

Planning visualization during rail possessions

MSc. Thesis – Transport, Infrastructure & Logistics

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Preface

This thesis is the deliverable for the final project of the MSc program Transport, Infrastructure and Logistics at the Delft University of Technology. The objective of the master thesis is to apply knowledge acquired during the master program to a real-life situation. At the OV SAAL construction site BAM encountered a planning related problem and asked me to find a solution. The project combines technical aspects, social aspects and software aspects and challenged me to integrate these. During the research I gained valuable insight in operational aspects of complex construction sites, communication between construction site managers, model design and software design.

I would like to thank BAM for granting me the opportunity to perform my MSc research at a fantastic and very complex rail project. I would like to thank all planners, construction site managers and other experts at OV SAAL for their advice, thoughts and tips regarding my research. Special thanks go out to Bart van Riel for his expert supervision, regular meetings and brainstorm sessions and Jan Kardux for his advice and time. Additionally I would like to thank Frank de Zoeten and Maarten van Hulzen from Esri Nederland and Arnout van Raaij from BAM Infraconsult for their time and advice in ArcGIS. Furthermore I would like to thank the members of my TU Delft graduation committee for their feedback, advice and keeping me sharp: Alexander Verbraeck, Jos Vrancken and Sander van Nederveen. Finally, I would like to thank my family and friends for their support, suggestions and sharp eye.

I am pleased to present the outcomes of this research, a high-level design for a planning visualization model for rail possessions.

I wish you pleasant reading.

Luc Schouten

Delft, 18th of August 2015

Translations and abbreviations

Contractors have a strong tendency to use industry specific language and abbreviations. Key words in Dutch are often hard to translate in English and sometimes multiple translations exist. A list of translations is presented to clarify the translation from Dutch to English jargon. To facilitate a readable research, the abbreviations used in the text are abbreviated from the Dutch words.

Translations

This list presents the translations of English words to Dutch words.

English (UK)	Dutch	Abbreviation
Amsterdam transportation company	Gemeentelijk vervoersbedrijf	GVB
Bar-chart / Gantt-chart	Balkenplanning	-
Cables & pipes	Kabels & Leidingen	K&L
Chief constructen site manager	Hoofduitvoerder	-
Construction site manager	Uitvoerder	-
Coordinating construction site manager	Bouwcoördinator uitvoering	BCU
Dutch road authority	Rijkswaterstaat	RWS
Head workplace safety	Leider werkplekbeveiliging	LWB
Integral script meeting	Integraal draaiboek overleg	IDO
Level of Detail	Detailniveau	LoD
Machinery	Materieel	-
Material	Materiaal	-
National coordinate system	Rijksdriehoekstelsel	RDS
Overhead lines	Bovenleiding	-
Planner	Werkvoorbereider	-
Rail possession	Treinvrije periode	TVP
Progress line	Standlijn	-
Railway safety organization	Normenkader Veilig Werken organisatie	NVWO
Railway sleepers	Dwarsliggers	-
Structured query language	-	SQL
Tamping machine	Stopmachine	-
Track access location	Rail inzetplaats	RIP
Track foundation	Baanlichaam	Baan

Abbreviations

This list presents a list of abbreviations in alphabetical order.

Abbreviation	English (UK)
BCU	Coordinating construction site manager
GVB	Amsterdam transportation company
IDO	Integral script meeting
K&L	Cables & pipes
LoD	Level of Detail
LWB	Head workplace safety
MCDA	Multi Criteria Decision Analysis
NS	Nederlandse Spoorwegen
NVWO	Railway safety organization
RDS	National coordinate system
RIP	Track access location
RWS	Dutch road authority
SQL	Structured query language
TVP	Rail possession

In addition, a simplified section of a railway track is presented in Figure 1. Several definitions are included.

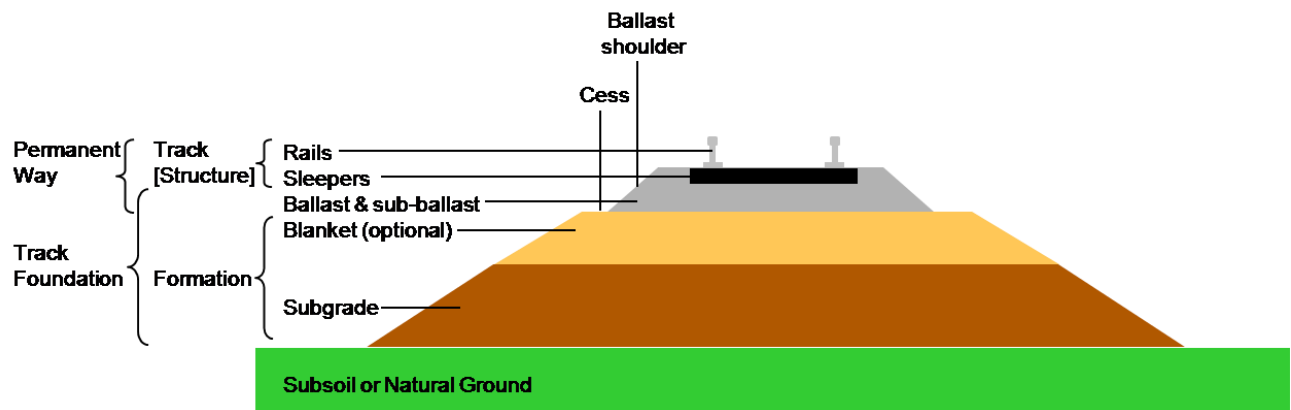


Figure 1: Example section railway track (Ellis, 2010)

Definitions

Since many definitions exist for scientific concepts, it is necessary to define an interpretation for key concepts. The following working definitions are applied in this thesis:

<i>Autodesk</i>	Software developer of AutoCAD, Navisworks and Revit.
<i>BAM</i>	Royal BAM Group is the company overarching several specialised construction companies as BAM Rail, BAM Civiel and more. For the OV SAAL project, all of these companies act as one company: BAM Combinatie Amstelspoor v.o.f. Within this company, several departments are identified, all specialised in a specified work field.
<i>Brownfield</i>	A brownfield site is defined as a construction site that at some point was occupied by a permanent structure. In a brownfield project the structure would need to be demolished or renovated.
<i>Esri</i>	Software developer of ArcGIS. The full company name is Esri Nederland BV.
<i>Method</i>	The protocol used to carry out the objective of this research.
<i>Model</i>	A model is a representation of the system, which can be used to help people understand or simulate the system the model represents.
<i>OV SAAL</i>	Rail construction project to increase the rail capacity. Between Schiphol, Amsterdam, Almere and Lelystad extra railway tracks are constructed.
<i>System</i>	The collection of elements and their mutual relationships within the 8 kilometre long railway track between de Schinkelbridge and Duivendrecht, related to the 9-day rail possession from 30 July 2016 to 7 August 2016.
<i>Tool</i>	An applied version of a method.

