub-system of each replication

<table>
<thead>
<tr>
<th>Sub-system</th>
<th>Normal Design</th>
<th>Improved Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>3,67</td>
<td></td>
</tr>
<tr>
<td>CCTV</td>
<td>5,15</td>
<td>4,85</td>
</tr>
<tr>
<td>VENT</td>
<td>3,75</td>
<td>3,46</td>
</tr>
<tr>
<td>VGV</td>
<td>9,52</td>
<td>9,43</td>
</tr>
<tr>
<td>HD</td>
<td>4,73</td>
<td>4,50</td>
</tr>
<tr>
<td>OV</td>
<td>4,95</td>
<td>4,40</td>
</tr>
</tbody>
</table>

Table 22 Average breakdown times per sub-system of each replication

Based on the average breakdown times per sub-systems (table 22) no penalty costs occur. Only if a red phase would occur. These phases are not in the scope of the executable model of the tidal flow.
### 9. Conclusion and recommendations

In the last chapter of this thesis the main conclusion, recommendations and further research is discussed.

#### 9.1 Conclusions

As a result of changing the responsibility in traffic tunnel design from the government to the involved companies developing and maintaining the tunnels, the need of an understandable SE approach is required. During the development of the TTTI in the Coentunnel project RHDHV and Soltegro started the development of the Diamond model. This is a software tool, which can generate stakeholder specific documents. Instead of full text documents these can be partially supported with model based diagrams or even completely model based documents. The diagrams have to increase transparency and show the consistency between various installations. The stated system engineering language, SysML, is used to create the structure of these static diagrams.

As an evaluation on the Diamond Model issues like a large throughput time of the SE approach and understandability of the complex system to non-experienced SysML stakeholders have to be resolved. In order to do research to the possibilities of resolving these issues the following research question is formulated.

“Can a dynamic 3D simulation be developed that merges the SysML system specifications with 3D CAD models to improve the understanding to less experienced SysML stakeholders?”

To answer this question the research is split into five stages each answering different sub-questions to eventually answer the main question.

**Stage 1: Conceptualization**

*The sub-questions that have to be answered during this stage:*

- What are the requirements for the executable model?
- What are the most important analyses that the executable model has to support?
- What data has to be collected for the executable model?

As starting point in the conceptualization phase, the current available information has been gathered to start modeling a conceptual model in CPN Tools. The early start of conceptual modeling helped specifying the executable model requirements in an early stage. The concept model is also used as data collection tool, to recognize through modeling what data is missing. The executable model requirement is below followed by some performance indicators:

- The main purpose is to develop a dynamic 3d simulation capable of simulating what-if scenario’s based on scenario information and failure information. With the analysis of this simulation the SE can gain knowledge about the availability of the tunnel tube containing the tidal flow. The visualization of the complete scenario has to improve the understanding of the interactions of human handlings and system handlings to less experienced SysML stakeholders.
- Road inspectors have an average arrival time estimated on 15 minutes
- Objects appearing on the road are assumed to happen 55,73 times a year
- The handling ‘Inspecting” by the Traffic managers is calculated to have a mean of 61 seconds and a standard deviation of 9 seconds
- The handling “confirming” by the Traffic managers is calculated to have a mean of 29 seconds and a standard deviation of 54 seconds
- All RAMS data is stated in appendix 13

**Stage 2: Identify a suitable modeling tool**

*The sub-questions that have to be answered during this stage:*

...
In order to identify a suitable modeling tool an in house initialization of software is conducted. This has reduced the design alternatives from a design and architecture aspect to one; Use a software program to do the system behavior analysis with the system information from EA and a software program to do the visualizations. The 3D models has to be compatible with 3DS Max. This alternative, and more specified selection criteria in combination with a potential software program list are the inputs for the software selection tool. By specifying the strengths and weaknesses of each software program based on gathered documentation one suitable software program is selected. The selected program is Flexsim.

Stage 3: A New MBSE approach: SysML, 3D CAD model, Flexsim

The sub-questions that have to be answered during this stage:

- What will be the role of the new modeling tool in the model based system engineering approach and how can it be executed?
- How can the SysML diagrams and the 3D CAD Models be connected to Flexsim?
- What are the leverages of this new approach?

Introducing Flexsim in the software environment of RHDHV will change the process of system engineering. The new defined SE approach will be a Vee model with in the center the tools:

- EA: holding the requirements and parameters in some SysML diagrams;
- AutoCad 3DS Max: to develop, change and contain 3D models (in .3ds format) and;
- Flexsim: merges the information of EA and 3DS max to an executable model.

The steps conducted to develop the executable model in this research are described and possible improvements of the approach are given. The new additional possibilities which probably enhance the previous approach are:

- Testing SE designs in the early development phase with executable models
- Creating a 3D model to increase understanding of the SE design, to other less experienced SysML stakeholders.

These aspects eventually have to reduce errors in the physical systems, lower project costs and increase the throughput time of SE projects.

Stage 4: The executable model

The sub-questions that have to be answered during this stage:

- What will be the boundaries of the simulation?
- Which assumptions have been made?
- How the executable model is made understandable?
- What kind of verification is used to verify if the model is working as it has to?
- What kind of validation is used to check if the executable model suits the real world scenario of the “Tidal Flow”?

Concerning the development of the executable model an assumption document is created stating the simulation scope and the assumptions (chapter 7.1). The executable model is created in 3D with all human handlings specified by a human hand as flow object and the system handlings by a yellow sphere, this increases the understanding of simulating the system behavior in the model. The
verification and validation of the executable model is done both in sub-models as well as the mean model.

**Stage 5: Analysis**

The sub-questions that have to be answered during this stage:

- How do you create a setup plan to conduct a reliable simulation?
- What is the throughput time of the tidal flow scenario?
- What is the availability of the tidal flow?
- What are the total penalty costs according to the level-0 document?

As a starting point the tidal flow is set on 365 x to analyze the complete opening and closing cycle once a day over one year. The average throughput time of the complete cycle per day is 6017 seconds and the average availability is calculated on 97.36%. The height detection is discovered as the bottleneck of the system. An improvement of the height detection of 5% on the mean time before failure has a positive effect on both the availability and the maximum throughput time. It has no or low effect on the average throughput time. The specification on penalty costs is not possible because the values do not exceed the stated requirements, so no costs could be acquired.

Table 23 Artifact descriptions below will discuss this research in perspective of the IS research model described in sub-chapter 2.5.

<table>
<thead>
<tr>
<th>Guideline nr and description</th>
<th>Artifact 1</th>
<th>Artifact 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 <strong>Design as an Artifact:</strong> Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.</td>
<td>This software selection model first artifact will be a model supported with grounded theory from the literature research.</td>
<td>A working executable model will be developed as the main objective of this graduation project.</td>
</tr>
<tr>
<td>2 <strong>Problem Relevance:</strong> The objective of design-science research is to develop technology-based solutions to important and relevant business problems.</td>
<td>The software selection model will be important in selecting a software package compatible with the company’s CAD and SysML software and the other criteria that will be selected and ranked in corporation with the company’s supervisors and some key stakeholders. With this compatible software program the communication between software and different stakeholders have to be improved.</td>
<td>The executable model will correspond with the already created SysML models from the Tidal Flow created by RHDHV’s system engineers, and should be finally connected to their 3D CAD systems to prevent communication problems in the development phase.</td>
</tr>
<tr>
<td>3 <strong>Design Evaluation:</strong> The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation</td>
<td>The software selection tool will be depended on several evaluated theories that support the utility, quality and efficacy of the software selection model.</td>
<td>The evaluation of the executable model will be based on verification techniques stated in the literature review (Law, 2007).</td>
</tr>
<tr>
<td></td>
<td>Research Contributions: Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.</td>
<td>The software selection model will give a minor contributions to research. Perhaps it will be designed from several theories and will be a mixture of these theories.</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>5</td>
<td>Research Rigor: Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.</td>
<td>The final model will have rigorous influences like the development of selection criteria in corporation with experts and interviews with experts about the evaluation of the software package that will be ranked first.</td>
</tr>
<tr>
<td>6</td>
<td>Design as a Search Process: The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.</td>
<td>In the search for an effective selection model the available theories from the literature review and the ranked criteria from the company’s experts will support to finally choose an appropriate software package.</td>
</tr>
<tr>
<td>7</td>
<td>Communication of Research: Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.</td>
<td>For this selection model it is a requirement to be presented effectively both to technology-oriented as well as management-oriented audiences, because both of them are involved in ranking the criteria and evaluate the outcome of the model.</td>
</tr>
</tbody>
</table>

Table 23 Artifact descriptions
9.2 Recommendations

- If in the future executable models have to be created, demand actual data from the promoter of the project. From the experience of this project it is hard to receive an actual data log. In the end this real data will describe the behavior of a system the best. This data could also consists log info on the human interaction of the traffic control manager.

- Make arrangements with sub-contractors about sub-system information. It is perhaps useful to make arrangements with all sub-contractors to retrieve the most up to date data of the sub-systems (MTBF, MTTR) and perhaps the 3D sketch-ups of installations that are used.

- Take into account the Flexsim structure to make templates of the lower level SysML diagrams in Enterprise Architect. Try to define SysML block diagrams as objects of Flexsim with the parameter information it needs and hold this as a template of all objects. In this way the connection between the SysML and Flexsim could be enhanced.

- When integrating Flexsim as the new modeling program, some modeling courses are advised. From experience it is hard to learn all aspects of Flexsim by the tutorial and the Flexsim forum. Especially in domains that are in a less mature state of development in Flexsim and were modeling coding can be a solution. Perhaps it is possible to work together with Talmulis (the provider of Flexsim in the Netherlands) to develop a SysML connection. One possibility that does exist is to create a custom library.

- When integrating Flexsim as the new modeling program, use the defined steps from sub-chapter 6.1. These steps define the development of the executable model in Flexsim in an efficient way.

- Investigate the possibilities for improving the height detection. From the analysis it is obvious that the height detection is the bottleneck in all runs. This conclusion is confirmed with the reactions from the traffic control managers. Other possibilities with higher MTBF or lower MTTR has to be investigated in more detail.