Assumptions

A list of assumptions is given to present the essential conditions necessary to allow a reproduction of this research.

- All dependency relations between activities are correctly inserted in the Gantt chart for all clashes to be detected by the model.
- For all activities the state initiation relation and dependency relation between states and activity are correctly captured in a table and inserted in the visualization model.
- The expected time duration of each activity is determined by an expert and assumed deterministic. In addition the effect of unwanted events causing delays is assumed to be deterministic.

Executive summary

Research context

OV SAAL Zuidtak Oost is a large construction site where BAM Rail expands rail capacity from two to four railway tracks over 8 kilometre. In order to have a safe work environment, BAM Rail is allowed to possess the railway tracks for variable durations. For OV SAAL Zuidtak Oost a 9 day-rail possession is scheduled for the beginning of August 2016. For these nine days, at four different connected construction sites rail related construction works are executed. A strict and complex planning schedule is needed to guarantee all construction works can be completed before the deadline.

In preparation for rail possessions, Gantt-charts and time-distance diagrams are used to create the planning schedules. Gantt-charts consist of a chain of linked activities representing the different tasks the construction site managers have to execute.

Problem statement

The planning methods that are currently used provide insufficient overview over complex TVPs ('TreinVrije Perioden'). Only very experienced planners have the knowledge to make and interpret these planning schedules. Users identify three missing aspects resulting in failure costs and inefficiencies:

- The currently used planning methods show no spatial overview of the state of the complete line system at each moment of time.
- No clashes between different operational activities can be detected.
- Construction logistics (working trains, heavy machinery) cannot be represented with the current methods.

BAM Rail experiences failure costs and expensive operational inefficiencies by the application of Gantt-charts and time-distance diagrams for general rail projects. Many users indicate that a spatial representation of a Gantt-chart would be useful in eliminating risks and inefficiencies. Therefore, the objective of this research is described as follows:

To design a planning visualization method which assists BAM Rail in enhancing insight into the state of a linear construction site over time.

Apart from the design of a planning visualization method, this research presents several additional recommendations related to observed processes during rail related construction works.

Current situation

User interviews and site visits were conducted to perform an in-depth analysis of the current situation. After categorizing the users' responses, six main causes of risks and inefficiencies were identified:

1. *Absence of clash detection*: some clashing activities and invalid state sequences are left unidentified in the planning phase, resulting in failure costs during the construction phase.
2. *High project complexity*: Gantt-charts become too complex to comprehend, resulting in experts making mistakes when creating planning schedules.
3. *Missing project overview*: no basic site overview is available, resulting in non-expert decision makers making wrong decisions.

4. *The impossibility to perform a scenario analysis*: this results in failure costs as no control measures and fall back scenarios can be quantitatively analysed.
5. *The impossibility to show construction logistics real-time*: train paths and machinery locations are unknown, resulting in failure costs when making operational decisions.
6. *The impossibility to determine delay propagations real-time*: measures to settle delayed activities cannot be quantitatively analysed real-time, resulting in failure costs when making operational decisions.

A requirements analysis presents a set of requirements for a visualization method. The complete set of requirements spans a solution space for a high-level design.

High-level design

Stakeholder interviews and test runs resulted in insights in the desired model output. The desired model output has been used to create a platform-independent high-level design. The high-level design consists of a model architecture, software architecture, pseudo code and system specification for use in the implementation in a software package. An important aspect of the high-level design is clash detection. Five different types of clashes are identified. For all five an automatic clash detection module is required. Activities moving in time are included in the high-level design as well.

Implementation

The suitability for implementation of the high-level design has been evaluated for two software packages, Navisworks and ArcGIS. The four main categories of evaluation criteria are defined as functional criteria, project management criteria, user interface criteria and configuration criteria. Preliminary tests with both software packages formed the basis for the evaluation. ArcGIS outperformed Navisworks in three out of four main criteria. After a sensitivity analysis, it was decided to create a prototype of the high-level design in ArcGIS.

During the process of generating and validating the desired user output in ArcGIS, several shortcomings of ArcGIS were detected. These shortcomings were sorted based on the main functional aspects of the visualization model. Software developer *Esri Nederland BV* has been consulted to confirm the identified shortcomings and asked for strategies to overcome these limitations. Several recommended adjustments for ArcGIS are presented to *Esri* before a fully functional model can be implemented. *Esri* estimated that an investment of [CONFIDENTIAL] necessary to deliver a fully functional visualization model, satisfying all user requirements.

Research conclusions

The conclusions of this research answer the main research question of this research:

How can BAM Rail get insight into the state of the construction works at a line construction site at each time step?

Firstly, it can be concluded that failure costs are associated with the identified risks and inefficiencies. Providing an adequate insight into the state of the construction site system at each time step reduces the planning related risks and thus the failure costs. It can be concluded that the state of the construction works can be represented best by several aspects:

1. For each planned activity the location must be presented in a geospatial overview. Both static and dynamic activities must be included.
2. For each user-defined track section the state of that section must be presented in the geospatial overview.
3. Time and infrastructure constraints must be included in the geospatial overview.

It is concluded that a planning visualization method is necessary to get insights into the state of the construction works of a line system for each time step. A module to automatically detect clashes is necessary to assist users in detecting the identified types of clashes. The high-level design included how the model architecture and software architecture of a planning visualization model should look like. By implementing a software package with these characteristics and structure, insights into the state of a construction site system can be provided.

Esri's ArcGIS is found to be most suitable for the implementation. The possibility to present activities and states as polygons matches with the desired user output. Furthermore, CAD drawings and aerial photos facilitate an overview on scale. Finally, intuitive navigation through ArcGIS is considered as user-friendly. Concluding, creating a planning visualization model in ArcGIS results in satisfying the user requirements— from planner to site manager – and thus solve the six main causes of risks and inefficiencies.

Recommendations

BAM Rail is advised to request an official proposal from *Esri* for a visualization method in ArcGIS. In addition, a BAM project team leading the implementation in ArcGIS should be formed. This team is responsible for monitoring the progress and deadlines, organizing test runs and defining milestones and showstoppers.

Additional recommendations are presented. First, two recommendations for BAM Rail are presented. Then, recommendations for further research are presented.

It is observed that the communication between the coordinating construction site manager (BCU) and construction site managers ('uitvoerder') during the construction works is done only by phone, once every 2-4 hours. Users consider these phone calls as inefficient for regular operations. Therefore it is recommended to investigate the implementation of an integrated mobile system for site managers to report the progress using an application on a mobile phone or tablet.

Furthermore, it is recommended that a more thorough workplace inspection is executed before a TVP starts. Currently, it often occurs that physical obstacles or deviating situations are only discovered during the construction phase, resulting in a wrong initial state. When these deviations are discovered in an early phase, failure costs can be prevented.

This research presents a visualization algorithm rather than an optimization algorithm. It is recommended to investigate the possibility of implementing an optimization algorithm to not only *visualize* planners' decisions, but also *making* them. Two aspects must be changed when designing an optimization algorithm. First, the addition of a probabilistic activity duration instead of a deterministic

activity duration must be added. Second, expressing the starting time of each activity in completion time of prior activities must be added.

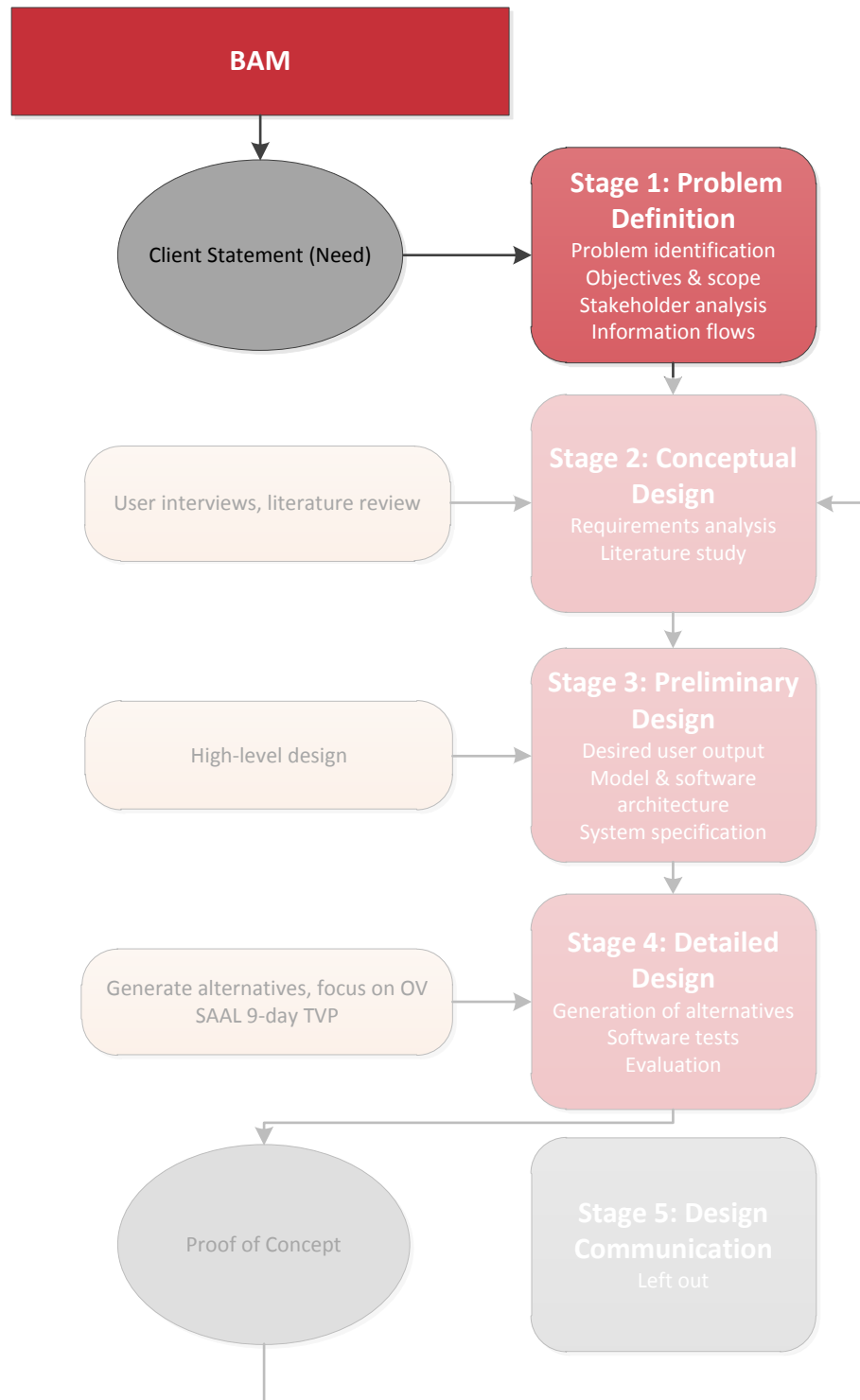
Finally, it is recommended to research the possibility of implementing resources in the model. By considering available working crew, machinery or costs, the use of these materials can be viewed at each moment in time. Also for the extra resources constraints can be defined. Resources can be implemented in the clash detection model as well.

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DYM & LITTLE STAGE 1: PROBLEM DEFINITION



1. Introduction

This introduction starts with background information to illustrate the context and relevance of this research. Furthermore, the problem as defined by problem owner BAM Rail is stated. The research objective resulting from the problem statement concludes the first chapter.

1.1 Background information OV SAAL

In order to guarantee the accessibility of Amsterdam, the railway connection between Schiphol, Amsterdam, Almere and Lelystad (SAAL) requires an enhancement. Figure 2 presents an overview of the complete corridor. The goal of the OV SAAL project is to facilitate 6 Sprinter trains and 6 Intercity trains per hour, which is twice the current frequency. In order to facilitate these high frequencies, the infrastructure between Hoofddorp and Duivendrecht must be increased from 2 to 4 tracks.