9.3 Further research

- A limitation of this research is that the data of the traffic control manager handlings is assumed on two to five measurements. A possible research could be to retrieve more exact data about the traffic control manager handlings. From this data a more exact analysis can be made about the throughput time.

- A limitation of this research is that the changing of textual scenarios on changes in the executable model is not investigated. A possible future research could be to investigate model adjustments translating into text. When this option would be possible SE could be more focused to create executable models and make adjustments in these models. This could speed up the SE process even more.

- A limitation of this research is the exclusion of the traffic in the model. A possible further research could be to add traffic to the executable model. Or use the executable model to predict the future throughput time of highway around Amsterdam.

- A limitation of this research is the non-available direct connection to SysML. A possible future research could be to investigate the possibilities of connecting Flexsim to SysML diagrams. A possible partner to conduct this research could be Talmulis.
- A *limitation of this research is the 3D model*. The visualization of the 3D model is not complete. Particular parts for the tidal flow where outside the boundaries of the 3D model of the Coentunnel. A possible research is to complete the full 3D model and for an extension of the research add extra scenarios to the model.
References


Information Systems Research Center.


Theodoulou, G. & Wolshon, B. (2004). Alternative methods to increase the effectiveness of freeway contraflow evacuation. Transportation Research Record: Journal of the Transportation Research


Reading guides

List of Figures

Figure 1 Forsberg & Mooz Vee Model .................................................................................. 3
Figure 2 Project outline in stages ....................................................................................... 5
Figure 3 IS research framework ......................................................................................... 9
Figure 4 The IBM Telelogic Harmony-SE ........................................................................... 13
Figure 5 The difference between traditional development approach and the COTS approach .............................................................................................................. 15
Figure 6 Sample of an AHP hierarchy ................................................................................. 17
Figure 7 Steps of sound simulation study .......................................................................... 18
Figure 8 Simulation Studies: Key Stages and Processes ................................................... 18
Figure 9 stage 1: Conceptualization .................................................................................. 20
Figure 10 the conceptual model in CPN tools ................................................................... 20
Figure 11 Black box representation ................................................................................... 23
Figure 12 Stage 2: Identify a suitable modeling tool .......................................................... 25
Figure 13 The software environment at RHDHV .............................................................. 26
Figure 14 part of the scenario in the flow chart and in text .................................................. 27
Figure 15 the complete 3D visualization of the Coentunnel ............................................. 27
Figure 16 A schematic view of the software environment at RHDHV ................................ 28
Figure 17 Stage 3: A new MBSE approach: SysML, 3D CAD Models, Flexsim .................. 34
Figure 18 The new software environment ....................................................................... 34
Figure 19 The SysML diagrams ....................................................................................... 35
Figure 20 Flexsim object structure ................................................................................... 36
Figure 21 stage 4: the executable model ......................................................................... 38
Figure 22 the schematic simulation model ..................................................................... 38
Figure 23 the essential part "Main flow" .......................................................................... 40
Figure 24 the essential part "breakdown" ....................................................................... 40
Figure 25 the essential part "video wall" .......................................................................... 41
Figure 26 the essential part " the 3D coentunnel in Flexsim " .......................................... 42
Figure 27 Stage 5: Analyses ............................................................................................. 44
Figure 28 Percentage of cumulative downtime (Replication 3) ....................................... 46
Figure 19 the maximum and average stay time of Command Openen. .......................... 46
Figure 20 Percentage of downtime per sub-system for both the Normal and Improved design 48
Figure 21 Coentunnel project organization .................................................................... 49
Figure 22 Schematic view of the road in the final situation with the Tidal flow .................. 50
Figure 23 On the left the renovated Coentunnel I and on the right the Coentunnel II ....... 51
Figure 24 Location Coentunnel I and Coentunnel II ......................................................... 51
Figure 35 The Organization chart of Royal HaskoningDHV ............................................. V
Figure 36 Costs of management and maintenance in units of one million Euros' ............ VI
Figure 37 Costs of construction projects in units of one million Euros' ........................... VI
Figure 25 Flowchart scenario opening Tidal flow ............................................................. XII
Figure 39 Conceptual model in CPN Tools .................................................................... XIII
List of Tables
Table 1 Sub-systems of the TTTI................................................................. 7
Table 2 The differences between the two research programs ............................................. 8
Table 3 Criteria from several writers divided in Simulation, Model transformation and Visualization criteria ........................................................................................................ 16
Table 4 The selection techniques used in different software selection approaches ............... 17
Table 5 RAMS data ........................................................................................................ 21
Table 6 Measurement process times opening Tidal flow A1 ............................................. 22
Table 7 Environmental variable distributions ................................................................... 23
Table 8 Calculation human handlings .............................................................................. 23
Table 9 Calculation object appearance .......................................................................... 24
Table 10 Initialization of Inhouse software programs ....................................................... 25
Table 11 design alternatives ............................................................................................ 26
Table 12 Potential software programs on the market ....................................................... 28
Table 13 Shortlisting long list .......................................................................................... 30
Table 14 the software selection tool ............................................................................... 31
Table 15 Average throughput times per sub-scenario in seconds ...................................... 45
Table 16 Calculated availability ...................................................................................... 45
Table 17 The human handlings with depending breakdown objects .................................. 46
Table 18 Comparison of throughput times ....................................................................... 47
Table 19 Comparison of availability ............................................................................... 48
Table 20 Cumulative breakdown time Height detection .................................................. 48
Table 21 The summarized Availability discount and Performance discount ..................... 49
Table 22 Average breakdown times per sub-system of each replication ............................. 49
Table 23 Artifact descriptions ......................................................................................... 53
Table 24 Ranking of the A10 in the traffic jam top 10 (2007 - 2009) ................................. I
Table 25 Stocktaking of software programs ..................................................................... XVII
Appendices

Appendix 1 Introduction information ........................................................................................................ I
  1.a Rankings involving the Coentunnel in the Dutch Traffic Jam top 10.................................................. I
  1.b Coentunnel project organization ........................................................................................................ I
Appendix 2 The Tidal flow scenario ............................................................................................................. II
Appendix 3 Stakeholders............................................................................................................................... IV
  3.a Royal HaskoningDHV ......................................................................................................................... IV
  3.b Soltegro ............................................................................................................................................. V
  3.c Rijkswaterstaat, Ministry of Environment and Infrastructure........................................................... VI
  3.d Croon TBI techniek ........................................................................................................................... VI
Appendix 4 An explanation of the AHP selection method ............................................................................. VIII
Appendix 5 Flowchart Scenario Open Tidal Flow ..................................................................................... XI
Appendix 6 The Conceptual model ............................................................................................................ XIII
Appendix 7 Enterprise Architect information ........................................................................................... XIV
Appendix 8 Information software environment RHDHV .......................................................................... XV
  8.a Relatics .............................................................................................................................................. XV
  8.b Reliability workbench ....................................................................................................................... XV
Appendix 9 Stocktaking software programs at RHDHV Nijmegen ........................................................... XVII
Appendix 10 Information software on the long list ................................................................................... XVIII
Appendix 11 Input data ............................................................................................................................... XXII
  11.a Tidal flow sub-installation RAMS data.............................................................................................. XXII
  11.b RAMS data MTM from Level 0 document ....................................................................................... XXIII
  11.c Information about object appearances on Highways. .................................................................... XXIII
Appendix 12 Information about Solvea Intercax ....................................................................................... XXIV
Appendix 13 Modeling Codes of Essential parts of the Executable Model................................................. XXV
Appendix 14 A Screenshot of the verification process in Flexsim............................................................ XXVII
Appendix 15 Determining Warm-up period ............................................................................................. XXVIII
Appendix 16 Equations used to calculate simulation output ....................................................................... XXIX
Appendix 17 Simulation Output 1 .............................................................................................................. XXX
  17.a Confidence intervals ....................................................................................................................... XXX
  17.b Raw data ........................................................................................................................................ XXXI
  17.c Graphs Maximum Stay time vs. Average Stay time per object ......................................................... XXXIII
  17.D Percentages of downtime per installation per replication ............................................................... XXXVI
Appendix 1 Introduction information

1.a Rankings involving the Coentunnel in the Dutch Traffic Jam top 10.

<table>
<thead>
<tr>
<th>Year</th>
<th>Ranking</th>
<th>Road</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>#2</td>
<td>A10</td>
<td>Coentunnel to Zaandam</td>
</tr>
<tr>
<td>2008</td>
<td>#4</td>
<td>A10</td>
<td>Ring Amsterdam to Zaanstad node De Nieuwe Meer and the Coentunnel</td>
</tr>
<tr>
<td>2009</td>
<td>#7</td>
<td>A10</td>
<td>Coentunnel to Zaandam</td>
</tr>
</tbody>
</table>


Table 24 Ranking of the A10 in the traffic jam top 10 (2007 - 2009)

1.b Coentunnel project organization

Figure 31 Coentunnel project organization
Appendix 2 The Tidal flow scenario

Figure 32 Schematic view of the road in the final situation with the Tidal flow.
Figure 33 On the left the renovated Coentunnel I and on the right the Coentunnel II.

Figure 34 Location Coentunnel I and Coentunnel II
Appendix 3 Stakeholders
The master thesis project will be conducted at the traffic engineering department of Royal HaskoningDHV in Nijmegen. Among the projects that are conducted in this department some are about designing traffic tunnel systems. Royal HaskoningDHV is collaborating with Soltegro to create a new system setup to develop tunnel support systems. Most of these tunnel support systems are developed for Rijkswaterstaat, the Ministry of Environment and Infrastructure. The remaining of this chapter elaborates on these involved stakeholders.

3.a Royal HaskoningDHV
Royal HaskoningDHV is a recently merged company consisting of Royal Haskoning and DHV. First the two company’s histories are described, due to the young history of Royal HaskoningDHV. The final sub-chapter will elaborate on the merged company.