Figure 2: The OV SAAL project scope (Projectorganisatie OV SAAL, 2011)

The OV SAAL project is split up into several parts by client ProRail (Projectorganisatie OV SAAL, 2011). Of the four 'branches', ProRail split the South Branch into two parts: Zuidtak Oost (Schiphol – Amsterdam Zuid) and Zuidtak West (Amsterdam Zuid – Duivendrecht). For each of the two parts of the South branch, a different contract was made. Different parties subscribed in the competition to win the contracts. The South branch east (from now: *Zuidtak Oost*) was won by Alliantie Amstelspoor (ProRail, 2011a), which is a contractual cooperation between ProRail and contractor Royal BAM Group (BAM/ProRail, 2010). In Figure 2, the orange line presents BAMs working area: Zuidtak Oost.

Contractor Royal BAM Group (from now on: BAM) is the largest Dutch contractor in the Netherlands (based on revenue (Cobouw, 2014)). Within the Alliantie Amstelspoor, BAM acts as general contractor of the contract for Zuidtak Oost. BAM is responsible for the construction of the contract, which states an increase of 2 to 4 railway tracks for 8 km's between station Amsterdam Zuid and station Duivendrecht. The extension of 2 extra railway tracks includes the following construction works:

- Expanding all track foundation layers over 8 km, including the adjustment or construction of several fly-overs and underpasses.

- Constructing two railway tracks equipped with overhead lines, train safety equipment and several switches.
- Constructing two extra platforms at station Amsterdam RAI. In addition, several adjustments to station Duivendrecht are done as well.

Risks must be carefully controlled, as these construction works are executed in a high-density urban area, close to two infrastructural arteries: the A10 highway and existing railway lines. BAM started in September 2011 with the first steps of the construction of this project. In December 2016 the OV SAAL Zuidtak project is expected to be completed.

During the project, construction works nearby operational railway tracks are executed. ProRail's safety rules state that if there are construction or reconstruction works nearby a railway track, the regular train operations at this railway track must be temporarily stopped (RailAlert, 2012). The contractor therefore 'possesses' the railway tracks. These rail possessions (from now on: TVP, TreinVrije Periode) can last from a few hours to multiple days. During each TVP, different parts of the construction project can be done, while keeping the working conditions safe for both the construction workers and train passengers.

From 30 July 2016 to 7 August 2016 a 9-day TVP is planned to facilitate space and time for BAM at OV SAAL. During these 9 days, construction works nearby the existing rail tracks are executed. A 9-day rail possession at this infrastructural artery can be considered unique, as Schiphol and Amsterdam are not accessible directly from the eastern access routes during the TVP. Construction works include connecting the newly built rail to the existing railway network. A 24h per day work schedule is necessary to complete all operations within the TVP. If the deadline stated by ProRail for completing the construction works are not met, high fines are contractually awarded. A precise planning schedule is therefore needed.

Rail based infrastructure

Rail infrastructure is different from other construction industries because of four distinguishing characteristics (Van Riel, 2015; Vuist, 2015; Janssens, 2015):

1. Railway construction works are linear, repetitive projects that can be represented in a geographical map with a set of lines.
2. A railway construction project can be represented as layer-based, in which several 'operational layers' are stacked onto each other in a certain sequence. The height dimension is of little importance.
3. The final product (bolted railway) must be finished to facilitate logistic operations. Many types of machines need a completed track to move and perform operations.
4. Complicated logistic operations by rail-bound machines make the logistical scheduling difficult, as turning and bypassing of these machines is impossible.

To be even more specific, a TVP is different from a regular, long term rail construction project because of the following two distinguishing aspects:

1. Extremely time critical operations in a short time window are executed. Often, delay settling times are impossible to schedule.

2. *Brownfield situations* occur, where the construction site needs to be cleared or adjusted before new construction works can start.
3. If the deadline is not met, operational train disruptions affect country-wide train traffic. High reputational damage for NS, ProRail and BAM is expected to be the result.

At BAM Rail many experienced planners are involved in the creation of planning schedules. Project planners rely on their experience and knowledge from previous projects. With regard to new planning techniques, there is little room for innovation in the planning department of BAM Rail. With major, unique infrastructure projects as OV SAAL, there is no general, repeatable plan available to execute. Instead, the planning experts manually create plans for high time pressure phases as TVPs.

Currently BAM uses 3 planning methods for line based infrastructure projects (Vuist, 2015).

1. *Gantt-charts* assist in comprehending time related complexity into detail. It is easy to use for employees on all levels, as the priority relations between processes are visible. However, a Gantt-chart has no relation with the spatial dimensions of the project and is therefore not suitable as a single tool.
2. *Time-distance diagrams* can be used for simple, linear projects. The link with the spatial dimension is an important characteristic which makes it easy to quickly see what happens at each location. However, for complex, multi-dimensional projects, the diagram is unclear once the level of detail increases. In addition, time-distance diagrams regularly suggest sections of the planning are unfeasible, while in reality a suitable plan is possible.
3. *Network diagrams* are occasionally used by BAM as well. These diagrams can directly be exported from Gantt-charts, but better represent dependency relationships between activities.

1.2 Problem statement

Construction site planning and management can be considered as a core business for BAM. For TVPs, high time-pressure plays a major role in this core business. Therefore, the need for BAM Rail can be described as following:

BAM Rail needs to be able to define a feasible, clash-free TVP construction site operation plan within the defined time constraints.

The currently used planning methods provide insufficient overview of complex TVPs. Only the very experienced planners have the knowledge to make and interpret these planning schedules (Kardux, 2015). Even for these planners, there are missing features in the previously mentioned methods:

- The combination of planning techniques shows no overview in the state of the complete line system at each moment into time. If this insight would be available, operational conflicts could be detected earlier and insight in delay propagation would be possible.
- The possibility of scaling in the spatial dimensions is limited. Currently, only schematic overviews can be produced, which eliminates the implementation of environmental elements in the planning.

- The level of detail in the time – distance diagram is a limitation. If the level of detail increases, the planning becomes increasingly unclear. A low level of detail provides a clear diagram but suffers from the lack of detail, for instance, clash detection.
- Construction logistics cannot be represented with the current planning methods. Aspects such as access routes for heavy machinery and routing are not accessible in an acceptable way.

The absence of these features results in risks and inefficiencies for BAM. These inefficiencies and risks are considered unacceptable for the 9-day TVP. Hence, the problem statement for problem owner BAM Rail can be described as follows:

The planning methods BAM Rail currently uses, provide insufficient insight into the state of the line system at each user defined time step during the construction phase. Also the relations between activities and how delays propagate spatially and temporally across the system are essential but currently not available in high detail. In addition, the construction related logistic operations cannot be visualized with the current planning tools.

1.3 Objective

Based on this problem statement, the objective of this research can therefore be described as follows:

To design a planning visualization method which assists BAM Rail in enhancing insight into the state of a linear construction site over time.

The 9-day TVP at OV SAAL is the reason for BAM Rail to request this research. The 9-day TVP forms a test-case for the final product of this research. In addition, many experienced rail experts are located at the OV SAAL project office. However, the overall objective is not *only* to solve OV SAAL related TVPs. It is designed for general BAM Rail construction as well.

2. Research structure

In this chapter, the structure of the research is presented. First of all, the research questions are described. Then, the methodology to answer these research questions is presented. Finally, the different scopes for the research are presented.

2.1 Research questions

Based on the problem statement and objectives, the main research questions can be formulated as:

How can BAM Rail get insight into the state of the construction works at a line construction site at each time step?

In order to answer this question, the following sub questions are formulated:

1. What planning methods and tools are currently used at construction sites?
2. What are the risks and inefficiencies resulting from these currently used methods?
3. What are user requirements for a method to provide extra insight into the state of a construction site?
4. What high-level model design and software design describes a method to provide extra insight?

5. What planning related software packages are currently available?
6. Which design options can be distinguished for the method to visualize the 9-day TVP at OV SAAL?

2.2 Methodology

In this section the methodology used for this research is presented. Dym and Little present a five-stage descriptive design framework which is used to structure the design process in this research. This framework is chosen because it describes the design process as a linear sequence of five stages (Dym & Little, 2008). The logical order of stages provides guidance both in the design process and in the report. Figure 3 presents a graphical representation of the framework. For each of the steps in the framework, a description about the implementation for this research is presented.

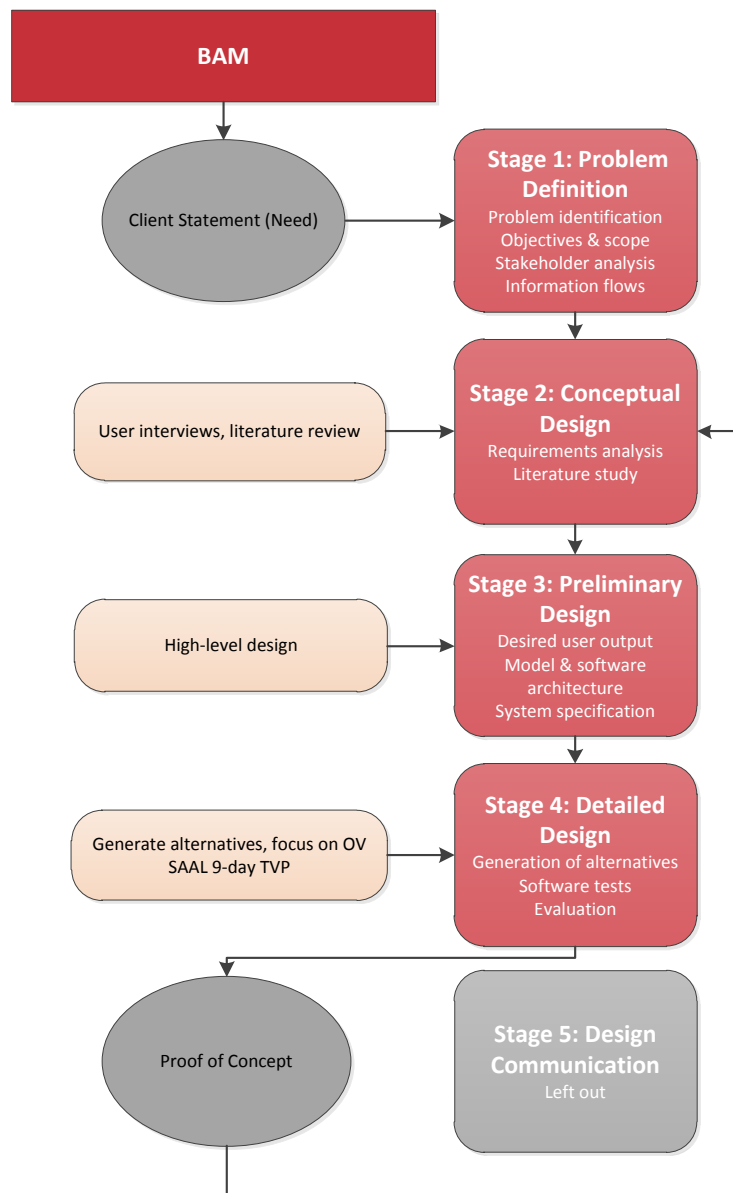


Figure 3: Dym & Little adapted 5-stage model

Client Statement

The first step in this research is BAM's need statement. This describes the need for a design and can be seen as the input for the follow-up steps in the design process.

Stage 1: Problem Definition

The problem definition stage is the first stage in the design process. In this stage, the precise problem is refined with help of a set of user interviews. A stakeholder analysis is conducted to consider all stakeholders and their influence and interests for the new planning method. Stakeholders, both in the planning phase and construction phase, are identified with help of the interviews. Furthermore, the scope of this research is refined and constraints identified.

Furthermore, the first stage describes the current planning process at TVP construction sites. An in-depth research in the currently used tools is presented. Both the OV SAAL project as well as other projects are studied with help of expert interviews and case studies with current software packages.

Means: interviews, building site observations, existing plans, current software

Output: revised problem statement, objectives and scope, constraints, stakeholder analysis, information flows

Stage 2: Conceptual design

A requirements analysis is conducted to gain insight in all the different requirements that have to be considered for the new visualization method. The requirements analysis addresses the requirements and wishes of the stakeholders and refines the previously stated constraints. The conceptual design stage consists of a literature study as well. Established, traditional planning techniques are presented as well as possible new directions for this research. In addition, analogue industries are studied. These similar fields may use relevant planning techniques for this research.

Means: interviews, literature review, building site observations, analogies, software testing

Output: requirements analysis, knowledge from literature review

Stage 3: Preliminary design

The third stage of the Dym & Little framework presents a high-level design of the planning visualization method. A platform-independent design is presented based on the requirements. First, the desired user output is presented. In addition, the relation between activities and states is explained. Then, the architectural diagram of both the clash detection model and the software package is presented.

The preliminary design section describes the necessary input for the high-level design. In addition, a profound step in the clash detection model is presented. To conclude the high-level design, a pseudo code and system specification present the deliverables of the high-level design.