Royal Haskoning
Royal Haskoning was an independent international consultancy company with technical roots. It was active in 17 countries with 57 offices. Their mission was to develop solutions in collaboration with their clients for issues related to sustainable interaction between people and their environment. With their worldwide network of professionals and strong industry relationships established over 130 years ago they contributed effectively to the successful planning, design, implementation commissioning and operation of client’s projects and programs. These projects have been conducted in multi-disciplinary services related to urban areas and buildings, infrastructure and ports, industry and energy, water and environment resulting in an operating income of € 312 million in 2011.

DHV
DHV was an international consultancy and engineering office, famous about their expertise and leadership in innovation and sustainability. It was founded and named by the creators Dwars, Heederik and Verhey. In 2010 DHV had 4300 employees working in 70 offices around the world, resulting in a turnover of € 469 million. The company was acknowledged with their complex working method to solve multi-discipline issues in the field of infrastructure & mobility, water & environment, spatial planning & real estate. The focus of their projects was on the total project cycle consisting of management consultancy, design & engineering, project management, contract management and asset management.

Royal HaskoningDHV
With the merge of Royal Haskoning and DHV, Royal HaskoningDHV is one of Europe’s leading independent project management, engineering and consultancy service providers, ranking globally in the top 10 of independently owned, non-listed companies and top 40 overall.

With a total of 8000 employees providing services from more than 100 offices over 35 countries, Royal HaskoningDHV has a turnover in excess of € 700 million. The company annually accomplishes approximately 30000 projects in among others, the fields of planning and transport, infrastructure, water, maritime aviation, industry, energy, mining and buildings (see figure 35 ). In combination with its international office network it can deliver world-class solutions locally to clients around the globe, for the public and private sector. As leader in sustainability and innovation, Royal HaskoningDHV provides the next step in working towards enhancing society together.
3.b Soltegro

Soltegro has been established as a consultancy firm in 2009 by a number of experienced managers and specialist who had earned their spurs in the world of complex technical systems in diversity of markets.

Currently the company is specialized in the field of Reliability Engineering and focuses itself on the infrastructure & mobility and industrial markets. In these markets availability, reliability and safety play an important role. Soltegro ensures reliability without losing sight of the business objectives and the functionality of the systems for the users. Soltegro’s Reliability Engineering services mainstream is on different disciplines such as System Engineering, Reliable Software Engineering and Manufacturing IT.
3.c Rijkswaterstaat, Ministry of Environment and Infrastructure

Rijkswaterstaat is the executive agency of the Ministry of Environment and Infrastructure in the Netherlands. The agency founded in 1798 is called Rijkswaterstaat from 1848. This organization manages and develops the nation’s main roads (5.695 km), main waterways (1.686 km channels, rivers and 6.165 km sail way in open water) and main water systems (65.250 km²) by order of the Ministry of Environment and Infrastructure.

The mission of Rijkswaterstaat is to accommodate a smooth and safe traffic flow, a clean and useable national water system and the protection of flooding.

The agency has to accomplish this mission with their 9000 employees divided over one main office, several national service offices and regional service offices consisting of district service offices. Figure 37 and figure 36 give an indication about the development and maintenance costs that the agency spends on an annual basis (Jaarbericht Rijkswaterststaat 2011, June 2012). For construction projects of the main road network it costs 1.794 million euros and to manage and maintain these roads it costs 722 million euros.

![Figure 37 Costs of construction projects in units of one million Euros'](image)

![Figure 36 Costs of management and maintenance in units of one million Euros'](image)

3.d Croon TBI techniek

For more than 135 years it has been impossible to think of the leaders in the Dutch installation sector without thinking of Croon Elektrotechniek. We are at the basis of many technological developments. We are responsible for the complete electrical installations in thousands of buildings, countless ships and many industrial complexes and tens of thousands of other projects in all kinds of market sectors.

Croon Elektrotechniek forms part of TBI, one of the most important property, construction and engineering concerns in the Netherlands. The size of TBI offers benefits such as financial security and opportunities to reduce costs and increase quality.
Croon is a reliable, sound provider of technical services offering first-rate solutions for ambitious clients in industry and the non-profit sector. We carry out simple as well as bold, leading-edge projects. With our services we contribute to the proper, sustainable and cost-efficient operation of organisations, buildings, ships, infrastructure and industrial installations. From design to management and maintenance, nationally and internationally, our aim is always to establish a long-term relationship with our clients.

An important feature of our culture is that we strive to be better every day. The people working for us know what they are talking about. They are people with a passion for engineering. Our people are our product and our business. We are among the top 10 best employers in the Netherlands. Thanks to our staff policy we are the only electrical engineering firm in the Netherlands with the international Investors in People quality mark.
Appendix 4 An explanation of the AHP selection method

In this example case the goal is to choose a leader based on four specific criteria and three alternatives. To explain the AHP the following steps defined by (Kontio, 1996) will be used in combination with assumed numbers.

1) Define a hierarchy of factors that influence the decision, resulting in a hierarchical structure of factors that have alternatives as the leaf nodes in the hierarchy.

In the figure the complete hierarchical structure is defined.

2) Define the importance of factors on each level

To define the importance of the factors a pairwise comparison has to be made. In this case it will result in six comparisons, see table below. The scores be values from the scale of Saaty to value the importance.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Numerical Rating</th>
<th>Reciprocal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely preferred</td>
<td>9</td>
<td>1/9</td>
</tr>
<tr>
<td>Very strongly to extremely</td>
<td>8</td>
<td>1/8</td>
</tr>
<tr>
<td>Very strongly preferred</td>
<td>7</td>
<td>1/7</td>
</tr>
<tr>
<td>Strongly to very strongly</td>
<td>6</td>
<td>1/6</td>
</tr>
<tr>
<td>Strongly preferred</td>
<td>5</td>
<td>1/5</td>
</tr>
<tr>
<td>Moderately to strongly</td>
<td>4</td>
<td>1/4</td>
</tr>
<tr>
<td>Moderately preferred</td>
<td>3</td>
<td>1/3</td>
</tr>
<tr>
<td>Equally to Moderately</td>
<td>2</td>
<td>1/2</td>
</tr>
<tr>
<td>Equally Preferred</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*Scale of Saaty*

<table>
<thead>
<tr>
<th>Pairwise comparison with respect to the goal</th>
<th>criteria 1 score</th>
<th>criteria 2 score</th>
<th>explanation score 1</th>
<th>explanation score 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>1</td>
<td>Experience 7</td>
<td>Age important to a leader, has to handle young and old employees</td>
<td>Experience is a vitally importance requirement, with experience age doesn't matter</td>
</tr>
<tr>
<td>Age</td>
<td>1</td>
<td>Education 3</td>
<td>same as above</td>
<td>Education is important for a thoughtfully future of the company</td>
</tr>
<tr>
<td>Age</td>
<td>1</td>
<td>Charisma 4</td>
<td>same as above</td>
<td>Charisma will be needed to lead</td>
</tr>
<tr>
<td>Experience</td>
<td>4</td>
<td>Education 1</td>
<td>needed to implement plans</td>
<td>also important but, could have learned from experience</td>
</tr>
</tbody>
</table>
Experience | 3 | Charisma | 1 | same as above
---|---|---|---|---
Gives extra power to convince, but without experience it has less credibility

Education | 1 | Charisma | 3 | is useful
---|---|---|---|---
is seen more useful

Create a matrix of all outcomes to calculate the importance of each factor. The matrix and the outcomes are stated below. The sum off all priorities has to be one.

### Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Experience</th>
<th>education</th>
<th>charisma</th>
<th>age</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experience</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>7</td>
<td>0.547</td>
</tr>
<tr>
<td>education</td>
<td>1/4</td>
<td>1</td>
<td>1/3</td>
<td>3</td>
<td>0.127</td>
</tr>
<tr>
<td>charisma</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td></td>
<td>0.27</td>
</tr>
<tr>
<td>age</td>
<td>1/7</td>
<td>1/3</td>
<td>1/5</td>
<td>1</td>
<td>0.056</td>
</tr>
</tbody>
</table>

3) **Define the preference of alternatives**

For each criterion a pairwise comparison has to be made with the three alternatives. This will result in this case for three comparisons per criteria, resulting in twelve pairwise comparisons. The calculation of these comparisons will be in the same way as told above.

4) **Check the consistency of rankings and revise the ranking if rankings are too inconsistent**

Do a last check if all rankings are understood by everybody who is involved with the ranking. Resolve the last errors if there are some. Calculate the aspects in relation with the other candidates (table)
5) Present the results of the evaluation, the alternative with the highest priority being the one that is recommended as the best alternative.

Finally all outcomes will be put in a matrix to calculate score of the alternative to the main goal. The result from this case is that Dick is the best alternative, followed by Tom and Harry.

<table>
<thead>
<tr>
<th>Priority</th>
<th>Experience</th>
<th>education</th>
<th>charisma</th>
<th>age</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tom</td>
<td>0.119</td>
<td>0.024</td>
<td>0.201</td>
<td>0.015</td>
<td>0.358</td>
</tr>
<tr>
<td>Dick</td>
<td>0.392</td>
<td>0.01</td>
<td>0.052</td>
<td>0.038</td>
<td>0.492</td>
</tr>
<tr>
<td>Harry</td>
<td>0.036</td>
<td>0.093</td>
<td>0.017</td>
<td>0.004</td>
<td>0.149</td>
</tr>
<tr>
<td>Totals:</td>
<td>0.547</td>
<td>0.127</td>
<td>0.27</td>
<td>0.056</td>
<td>1</td>
</tr>
</tbody>
</table>
Appendix 5 Flowchart Scenario Open Tidal Flow

Scenario NB.1.2: Openen en sluiten Tidal Flow buis (incl omschakelen van de TTI en VTI in juiste rijrichting) openen

<table>
<thead>
<tr>
<th>Omgewing</th>
<th>Techniek</th>
<th>RWS WWL</th>
<th>Weginspecteur</th>
<th>Wisselsloot mode (staat)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Diagram weergeven

Voorbeeld:

- Onderdelen van de Tidal Flow buis
- Stappen bij openen en sluiten
- Invloed op de RWS WWL en weginspecteur
- Wisselsloot mode bij operationele stadia

**Note:** Details van de stappen en invloeden zijn in de diagram weergegeven.
Figure 38 Flowchart scenario opening Tidal flow
Process description:
The blue lines show the similar process as the process in the flow chart (Appendix .. ), where the blue transitions represent the human interactions. This is the main process without from the scenario specifications, any added assumptions.