Means: software testing, literature reviews

Output: desired user output, model architecture, software architecture, pseudo code, system specification

Stage 4: Detailed design

Following from system specifications, model architecture and software architecture, a first step into the implementation for OV SAAL is taken. First, two software alternatives are described, tested and

reviewed. The alternatives are software packages in different combinations in different disciplines. After test runs, the alternatives are evaluated with help of a Multi Criteria Analysis (MCA) different applications and work fields. The best performing package, resulting from the MCA, is tested in more detail.

By implementing datasets retrieved from actual TVPs at OV SAAL, a first functional model is presented in ArcGIS. Together with users, test runs are done to apply the high-level fluently for actual TVPs. The output of this phase is a proof of concept of a new planning visualization tool, tested for a section in the OV SAAL 9-day TVP. An advice for BAM Rail on implementation of the high-level design is a deliverable of this research as well.

Means: software testing and optimizing, interviews, test runs with planners from BAM, scenario analysis

Output: a selected software package, test-and-evaluation results, rough proof of concept

Stage 5: Design communication

Dym and Little state a final design communication stage is necessary for the complete design framework. In this step “fabrication specifics and justification of the fabrication specs is presented” (Dym & Little, 2008). However, as the final product of this report is a high-level design combined with a proof of concept, a fabrication specifics is not relevant. This fifth step is therefore not included in the research.

It can be noticed in Figure 3 a feedback loop is included from the final Proof of concept back towards the Conceptual design step. A *cyclical process* is implemented to allow a refinement of the stakeholder requirements, system specification and design steps.

Finally, a discussion, conclusions and recommendations chapter concludes this thesis. During this final step, the results are discussed, the research question is answered and recommendations for further steps are presented.

The previously stated research questions can be connected to the Dym and Little 5 stages model. Table 1 presents the link between the research questions and the 5 stages model. The main research question is answered in the conclusions and recommendations chapter.

Table 1: Research questions connected to Dym & Little framework

#	Question	Dym & Little stage	Means
1	What planning methods and tools are currently used at construction sites?	Stage 1	Expert interviews, site observations, analogies
2	What are the risks and inefficiencies resulting from these currently used methods?	Stage 1	Expert interviews, literature review, building site observations, analogies
3	What are user requirements for a method to provide extra insight?	Stage 2	Expert interviews, building site observations, questionnaires, analogies
4	What high-level model design and software design describes the method to provide extra insight?	Stage 3	Literature study, expert interviews, software testing

5	What planning related software packages are currently available?	Stage 4	Literature study, expert interviews, software testing
6	Which design options can be distinguished for the method to visualize the 9-day TVP at OV SAAL?	Stage 4	Software testing and optimizing, validating test runs, scenario analysis

Deliverables

Three key deliverables are presented during this research:

1. The set of requirements stated by key stakeholders illustrates what they require to reduce the defined risks and inefficiencies.
2. A high-level, platform independent design of a visualization method. Including a model architecture, software architecture and system specification.
3. An advice to BAM Rail for the implementation of a planning visualization method in software package ArcGIS.

2.3 Scope

Several choices are made regarding the scope of this research. This section presents these scopes:

Spatial scope

The spatial scope defines the geographical area considered during the detailed design (stage 4) of this research. The spatial scope is set for the complete OV SAAL Zuidtak Oost project as defined in *OV SAAL Zuidtak Contract Oost* (BAM/ProRail, 2010). Within this 8km project scope, four major construction sites can be identified (Van Riel, 2015).

Temporal scope

The temporal scope defines the time span included in his research during the 4th stage of the research. The temporal scope is set from 30 July 2016 towards 7 August 2016.

Functional scope

This research considers the visualization model as a black box. Figure 4 illustrates the scope of the visualization method. A work planning and associated spatial information are input for the black box. The visualization method produces a product which shows the state of the construction works system at each time step.



Figure 4: Graphical representation of the functional scope

3. Current situation

This chapter describes the current situation in the planning phase and construction phase of a TVP. In this stage, 18 interviews and a construction site visit provide the basis of a complete overview of all activities, stakeholders and information flows related to a TVP. Most interviewees work at the OV SAAL project in different phases, from the design phase to construction phase. These interviews are presented in Appendix A. First of all, an overview of the activities scheduled during a TVP are presented. This step gives insight in the complexity of planning the construction works. Then, in Chapter 3.2 a stakeholder analysis is presented, focussing on the power-interest-attitude relation for all stakeholders. Then, all information flows between different stakeholders are presented for both phases. Finally, risks and inefficiencies in the current situation are presented.

The 18 interviewees are selected based on their role within the OV SAAL organisational structure. From the planning departments of Rail, Track Foundation and Civil structures interviewees provide information about activities, clashes and the communication between other departments. Several *coordinating construction site managers* (from now: BCU) illustrate how the communication during the TVP is organised. Two members of the Management Team (from now: MT) provided information about the management level of the OV SAAL project. An overview of the interviewees is presented in Table 2.

Table 2: Distribution interviewees

Name	Department / role
Aerts, Marcel	Planner Rail / BCU
Alink, Erik	Planner Civil structures
Bodegom, Martjan (2x)	Design manager
Groot, Henk de	TVP-coordinator / BCU
Hoek, Angela van der	BAM BIM department
Hulzen, Maarten van	GIS expert ESRI
Immers, Rogier	Planner Rail / BCU
Janssens, Michiel	Overall project planner
Kardux, Jan	Construction / MT
Moons, Bob	BAM GIS department
Peters, Hans	Chief construction site manager
Riel, Bart van	Planner Rail / MT
Rykkje, Brigit	BIM/GIS modeller
Thole, Franklin	Planner Track foundation
Vallentgoed, Jasper	BIM-coordinator OV SAAL
Vuist, Henrie	Planner Rail / BCU
Weeda, Ivo	Construction site manager / Monitor

3.1 Activities

Many months of preparation precede for each TVP. ProRail prescribes short TVPs (< 52 hours) must be requested at least 13 weeks in advance (Aerts, 2015). However, long TVPs are planned sometimes up to two years in advance. The 9-day TVP at OV SAAL is the final step in a long construction project. Immediately after the 9-day TVP, the railway will be cleared and officially released for regular train traffic. From this moment, the railway lines between Amsterdam Zuid and Duivendrecht are equipped with 4 tracks.

Integral design

The principle of integral design is applied at OV SAAL, which means different project phases are integrated instead of executed purely sequentially. Three phases can be identified to provide structure to general infrastructure projects. Figure 5 presents the three phases. In the *design phase*, the engineering of the infrastructure project is conducted. As the design phase is not in the scope of this research (highlighted grey), just the output of this phase is relevant. The output of the design phase can be CAD drawings, building plans or 3D models.

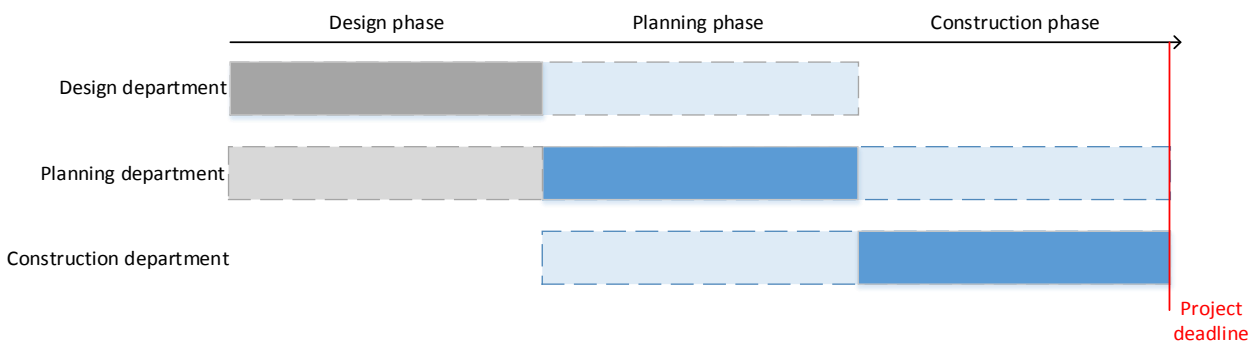


Figure 5: The 3 stages during integral design

During the *planning phase*, BAM prepares the work for the construction phase. The first step in this phase is consulting the output of the design phase, which includes all drawings and technical information. Based on this information, work planners make a conceptual work planning. Next, a single plan is created consisting construction logistics, resources and clashes. Finally, the conceptual work schedule is redesigned to match the logistics and resources. On an iterative basis, this cycle continues until the full plan is ready for construction.

The following planning products are constructed in the planning phase:

- Gantt-charts present all activities executed during the TVP. Activities are presented as bars. Dependencies can be detected by vertical lines between different activities. Figure 6 presents a section of a Gantt-chart of a TVP in January 2015. Appendix B presents a more complete illustration of Figure 6. During the planning phase, different planning departments communicate with the help of these schedules. The critical path in a Gantt-chart is highlighted to emphasise the importance of this sequence of activities.
- Appendix C presents a time-distance diagram. It can be observed that many coloured blocks are in the same location at the same instant in time, which indicates track sections occupied by

multiple activities at the same time. However, this can be caused by a parallel track layout as well.

- Appendix D presents a logistic plan of action for the TVP of January 2015. It includes the position of heavy machinery during several instances of time. This plan is constructed during the final steps of the planning phase by the TVP-coordinator to identify possible clashes in construction logistics.

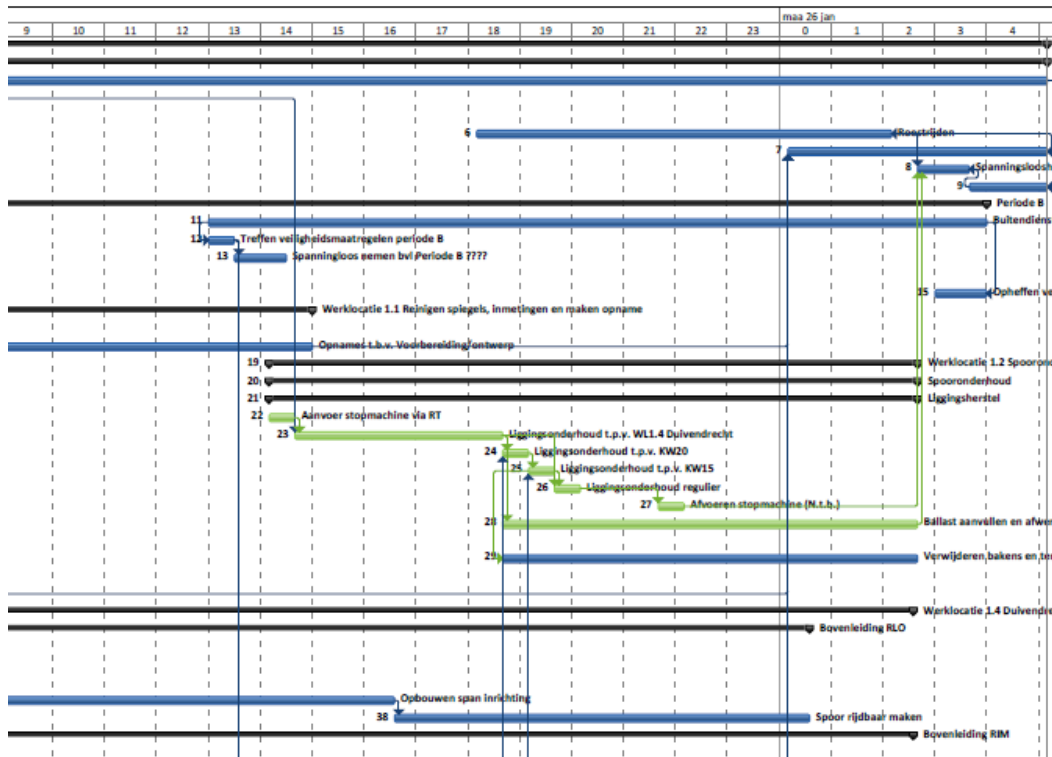


Figure 6: Section of Gantt-chart during a TVP

The construction of a feasible planning consists of more than just clash detection. Possible calamities and major conflicts are investigated and analysed beforehand with help of a TVP-dedicated risk analysis. For each TVP, a risk analysis is executed to predict and manage possible risks related to the construction works. Planners determine for each risk what control measure must be taken to decrease either the probability or expected result. Risks threatening the critical path must be made visible when designing a planning visualization (Van Riel, 2015).

During the *construction phase*, the operational construction work is executed. Based on detailed drawings, logistic plans and the plan of action the construction work starts. As many departments and sub-contractors are involved in different phases of the project, construction site managers coordinate the construction workers and guide the operations.