To activate the two loops in the process, respectively the resolve failure loop and the clean the driving lane loop, two generators are designed. Both these generators can change conditions over time. Another addition to the main process is the black place holding the state of the camera view, due to the importance of the visual aspect in this project.
Appendix 7 Enterprise Architect information


Model Simulation

Enterprise Architect’s model simulation brings your behavioral models to life with real-time execution. Simulating models offers several benefits by helping you to:

- Gain a better understanding of how a model actually works at run-time
- Validate that your behavioral models describe the correct process or event flow
- Identify potential bottlenecks, inefficiencies and other problems in your system model or business process
- Detect errors early in the development cycle – prior to committing resources for implementation.

Model simulation can be applied to four types of behavioral models in Enterprise Architect, including:

- UML Activities
- UML Interactions
- UML State Machines, including those rendered as a State Table

You control the speed of the simulation and the pathways through the simulated model: Either manually control the choices taken at each decision point or script in advance how each trigger fires. Using the latter approach you can automate several simulations of the same model, revealing how the system behaves under different run-time scenarios. With the ability to set arbitrary breakpoints, Enterprise Architect’s model simulation capability is a powerful tool for analyzing decision making, and improving business processes or executable system models in a risk-free environment.
Appendix 8 Information software environment RHDHV

8.a Relatics
http://www.relatics.com/nl/product/

Relatics biedt een totaal nieuwe benadering van Product Lifecycle Management (PLM)

Voor de eerste keer kunnen projectleden hun eisen, verificaties, risico’s, taken en alle projectobjecten beheren in een samenhangend netwerk van expliciet beschreven informatie. Relatics bevrijdt het project van een groot aantal spreadsheets en geïsoleerde toepassingen om informatie te bewaren. Als gevolg daarvan heeft Relatics bewezen controle over projecten te herwinnen en projectrisico’s te verminderen. Projecten worden sneller gerealiseerd, met minder faalkosten en een betere uitkomst.

Keypoints:
Transparant
Flexibel
Eenvoudig
Samenwerking

8.b Reliability workbench
http://www.reliabilityworkbench.com/

Reliability Workbench 11 incorporating FaultTree+
World Leading Reliability Analysis Software

What is Reliability Workbench?
Reliability Workbench incorporating FaultTree+ is Isograph’s flagship suite of reliability, safety and maintainability software. Reliability Workbench is well proven in use at thousands of sites worldwide. It is intuitive to use and provides quick, professional results.
Reliability Workbench includes Fault Tree, Reliability Prediction, Maintainability Prediction, FMECA, RBD, Reliability Allocation, Reliability Growth, Event Tree, Markov and Weibull Analysis modules

Brand New Enterprise Facility
Reliability Workbench incorporating FaultTree+ now includes a cutting-edge enterprise facility allowing large-scale collaboration, access control and version control across corporate networks.
Fully Integrated Software Suite
The design of Reliability Workbench allows data to be shared between the various modules. For example, you might have failure data in Prediction that you want to use in a Fault Tree Analysis. In this case, you can set up a "Data Link", so that whenever your Prediction results are updated, the data is automatically updated in the Fault Tree.

About Isograph
Isograph was founded in 1986 and is now one of the world's leading companies in the development and provision of integrated Reliability, Availability, Maintainability and Safety software.
Isograph products are well proven in use at over 7000 sites worldwide where they are used on many high profile projects. All of our software is fully maintained and supported by a group of industry specialists.
Appendix 9 Stocktaking software programs at RHDHV Nijmegen

Royal HaskoningDHV has various software programs to make visualizations and to design different parts. For the 3D visualization the 3D-CAD designs are either developed by the other business unit Infrastructure or developed by other companies that received the Civil engineering order of a tunnel. Table 25 below shows which software programs are used, what the specific supported file extensions are and how many users use these programs.

<table>
<thead>
<tr>
<th>System engineering</th>
<th>Program</th>
<th>Used for</th>
<th>Supported file extensions</th>
<th>how many users</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Autocad 2012</td>
<td>2D Design, System engineering</td>
<td>.dwg,  .dxf, .dws, en .dwt</td>
<td>1-2</td>
</tr>
<tr>
<td></td>
<td>Autodesk 3DS</td>
<td>3D Visualistion (no design)</td>
<td>AutoCAD®, Autodesk® Inventor®, Autodesk® Alias® industrial design software, Dassault Systèmes SolidWorks® and CATIA® system, PTC Pro/ENGINEER®, Siemens PLM Software NX, JT™, and certain other applications, with the new support for the Autodesk® DirectConnect family of translators.</td>
<td>5-10</td>
</tr>
<tr>
<td></td>
<td>VR4MAX</td>
<td>3D Virtual reality, Interactive, (no design)</td>
<td>Autodesk 3Ds Max</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Autodesk 3DS</td>
<td>3D project viewing, project reviewing, simulation and analysis, and Coordination (used for construction building projects)</td>
<td>.nwd, .3D dwf</td>
<td>2-3</td>
</tr>
<tr>
<td></td>
<td>Navisworks</td>
<td>System engineering modeling program in SysML</td>
<td>XMI 2.0, XMI 2.1 and UML 2.x</td>
<td>10 from Soltegro and 2 from Royal Haskoning DHV</td>
</tr>
<tr>
<td></td>
<td>Matlab/Simulink</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Labview</td>
<td>Graphical programming environment (used for Data acquisition only)</td>
<td>PLC’s (ladder, SFC, ST, IL, FBD) PLD’s (VHDL) C, C++, Java</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Civil Engineering Program</th>
<th>Used for</th>
<th>Supported file extensions</th>
<th>how many users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revit Autodesk</td>
<td>3D CAD Design e.g. tunnels</td>
<td>Designs, documents and part drawings with .DWG extension. Every Autodesk file.</td>
<td>5-10</td>
</tr>
<tr>
<td>Allplan Architecture</td>
<td>3D CAD Design e.g. tunnels</td>
<td></td>
<td>2-3</td>
</tr>
<tr>
<td>Navisworks Autodesk</td>
<td>3D simulation coupled with construction planning</td>
<td>See appendix 6</td>
<td></td>
</tr>
</tbody>
</table>

Table 25 Stocktaking of software programs
Appendix 10 Information software on the long list

Allplan
http://www.allplan.nl/content.aspx?pag=5

Allplan Architecture Starter
Allplan Architecture Starter is dé opstap richting BIM, speciaal ontwikkeld voor ontwerpen modelleren, hoeveelheden genereren en het uitwerken van bouwplannen.

Allplan Architecture
Allplan Architecture is een bouwdeel georiënteerd 3D CAD-systeem voor Bouw informatie model (BIM). Allplan Architecture bestrijkt het gehele bouwproces, van eenvoudige tekeningen tot 3D gebouwmodellen met geïntegreerde hoeveelheden en kostencalculatie. Naast de traditionele uitwisselingsformaten ondersteund Allplan de formaten PDF en IFC. Allplan zorgt hiermee voor een probleemloze uitwisseling tussen de verschillende partners in een project.

Arena simulation software Rockwell automation
http://www.arenasimulation.com/Arena_Home.aspx

Value-driven solutions to solve industry challenges.

Use Arena simulation software to help demonstrate, predict, and measure system strategies for effective, efficient and optimized performance.

Arena simulation software helps protect your business by analyzing the impact of new, "what-if" business ideas, rules, and strategies before implementation on live customers—offline, without causing disruptions in service.

When the life of your business is at stake, let Arena help you improve your business performance.
The digital product experience
CATIA is Dassault Systèmes' Pioneer Brand. It is the World's Leading Solution for Product Design and Innovation.

3D CAD Design Software & Beyond
CATIA goes far beyond traditional 3D CAD software tools to offer a unique Digital Product Experience, based on the 3DEXPERIENCE platform. Sustainable development is driving companies around the globe to create a constant stream of innovative and inspiring smart products. Engineering, Design, Systems Architecture and Systems Engineering of these products becomes more demanding.

Functional behaviour modeling of products and components
Our Systems Engineering solution allows you to use many different models to simulate the behavior of complex systems and products. These models rarely interoperate with one another and don’t exist in an ‘aggregated’ environment that allows a ‘whole-system multi-physics simulation’ of the complete product. The Dassault Systèmes solution set provides a fully integrated systems modeling environment that leverages behavioral simulation for systems as well as for mechanical product assemblies.

CPN Tools
http://cpntools.org/

CPN Tools is a tool for editing, simulating, and analyzing Colored Petri nets. The tool features incremental syntax checking and code generation, which take place while a net is being constructed. A fast simulator efficiently handles untimed and timed nets. Full and partial state spaces can be generated and analyzed, and a standard state space report contains information, such as boundedness properties and liveness properties.

CPN Tools is originally developed by the CPN Group at Aarhus University from 2000 to 2010. The main architects behind the tool are Kurt Jensen, Søren Christensen, Lars M. Kristensen, and Michael Westergaard. From the autumn of 2010, CPN Tools is transferred to the AIS group, Eindhoven University of Technology, The Netherlands.

Enterprise Dynamics
INCONTROL simulation solutions

http://www.incontrolsim.com/

World leading Simulation Software Enterprise Dynamics

Enterprise Dynamics® is a leading simulation software platform for business modeling; quick and easy. With Enterprise Dynamics you can analyze and optimize the current and future behavior of your system or infrastructure. Don’t speculate… Simulate!

The Enterprise Dynamics Platform
Enterprise Dynamics® is the leading simulation software platform to design and implement simulation solutions. It allows a problem solver to model virtually any problem and, by
experimentation, look for a solution for a given problem or an answer to a specific question.

To be able to perform simulation studies, a good simulation software platform is required. A good simulation software platform does not only provide fast modeling capabilities and good visualization features, but it also provides the possibilities for the re-use of previous made models, segments of models and components used in previously made models.

**Our market-specific products developed with the Enterprise Dynamics Platform**

Every branch or industry deals with unique materials, equipment and other resources. In collaboration with specialists in these markets, INCONTROL developed specific objects with corresponding functionality and merged these into a library. The following products are available:

- ED Logistics
- ED Airport
- ED Transport
- ED Warehouse
- Pedestrian Dynamics
- ED Educational
- ShowFlow

**IDA Simulation Environment**

EQUA

http://www.equa.se/en/software/tunnel-metro

IDA Simulation Environment (IDA SE) is a general purpose modeling and simulation tool for modular systems where components are described with equations. Each component contains somewhere between a single and a few hundred differential and/or algebraic equations. Ready-made components are interconnected by the user in arbitrary combinations. Problems that are suitable for IDA SE occur in virtually all engineering disciplines and industrial sectors.

**IDA Tunnel**

IDA Tunnel is a comprehensive Road and Rail Tunnel Ventilation & Fire Simulation Software, used by leading tunnel design companies, such as HBI Haerter, Gruner, Halcrow, WSP, Norconsult, Ramböll, Pöyry, and Sweco.

IDA Tunnel allows you to simulate road and rail tunnel design projects, including full range of ventilation and fire design tasks. You will be able to get computed results that can be animated in the context of a full 3D representation of the tunnel network.

**Simio**

http://www.simio.com/products/

Simio is a family of products that includes the Express, Design, Team, and Enterprise Editions. Models built with all four Editions are fully compatible both up and down the product family. All four products provide the same powerful 3D object-based modeling environment.

Many simulation packages are built on out-dated 2D technology that limits your ability to visualize your process or capture 3D spatial relationships in your system. Some of these older products limit you to 2D only models, while others offer expensive/complex 3D add-ons that require you to build a separate 3D visualization of your system, and then tie these two separate components together.
These extra steps add unnecessary work and time to your project, and make your model and animation difficult to edit and maintain.

In contrast, Simio provides a true object-based 3D modeling environment which lets you construct your 3D model in a single step from a top-down 2D view, and then instantly switch to a 3D view of your system. You simply drag and place your 3D objects from an Object Library into your facility view of the model.

**VSTEP**

[http://www.vstep.nl/](http://www.vstep.nl/)

**VSTEP Simulation & Virtual Training:** The next best thing to real life!

VSTEP is a leading European developer of simulators and virtual training software. Using interactive 3D technology from the computer gaming industry, VSTEP creates simulators, training applications and serious games that allow people to build their skills in a practical and cost effective way. Since its founding in 2002, VSTEP has successfully completed numerous training applications for leading industry clients and governmental organisations worldwide. As one of the industry leaders, VSTEP continues to innovate the virtual training world with professional, accurate and groundbreaking new simulation technology. VSTEP has several core products, including:

- NAUTIS – Maritime Simulation Training
- RescueSim – Virtual Emergency Response Training
- EyeObserve – Surveillance Camera Operator Training

As winner of multiple innovation prizes and awards, VSTEP continues to set the standard for virtual training & simulation and advocates more effective training through enhanced virtual reality.

**XVR**

e-semble


**Virtual training at the site of an incident**

XVR is VR training software to educate and train operational and tactical (bronze and silver level) safety and security professionals

Using a joystick XVR allows one or more incident response professionals to walk, drive or fly around in the simulated reality of an incident. This gives them the opportunity to train in observing and assessing the environment. Furthermore they have to assess risks and dangers, decide which measures to take and what procedures to apply, and report to the other rescue crew members. While the students are distracted by surrounding noise and confusion, they are expected to focus on their tasks and to set priorities.

An essential feature of XVR is that the instructor can easily build an incident scenario and has full control over the course of events in the scenario during the exercise. After starting the exercise, the instructor presents the student with questions and asks the student to motivate his decisions. He can also give feedback, for instance by role-playing the control room or other rescue staff. The instructor can respond to the student’s decisions by activating events in the virtual scenario. The instructor may also decide to condense time and jump to a next phase in the incident.
## Appendix 11 Input data

### 11.a Tidal flow sub-installation RAMS data

#### Onderhoudsgegevens en tijden voor het openstellen/sluiten van de Tidal Flow

<table>
<thead>
<tr>
<th>Deelinstallatie</th>
<th>MTBF</th>
<th>Faal definities:</th>
<th>Reactie:</th>
<th>MTTR (uren)</th>
<th>st. dev MTTR</th>
<th>Omschakel-tijden (uur)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingangsverlichting</td>
<td>0.1</td>
<td>Het falen bij het omschakelen van Z--&gt; N en andersom</td>
<td>Onderhoud moet worden gepleegd</td>
<td>2</td>
<td>0.5</td>
<td>0.160</td>
</tr>
<tr>
<td>CCTV</td>
<td>0.22</td>
<td>Het falen bij het omschakelen van Z--&gt; N en andersom</td>
<td>Onderhoud moet worden gepleegd</td>
<td>3</td>
<td>0.75</td>
<td>0.160</td>
</tr>
<tr>
<td>specifieke CCTV valt weg</td>
<td>0.042</td>
<td>Falen van Scherm + Netwerk + camera</td>
<td>Weginspecteur wordt verzocht te gaan kijken.</td>
<td>3</td>
<td>0.75</td>
<td>0.017</td>
</tr>
<tr>
<td>Tunnelventilatie</td>
<td>2.6</td>
<td>Het falen bij het omschakelen van Z--&gt; N en andersom.</td>
<td>Onderhoud moet worden gepleegd</td>
<td>3</td>
<td>0.75</td>
<td>0.160</td>
</tr>
<tr>
<td>Verkeersgeleidings-verlichting</td>
<td>0.3</td>
<td>Het falen bij het omschakelen van Z--&gt; N en andersom.</td>
<td>Onderhoud moet worden gepleegd</td>
<td>2</td>
<td>0.5</td>
<td>0.017</td>
</tr>
<tr>
<td>Hoogtedetectie</td>
<td>0.0096</td>
<td>Het falen bij het omschakelen van Z--&gt; N en andersom</td>
<td>Onderhoud moet worden gepleegd</td>
<td>8</td>
<td>2</td>
<td>0.080</td>
</tr>
<tr>
<td>Veva</td>
<td>0.174</td>
<td>niet verplaatst</td>
<td>Onderhoud moet worden gepleegd</td>
<td>3</td>
<td>0.75</td>
<td>0.080</td>
</tr>
<tr>
<td>Afsluitboom</td>
<td>0.247</td>
<td>Het falen bij het omschakelen van Open--&gt;Gesloten en andersom</td>
<td>Onderhoud moet worden gepleegd</td>
<td>3</td>
<td>0.75</td>
<td>0.033</td>
</tr>
</tbody>
</table>

Al deze faalfrequenties worden in het model gezet met een exponentiële distributie. De reparatie duur wordt verdeeld in de logistieke aanrijtijd, deze bedraagt voor alle onderdelen 1.5 uur +/- 0.5 uur. De bovenstaande MTTR is exclusief het gemiddelde van 1.5 uur en een st. dev 0.408248 uur.

Alle MTTR per deelinstallatie wordt omschreven met een normaal verdeling met één gemiddelde en een st.dev van 25% van dit gemiddelde.
11.b RAMS data MTM from Level 0 document

<table>
<thead>
<tr>
<th>Model name</th>
<th>Model Type</th>
<th>Fail Rate [aantal / jaar]</th>
<th>MTTR of Repair Rate</th>
<th>Inspection interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOTORAANDR+KLEP DORM</td>
<td>Dormant</td>
<td>0.08780</td>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td>MOTORAANDRIJVING (FTO)</td>
<td>Rate/MTTR</td>
<td>0.0506</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>MOTORAANDRIJVING (SO)</td>
<td>Rate</td>
<td>0.00632</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>MOTORGRENDEL</td>
<td>Rate/MTTR</td>
<td>0.0506</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>MOTORGRENDEL DORM (1/4)</td>
<td>Dormant</td>
<td>0.0508</td>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td>MTM6 BYZONDER BORD</td>
<td>Fixed</td>
<td>0.000000000121</td>
<td>0.000000707</td>
<td>0</td>
</tr>
<tr>
<td>MTM6 KANTELWAL</td>
<td>Fixed</td>
<td>0.000000003</td>
<td>0.00000175</td>
<td>0</td>
</tr>
</tbody>
</table>

11.c Information about object appearances on Highways.

Table uit “Verkeersindicatoren Hoofdwegennet Vlaanderen 2012”, januari-februari 2013 door S. Hoornaert, Verkeerscentrum Vlaanderen.
Appendix 12 Information about Solvea Intercax
http://www.intercax.com/products/solvea/

Solvea – SysML parametric solver and integrator add-in for Enterprise Architect

Solvea™ is the SysML parametric solver and integrator add-in for Enterprise Architect. With Solvea™, system engineers can execute SysML parametric models in Enterprise Architect to compute system performance, cost, reliability, and other measures-of-effectiveness; setup and perform automated requirements verification; and run automated trade studies to select best-in-class alternatives.

The Solvea™ – Excel® connection makes it easy to import/export data and generate graphs and charts. The MATLAB/Simulink® connection and the custom Mathematica® connection allow users to wrap existing MATLAB M-files and Mathematica functions as SysML constraint blocks, build high-fidelity SysML parametric models, and execute them in the context of the system-of-interest. Solvea™ orchestrates multiple solvers when executing parametric models.

Solvea™ is available in Standard and Pro editions. Solvea™ R1 is the first release of the Solvea™ add-in for Enterprise Architect. Download and get started with Solvea today.
Appendix 13 Modeling Codes of Essential parts of the Executable Model.

Function that will be released on breakdown of sub-processor:

```
(1) Sub_Processor1-Down Function:

treenode current = ownerobject(c);
treenode downobject = parnode(1);
int state = parval(2);
treenode membercoupling = parnode(4);
/**Stop object*/
/** \nExecute stopobject().*/
/** \nID: */
int id = /**/1/**/;
/** \nPriority: */
double priority = /**/0/**/;
inc(gettablecell("Output", 2,2),1);
settablenum("Output",1,2,1);
updatesates();
stopobject(downobject ,STATE_WAITING_FOR_OPERATOR, id, priority);
```

Function that will be released after the process of calling:

```
(2) Call Service Engineer-OnProcessFinish:

/**Custom Code*/
treenode item = parnode(1);
treenode current = ownerobject(c);
int port = parval(2);
{
   inc(gettablecell("Output",1,1),-1);
   closeinput(current);
   updatesates();
}
{
   //************* PickOption Start *************\n   ///Send Message*/
   int NoDelay = -1;
double delaytime = /**/0/**/;
treenode toobject1 = /**/centerobject(current,1)/**/;
treenode toobject2 = /**/centerobject(current,2)/**/;
treenode fromobject = /**/current/**/;
double param1 = 5;
double param2 = /**/0/**/;
double param3 = /**/0/**/;
/** \nCondition: */
int condition = ((getstatenum(toobject1) == 9) &&
(gettablenum("Output",1,3)==0));
int conditionb = ((getstatenum(toobject2) == 9) &&
(gettablenum("Output",3,3)==0));
/**tag:condition*/
if(condition)
{
   sendmessage(toobject1,fromobject,param1,param2,param3);
}
if(conditionb)
{
   sendmessage(toobject2,fromobject,param1,param2,param3);
}
```
Function that will be released when a message is received by the Sub-processor from the Calling Process:

```c
(3) Sub_Processor1-On Message:

/**Custom Code*/
treenode item = parnode(1);
treenode current = ownerobject(c);
int port = parval(2);

int open = msgparam(1);
if (open==5 && getstatenum(current) == 9)
{
    inc(gettablecell("Output",1,3),1);
    updatestates();

treenode dispatcher = node("/Dispatcher27", model()); // the dispatcher or task executer

double priority = getvarnum(current,"transportpriority"); // read the Priority value on the GUI
int preempting = getvarnum(current,"preempttransport"); // read the Preemption mode on the GUI

treenode ts = createemptytasksequence(dispatcher,priority,preempting);
inserttask(ts,TASKTYPE_TRAVEL,current,NULL);
inserttask(ts,TASKTYPE_SENDMESSAGE, current, NULL, 3);
inserttask(ts, TASKTYPE_DELAY, NULL,NULL, MTTR, STATE_UTILIZE);
inserttask(ts, TASKTYPE_STOPREQUESTFINISH, current , NULL, 0, 1);
inserttask(ts, TASKTYPE_STOPREQUESTFINISH, Mainproces , NULL, 0, 1);
inserttask(ts, TASKTYPE_SENDMESSAGE, current, NULL, 2);
inserttask(ts, TASKTYPE_SENDMESSAGE, Mainproces, NULL, 2);
inserttask(ts, TASKTYPE_TRAVEL, node("/NN1",model()));
inserttask(ts,TASKTYPE_BREAK,NULL,NULL);
inserttask(ts,TASKTYPE_CALLSUBLTASKS,outobject(Phonecall,port),NULL);
dispatchtasksequence(ts);
return 0;
}

if (open == 2)
{
    openinput(current);
    inc(gettablecell("Output", 2,2), -1);
    inc(gettablecell("Output", 1,3), -1);
    settablenum("Output",1,2,0);
    resumeobject(Mainproces);
    updatestates();
    openinput(centerobject(current,3));
}

if (open == 3)
{
    setstate(current,11);
}
```

XXVI
Appendix 14 A Screenshot of the verification process in Flexsim.
Appendix 15 Determining Warm-up period
Appendix 16 Equations used to calculate simulation output.

Equation to calculate the Sample Mean
\[
\bar{X}(n) = \frac{\sum_{i=1}^{n} X_i}{n}
\]

Equation to calculate the Sample Variance
\[
S^2(n) = \frac{\sum_{i=1}^{n} [X_i - \bar{X}(n)]^2}{n - 1}
\]

Equation to calculate a 95% confidence interval
\[
\bar{X}(n) \pm t_{n-1,1-\alpha/2} \sqrt{\frac{S^2(n)}{n}}
\]

Where t larger than 200 samples with and a confidence interval of 95 percent
\[
t_{200,0.975} = 1.960
\]
## Appendix 17 Simulation Output 1

Output of simulating the scenario (including each sub-scenario) 365 times

Run to Time: 150000000.00  
Warmup-Time: 1778000.00  
Replications per Scenario: 5.00

### 17.a Confidence intervals

#### Throughput times

<table>
<thead>
<tr>
<th>Average Throughput</th>
<th>Mean (95% Confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;</td>
</tr>
<tr>
<td>Opening A8</td>
<td>1471,95</td>
</tr>
<tr>
<td>Closing A8</td>
<td>886,59</td>
</tr>
<tr>
<td>Opening A5 + A10</td>
<td>2093,99</td>
</tr>
<tr>
<td>Closing A5+A10</td>
<td>1499,79</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Min Throughput</th>
<th>Mean (95% Confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;</td>
</tr>
<tr>
<td>Opening A8</td>
<td>1366,12</td>
</tr>
<tr>
<td>Closing A8</td>
<td>819,57</td>
</tr>
<tr>
<td>Closing A5+A10</td>
<td>1431,24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Max Throughput</th>
<th>Mean (95% Confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;</td>
</tr>
<tr>
<td>Opening A8</td>
<td>6997,58</td>
</tr>
<tr>
<td>Closing A8</td>
<td>883,61</td>
</tr>
<tr>
<td>Opening A5 + A10</td>
<td>10082,58</td>
</tr>
<tr>
<td>Closing A5+A10</td>
<td>1206,96</td>
</tr>
</tbody>
</table>
### 17.b Raw data

#### Cumulative Breakdown times per object of each replication

<table>
<thead>
<tr>
<th></th>
<th>Rep 1</th>
<th>Rep 2</th>
<th>Rep 3</th>
<th>Rep 4</th>
<th>Rep 5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>0</td>
<td>0</td>
<td>39667,66</td>
<td>0</td>
<td>0</td>
<td>39667,66</td>
</tr>
<tr>
<td>CCTV</td>
<td>55656,41</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>34918,17</td>
<td>90574,58</td>
</tr>
<tr>
<td>VENT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>VGV</td>
<td>40476,53</td>
<td>0</td>
<td>62232,49</td>
<td>0</td>
<td>0</td>
<td>102709,02</td>
</tr>
<tr>
<td>HD</td>
<td>685297,1</td>
<td>611024,5</td>
<td>1130970</td>
<td>569989,88</td>
<td>436872,98</td>
<td>3434154,53</td>
</tr>
<tr>
<td>BOV</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6579,49</td>
<td>7233,11</td>
<td>13812,6</td>
</tr>
<tr>
<td>BSS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>OV</td>
<td>0</td>
<td>0</td>
<td>119111,18</td>
<td>64796,63</td>
<td>0</td>
<td>183907,81</td>
</tr>
<tr>
<td>S</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BRV1</td>
<td>0</td>
<td>9985,39</td>
<td>7438,54</td>
<td>2180,93</td>
<td>0</td>
<td>19604,86</td>
</tr>
<tr>
<td>BRV2</td>
<td>10989,16</td>
<td>13006,41</td>
<td>29196,9</td>
<td>16678,48</td>
<td>17749,66</td>
<td>87620,61</td>
</tr>
<tr>
<td>BCO</td>
<td>0</td>
<td>6204,88</td>
<td>3293,26</td>
<td>3102,87</td>
<td>2398,49</td>
<td>14999,5</td>
</tr>
<tr>
<td>OC</td>
<td>0</td>
<td>0</td>
<td>53432,82</td>
<td>63395,92</td>
<td>0</td>
<td>116828,74</td>
</tr>
<tr>
<td>BAO</td>
<td>11800,14</td>
<td>2538,46</td>
<td>11274,94</td>
<td>3856,67</td>
<td>5332,36</td>
<td>34802,57</td>
</tr>
<tr>
<td>OA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MTM</td>
<td>7945,63</td>
<td>2893,53</td>
<td>7639,87</td>
<td>3852,98</td>
<td>4614,01</td>
<td>26946,02</td>
</tr>
<tr>
<td>ALB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MTM2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PPM</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DRIPS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PD</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>812165</td>
<td>645653,2</td>
<td>1464257,7</td>
<td>734433,85</td>
<td>509118,78</td>
<td></td>
</tr>
</tbody>
</table>

#### Maximum Stay time in object of each replication

<table>
<thead>
<tr>
<th></th>
<th>Rep 1</th>
<th>Rep 2</th>
<th>Rep 3</th>
<th>Rep 4</th>
<th>Rep 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>1152</td>
<td>37715,46</td>
<td>12281,41</td>
<td>27965,63</td>
<td>576</td>
</tr>
<tr>
<td>BOV</td>
<td>56,32</td>
<td>54,46</td>
<td>51,37</td>
<td>56,25</td>
<td>36,76</td>
</tr>
<tr>
<td>BSS</td>
<td>1772,63</td>
<td>1544,26</td>
<td>15733,3</td>
<td>1322,39</td>
<td>288</td>
</tr>
<tr>
<td>BRV</td>
<td>56,24</td>
<td>55,34</td>
<td>910,27</td>
<td>426,85</td>
<td>195,44</td>
</tr>
<tr>
<td>BCO</td>
<td>801,17</td>
<td>14686,45</td>
<td>17582</td>
<td>15437,96</td>
<td>120</td>
</tr>
<tr>
<td>BAO</td>
<td>553,69</td>
<td>174,61</td>
<td>8160,61</td>
<td>210,39</td>
<td>158,26</td>
</tr>
<tr>
<td>MTM</td>
<td>111,25</td>
<td>564,54</td>
<td>691,96</td>
<td>111,9</td>
<td>97,57</td>
</tr>
<tr>
<td>MTM2</td>
<td>838,67</td>
<td>114,9</td>
<td>114,62</td>
<td>112,26</td>
<td>98,2</td>
</tr>
<tr>
<td>DRIPS</td>
<td>114,46</td>
<td>114,24</td>
<td>110,57</td>
<td>114,03</td>
<td>95,2</td>
</tr>
</tbody>
</table>

XXXI
## Average Stay time in object of each replication

<table>
<thead>
<tr>
<th></th>
<th>Rep 1</th>
<th>Rep 2</th>
<th>Rep 3</th>
<th>Rep 4</th>
<th>Rep 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>577.58</td>
<td>626.88</td>
<td>593.35</td>
<td>618.4</td>
<td>576</td>
</tr>
<tr>
<td>BOV</td>
<td>29.11</td>
<td>28.86</td>
<td>29.07</td>
<td>29.09</td>
<td>25.27</td>
</tr>
<tr>
<td>BSS</td>
<td>288.82</td>
<td>289.02</td>
<td>297.67</td>
<td>288.96</td>
<td>288</td>
</tr>
<tr>
<td>BRV</td>
<td>29.1</td>
<td>28.98</td>
<td>29.42</td>
<td>29.19</td>
<td>40.1</td>
</tr>
<tr>
<td>BCO</td>
<td>120.38</td>
<td>126.66</td>
<td>128.23</td>
<td>128.48</td>
<td>120</td>
</tr>
<tr>
<td>BAO</td>
<td>149.1</td>
<td>149.01</td>
<td>152.77</td>
<td>149.24</td>
<td>149.68</td>
</tr>
<tr>
<td>MTM</td>
<td>88.84</td>
<td>89.27</td>
<td>89.46</td>
<td>89.28</td>
<td>90.41</td>
</tr>
<tr>
<td>MTM2</td>
<td>89.44</td>
<td>89.01</td>
<td>88.91</td>
<td>88.97</td>
<td>88.77</td>
</tr>
<tr>
<td>DRIPS</td>
<td>89.29</td>
<td>89.15</td>
<td>88.83</td>
<td>89.27</td>
<td>91.95</td>
</tr>
</tbody>
</table>
17.c Graphs Maximum Stay time vs. Average Stay time per object

1. Command Openen

2. Bevestiging Openen Veva

3. Bevestiging Start Schouwen
4. Bevestigin Rijbaan Vrij

5. Bevestiging Contraboom Open

6. Bevestiging Aanrijboom open
7. MTM instellen Lamelborden

8. MTM instellen Matrix

9. DRIPS instellen
17.D Percentages of downtime per installation per replication
Appendix 18 Simulation Output 2

Output of simulating the scenario (including each sub-scenario) 365 times with an improved MTBF of the Height detection of 5%.

Run to Time: 150000000.00
Warmup-Time: 1778000.00
Replications per Scenario: 5.00

18.a Confidence intervals

Throughput times

<table>
<thead>
<tr>
<th>Average Throughput</th>
<th>Mean (95% Confidence)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; Mean</td>
<td>&lt; Mean</td>
<td>S</td>
<td>Min</td>
</tr>
<tr>
<td>Opening A8</td>
<td>1462,58</td>
<td>1506,55</td>
<td>1550,53</td>
<td>67,31</td>
</tr>
<tr>
<td>Closing A8</td>
<td>883,09</td>
<td>885,68</td>
<td>888,27</td>
<td>3,96</td>
</tr>
<tr>
<td>Opening A5 + A10</td>
<td>2075,99</td>
<td>2097,76</td>
<td>2119,54</td>
<td>33,33</td>
</tr>
<tr>
<td>Closing A5+A10</td>
<td>1496,25</td>
<td>1517,28</td>
<td>1538,31</td>
<td>32,19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Min Throughput</th>
<th>Mean (95% Confidence)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; Mean</td>
<td>&lt; Mean</td>
<td>S</td>
<td>Min</td>
</tr>
<tr>
<td>Opening A8</td>
<td>1398,98</td>
<td>1404,59</td>
<td>1410,20</td>
<td>8,58</td>
</tr>
<tr>
<td>Closing A8</td>
<td>820,93</td>
<td>826,64</td>
<td>832,34</td>
<td>8,73</td>
</tr>
<tr>
<td>Closing A5+A10</td>
<td>1423,76</td>
<td>1430,34</td>
<td>1436,91</td>
<td>10,06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Max Throughput</th>
<th>Mean (95% Confidence)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; Mean</td>
<td>&lt; Mean</td>
<td>S</td>
<td>Min</td>
</tr>
<tr>
<td>Opening A8</td>
<td>3295,73</td>
<td>15671,03</td>
<td>28046,33</td>
<td>18941,79</td>
</tr>
<tr>
<td>Closing A8</td>
<td>1301,71</td>
<td>1610,23</td>
<td>1918,74</td>
<td>472,21</td>
</tr>
<tr>
<td>Opening A5 + A10</td>
<td>3876,45</td>
<td>10522,41</td>
<td>17168,37</td>
<td>10172,39</td>
</tr>
<tr>
<td>Closing A5+A10</td>
<td>1097,88</td>
<td>5728,59</td>
<td>10359,30</td>
<td>7087,83</td>
</tr>
</tbody>
</table>
### 18.b Raw data

**Cumulative Breakdown times per object of each replication**

<table>
<thead>
<tr>
<th></th>
<th>Rep 1</th>
<th>Rep 2</th>
<th>Rep 3</th>
<th>Rep 4</th>
<th>Rep 5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>35848,9</td>
<td>0</td>
<td>38723,33</td>
<td>35848,85</td>
<td>0</td>
<td>110421</td>
</tr>
<tr>
<td>CCTV</td>
<td>0</td>
<td>59257,79</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>59257,79</td>
</tr>
<tr>
<td>VENT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>VGV</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HD</td>
<td>422102</td>
<td>461825,7</td>
<td>159305,9</td>
<td>310821,2</td>
<td>458798,1</td>
<td>1812853</td>
</tr>
<tr>
<td>BOV</td>
<td>9248,7</td>
<td>5696,56</td>
<td>0</td>
<td>0</td>
<td>2741,35</td>
<td>17686,61</td>
</tr>
<tr>
<td>BSS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>OV</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>70660,62</td>
<td>0</td>
<td>70660,62</td>
</tr>
<tr>
<td>S</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BRV1</td>
<td>0</td>
<td>3706,41</td>
<td>11357,63</td>
<td>0</td>
<td>5123,54</td>
<td>20187,58</td>
</tr>
<tr>
<td>BRV2</td>
<td>0</td>
<td>15336,86</td>
<td>15961,14</td>
<td>26449,74</td>
<td>5542,55</td>
<td>63290,29</td>
</tr>
<tr>
<td>BCO</td>
<td>0</td>
<td>0</td>
<td>7724,47</td>
<td>2419,73</td>
<td>3293,26</td>
<td>13437,46</td>
</tr>
<tr>
<td>OC</td>
<td>51554,4</td>
<td>0</td>
<td>0</td>
<td>51554,39</td>
<td>0</td>
<td>103108,8</td>
</tr>
<tr>
<td>BAO</td>
<td>5020</td>
<td>4064,98</td>
<td>0</td>
<td>6796,68</td>
<td>0</td>
<td>15881,66</td>
</tr>
<tr>
<td>OA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MTM</td>
<td>0</td>
<td>3347,18</td>
<td>2893,53</td>
<td>0</td>
<td>0</td>
<td>6240,71</td>
</tr>
<tr>
<td>ALB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MTM2</td>
<td>0</td>
<td>3347,18</td>
<td>2893,53</td>
<td>0</td>
<td>0</td>
<td>6240,71</td>
</tr>
<tr>
<td>PPM</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DRIPS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PD</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>523774</strong></td>
<td><strong>556582,7</strong></td>
<td><strong>238859,5</strong></td>
<td><strong>504551,2</strong></td>
<td><strong>475498,8</strong></td>
<td><strong>1763604,3</strong></td>
</tr>
</tbody>
</table>
18.c Percentages of downtime per installation per replication

Replication 1

- CCTV: 0%
- VVENT: 0%
- VGV: 0%
- OV: 0%
- BRV2: 0%
- BCO: 0%
- OC: 0%

Replication 2

- VGV: 11%
- BSS: 1%
- OV: 1%
- S: 1%
- BRV2: 1%
- BCO: 0%
- OC: 0%

Replication 3

- IV: 5%
- VENT: 7%
- VGV: 0%
- BOV: 0%
- BSS: 7%
- OV: 0%
- S: 0%

Replication 4

- VGV: 14%
- HD: 10%
- BOV: 7%
- BSS: 0%
- OV: 0%
- S: 0%
- BRV1: 0%

Replication 5

- CCTV: 1%
- VGV: 0%
- HD: 96%
- OV: 0%
- S: 0%
- BRV2: 0%
- BCO: 0%

XXXIX
Appendix 19 Simulation results level 0 document

Cumulative amount of Breakdowns per object of each replication

<table>
<thead>
<tr>
<th></th>
<th>Normal design</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Improved design</th>
<th>Rep 1</th>
<th>Rep 2</th>
<th>Rep 3</th>
<th>Rep 4</th>
<th>Rep 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCTV</td>
<td>3</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VENT</td>
<td>3</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>14</td>
<td>5</td>
<td>9</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>VGV</td>
<td>18</td>
<td>17</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HD</td>
<td>20</td>
<td>18</td>
<td>33</td>
<td>17</td>
<td>13</td>
<td>12</td>
<td>14</td>
<td>5</td>
<td>9</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>OV</td>
<td>7</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC</td>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cumulative downtime of an object in each replication

<table>
<thead>
<tr>
<th></th>
<th>Normal design</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Improved design</th>
<th>Rep 1</th>
<th>Rep 2</th>
<th>Rep 3</th>
<th>Rep 4</th>
<th>Rep 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>11,02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9,96</td>
<td>10,76</td>
<td>9,96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCTV</td>
<td>15,46</td>
<td>9,70</td>
<td></td>
<td></td>
<td></td>
<td>16,46</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VENT</td>
<td>11,24</td>
<td>17,29</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VGV</td>
<td>190,36</td>
<td>169,73</td>
<td>314,16</td>
<td>158,33</td>
<td>121,35</td>
<td>117,25</td>
<td>128,28</td>
<td>44,25</td>
<td>86,34</td>
<td>127,44</td>
<td></td>
</tr>
<tr>
<td>HD</td>
<td>33,09</td>
<td>18,00</td>
<td></td>
<td></td>
<td></td>
<td>14,32</td>
<td></td>
<td></td>
<td>19,63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OV</td>
<td>14,84</td>
<td>17,61</td>
<td></td>
<td></td>
<td></td>
<td>14,32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC</td>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 20 Costs average system failure according to Level 0 document.

8.8 Kosten van een gemiddelde storing

Om de RAMS analyses te kunnen kwantificeren dienen uitgangspunten te worden vastgesteld ten aanzien van de kosten van een storing/falen. De hieronder genoemde kosten en daaraan gerelateerde eisen zijn louter indicatief en hieraan kunnen geen rechten worden ontleend.

De kosten van een storing zijn opgebouwd uit een aantal factoren:

1. Beschikbaarheidskorting:
   Deze wordt uitgedeeld indien aan de faaldefinities uit Tabel 8 wordt voldaan. De beschikbaarheidskorting is voor een tunnelbuis gemiddeld 14.000 euro per kwartier.
2. Prestatiekorting:

Deze wordt uitgedeeld indien:

- Door Tekortkoming ON direct boetepunten als niet wordt voldaan aan de eisen vastgelegd in de faaidefinities Tabel 9.
- Tekortkoming ON nog niet verholpen na het verstrijken van de tijdsoverhebbende EXTRA boete, boetepunten +1
- Tekortkoming ON nog steeds niet verholpen na nieuwe normduur waar EXTRA boete, boetepunten +1

Eén boetepunt kan worden gewaardeerd met ongeveer €10.000,-

Gevolg hiervan is dat storingen in een tunnelbuis enorm veel geld kosten voor de exploitatiefase (Coentunnel Company - CCY). Het heeft daarom zin om eisen te stellen aan de deelinstallaties om storingen zo veel mogelijk te voorkomen. Iedere storing die bespaard kan worden over de exploitatieduur, wordt daarom gewaardeerd met een bedrag gelijk aan de beschikbaarheidskorting.

Als voorbeeld:
Een besturings storing die 24 uur duurt en die impact heeft op de beschikbaarheid van een buis, kost CCY ongeveer 1,34 miljoen euro aan kortingsbedragen. Daarbij zijn de feitelijke herstekosten (mensen, materieel en materiaal) nog niet gerekend.

<table>
<thead>
<tr>
<th>Besluit-020</th>
<th>Kosten van storingen die een niet beschikbaarheid van een tunnelbuis veroorzaakt worden gewaardeerd met een bedrag van 14.000 euro per kwartier.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rationale</td>
<td>Dit is het gewogen gemiddelde van de dag en nacht periods, dat wordt opgevolgd aan beschikbaarheidskorting conform contractdocument ‘NHK-77007-050000 Bijlage 2 Betalingmechanisme’.</td>
</tr>
<tr>
<td>Bovenliggende eis:</td>
<td></td>
</tr>
<tr>
<td>Gerelateerde objecten:</td>
<td>Alle faakdefinities uit Tabel 9 met bijbehorende objecten</td>
</tr>
<tr>
<td>Opmerkingen:</td>
<td>Ook bekend als beschikbaarheidskorting. Besluit genomen ten behoeve van interne afhandeling. Om de RAMS analyses te kunnen kwalificeren dienen uitgangspunten te worden vastgesteld ten aanzien van de kosten van een storing/falen. De hieronder genoemde kosten en daaraan gelieve eisen zijn louter indicatief en hieraan kunnen geen rechten worden ontleend.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Besluit-021</th>
<th>Direct bij het optreden van een faakdefinie uit SD Tabel 9 (Prestatiekorting) wordt conform Tabel 9 boetepunten uitgedeeld wat gewaardeerd wordt met een bedrag van €10.000 euro per boetepunt, aanvullend wordt bij verstrijken herstelnormduur het aantal boetepunten vermeerderd met 1 en na het verstrijken van de nieuwe normduur weer vermeerderd met 1.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rationale</td>
<td>Het bedrag is afgeleid uit ‘NHK-77007-050000 Bijlage 2 Betalingmechanisme’ deel 4 hoofdstuk 15 en 16.</td>
</tr>
<tr>
<td>Bovenliggende eis:</td>
<td></td>
</tr>
<tr>
<td>Gerelateerde objecten:</td>
<td>Alle faakdefinities uit Tabel 9 met bijbehorende objecten</td>
</tr>
<tr>
<td>Opmerkingen:</td>
<td>Om de RAMS analyses te kunnen kwalificeren dienen uitgangspunten te worden vastgesteld ten aanzien van de kosten van een storing/falen. De hieronder genoemde kosten en daaraan gelieve eisen zijn louter indicatief en hieraan kunnen geen rechten worden ontleend.</td>
</tr>
<tr>
<td>Tabel 9</td>
<td>Eis</td>
</tr>
<tr>
<td>--------</td>
<td>-----</td>
</tr>
<tr>
<td>Ja</td>
<td>VMS- TD1-0111</td>
</tr>
<tr>
<td>Ja</td>
<td>VMS- BD1-0190</td>
</tr>
<tr>
<td>Ja</td>
<td>VMS- VDC-0080</td>
</tr>
<tr>
<td>Ja</td>
<td>VMS- BWK-0144</td>
</tr>
<tr>
<td>Ja</td>
<td>VMS- Q1-0308</td>
</tr>
<tr>
<td>Ja</td>
<td>VMS- AB-0020</td>
</tr>
<tr>
<td>Ja</td>
<td>VMS- CADO-0007</td>
</tr>
<tr>
<td>Taal</td>
<td>Zin</td>
</tr>
<tr>
<td>------</td>
<td>-----</td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NL</td>
<td></td>
</tr>
</tbody>
</table>
Tabel 1. Het effect van het doorharden van een stof op de struikellichamen van de betonstof (in mm)

<table>
<thead>
<tr>
<th>Betonstof</th>
<th>Na het doorharden</th>
<th>Na 28 dagen</th>
<th>Na 90 dagen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stof A</td>
<td>0.05</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>Stof B</td>
<td>0.07</td>
<td>0.12</td>
<td>0.18</td>
</tr>
<tr>
<td>Stof C</td>
<td>0.09</td>
<td>0.15</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Tabel 2. De resultaten van een experiment met verschillende concentraties van een stof in betonstof (in %)

<table>
<thead>
<tr>
<th>Concentratie</th>
<th>Na 28 dagen</th>
<th>Na 90 dagen</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1%</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>0.5%</td>
<td>0.07</td>
<td>0.12</td>
</tr>
<tr>
<td>1%</td>
<td>0.09</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Tabel 3. De uitkomsten van een onderzoek naar de invloed van een stof op de struikellichamen van de betonstof (in mm)

<table>
<thead>
<tr>
<th>Betonstof</th>
<th>Na het doorharden</th>
<th>Na 28 dagen</th>
<th>Na 90 dagen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stof A</td>
<td>0.05</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>Stof B</td>
<td>0.07</td>
<td>0.12</td>
<td>0.18</td>
</tr>
<tr>
<td>Stof C</td>
<td>0.09</td>
<td>0.15</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Tabel 4. De resultaten van een experiment met verschillende concentraties van een stof in betonstof (in %)

<table>
<thead>
<tr>
<th>Concentratie</th>
<th>Na 28 dagen</th>
<th>Na 90 dagen</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1%</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>0.5%</td>
<td>0.07</td>
<td>0.12</td>
</tr>
<tr>
<td>1%</td>
<td>0.09</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Tabel 5. De uitkomsten van een onderzoek naar de invloed van een stof op de struikellichamen van de betonstof (in mm)

<table>
<thead>
<tr>
<th>Betonstof</th>
<th>Na het doorharden</th>
<th>Na 28 dagen</th>
<th>Na 90 dagen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stof A</td>
<td>0.05</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>Stof B</td>
<td>0.07</td>
<td>0.12</td>
<td>0.18</td>
</tr>
<tr>
<td>Stof C</td>
<td>0.09</td>
<td>0.15</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Tabel 6. De resultaten van een experiment met verschillende concentraties van een stof in betonstof (in %)

<table>
<thead>
<tr>
<th>Concentratie</th>
<th>Na 28 dagen</th>
<th>Na 90 dagen</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1%</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>0.5%</td>
<td>0.07</td>
<td>0.12</td>
</tr>
<tr>
<td>1%</td>
<td>0.09</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Tabel 7. De uitkomsten van een onderzoek naar de invloed van een stof op de struikellichamen van de betonstof (in mm)

<table>
<thead>
<tr>
<th>Betonstof</th>
<th>Na het doorharden</th>
<th>Na 28 dagen</th>
<th>Na 90 dagen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stof A</td>
<td>0.05</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>Stof B</td>
<td>0.07</td>
<td>0.12</td>
<td>0.18</td>
</tr>
<tr>
<td>Stof C</td>
<td>0.09</td>
<td>0.15</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Tabel 8. De resultaten van een experiment met verschillende concentraties van een stof in betonstof (in %)

<table>
<thead>
<tr>
<th>Concentratie</th>
<th>Na 28 dagen</th>
<th>Na 90 dagen</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1%</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>0.5%</td>
<td>0.07</td>
<td>0.12</td>
</tr>
<tr>
<td>1%</td>
<td>0.09</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Tabel 9. De uitkomsten van een onderzoek naar de invloed van een stof op de struikellichamen van de betonstof (in mm)

<table>
<thead>
<tr>
<th>Betonstof</th>
<th>Na het doorharden</th>
<th>Na 28 dagen</th>
<th>Na 90 dagen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stof A</td>
<td>0.05</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>Stof B</td>
<td>0.07</td>
<td>0.12</td>
<td>0.18</td>
</tr>
<tr>
<td>Stof C</td>
<td>0.09</td>
<td>0.15</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Tabel 10. De resultaten van een experiment met verschillende concentraties van een stof in betonstof (in %)

<table>
<thead>
<tr>
<th>Concentratie</th>
<th>Na 28 dagen</th>
<th>Na 90 dagen</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1%</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>0.5%</td>
<td>0.07</td>
<td>0.12</td>
</tr>
<tr>
<td>1%</td>
<td>0.09</td>
<td>0.15</td>
</tr>
</tbody>
</table>