For OV SAAL Zuidtak Oost, BAM is responsible for the planning and construction. The project planning is roughly split up in 4 departments: Rail, Cables & Pipes (K&L), Track foundation and Civil constructions. Each of these departments is responsible for the construction of a set of elements within the system.

Figure 7 presents the distribution for each of the elements over the departments. Note that for each location during the TVP the involved departments can be different. It can be noted many spatial interfaces exist.

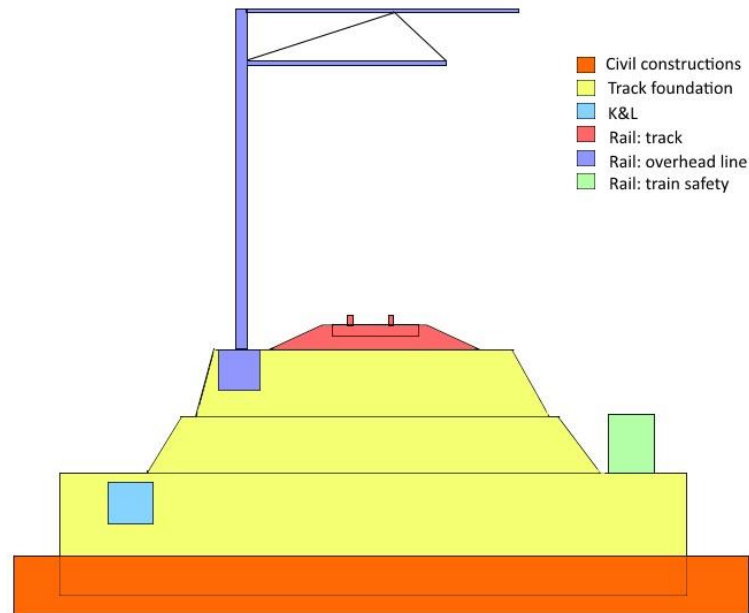


Figure 7: Schematic overview of different possible departments involved during a TVP

Construction logistics

There are many types of goods flowing from origin to destination related to a construction site. All flows of goods can be seen as logistical movements. However, to avoid indistinctness, a working definition is stated. During this report, *construction logistics* can be interpreted as following:

The transportation of necessary material and machinery in which either the origin, destination or path in between is in to the spatial scope of a TVP.

To further specify the scope, Van Riel (2015) and Kardux (2015) state the material logistics related to a TVP are usually not critical and can usually be prepared beforehand. For example, before the start of a TVP all sleepers ('dwarsliggers') are placed next to their final location, which reduces logistic operations during the TVP. The most difficult to plan are the machinery related logistic operations.

Integrating the various logistical plans during a TVP is a complex and time-consuming process. The different departments use a wide variety of, often rail-bound, materials. Three categories of heavy machinery can be identified at a rail building site during a TVP (Immers, 2015):

1. *Fully rail-bound machines* (Figure 8) are heavy material trains and machines, unable to leave the railway tracks. Tamping machines, ballast machines and rail delivery machines cannot operate without the existence of a railway track, as they can only move over the rail. The fully rail-bound

machines are usually diesel-electric powered and thus require no overhead line for operations through the construction site.

2. *Partly rail-bound systems* (Figure 9) are usually light cranes or special trucks able to leave the rail and continue on the regular surface by switching the wheel set. This switch can be done at dedicated rail-access-locations (RIP). RIPs can be quickly constructed and removed when flexibility is necessary.
3. *Non rail-bound machines* (Figure 10) are unable to operate on the railway tracks, and thus operate on the construction roads next to the tracks. These machines can also be used before the railway tracks are constructed. Examples are trucks, shovels, cranes and road rollers.



Figure 8: Tamping machine (BAM Rail, 2012)



Figure 9: Rail crane (BAM Rail, 2012)



Figure 10: Road roller (BAM Rail, 2012)

During a TVP, the construction works done by the different departments require the use of various types of materials. As four working locations are identified during the 9-day TVP, materials and machinery are transported over the complete scope of the system. When transporting rail-bound material and machinery between the working locations, two typical issues are taken into account (De Groot, 2015):

- Fully rail-bound machines cannot leave the tracks. Overtaking is impossible without the use of a switch. As switches are usually present near stations, there exist long sections without an opportunity of trains passing each other. In addition, the direction in which the train is facing is important. Work trains cannot simply 'turn'.
- Demolishing or relocating existing railway track makes it impossible for rail-bound material to travel past a construction site.

In the current situation, each of the planning departments identifies the material and resources necessary for their designed construction works. In integral planning meetings a combined logistic plan and a set of Gantt-charts is constructed to eliminate clashes and design a feasible plan. Chapter 3.3 shows the relations between the different departments related to the TVP.

Delays and risk scenarios

All activities during the TVP can in reality be considered stochastic processes, as the duration cannot be predicted deterministic (Vallentgoed, 2015). For this research it is assumed the duration of all activities is deterministic. During the preparations of a TVP, at least three milestones are defined which need to be completed before the railway tracks can be released back to ProRail. The first milestone is *track safety*, which states the rails must be safe to allow trains on. The second milestone is the *safety signal* milestone, which states all signals and blocks must work properly. The final milestone is the *overhead line safety* milestone, which states the overhead line must work properly.

The defined milestones are leading when a decision about a delay has to be made by a BCU. Figure 11 illustrates the process for a BCU once a construction site manager reports a delayed activity during a phone call. It can be observed extra resources and fall-back scenarios are means that a BCU can call in to avoid delay propagation. A *calamity* is defined as a situation which occurs once a delay results in danger to a milestone. Figure 11 is created based on the set of interviews, and verified by a planner (Immers, 2015).



Figure 11: Flowchart once a delayed activity occurs

During the planning phase, TVP related risks are defined in a risk analysis and scenario analysis. In this risk analysis, only weather related risks are accounted for. Risks as late deliveries, explosives objects and theft of material are not included in the risk analysis (Van Riel, 2015). In addition in the risk analysis, the TVP-coordinator sets up control measures to reduce the risks by either reducing the probability an activity is delayed or by reducing the delay itself. Finally the TVP-coordinator defines several fall back scenarios to guarantee the deadlines are met. These scenarios consist of measures which can be taken

to decrease the construction time, but often deliver only a temporary solution instead of a permanent one. This results in the need for an extra TVP (short) after the main TVP.

The risk analysis and scenario analysis are currently carried out qualitatively. Van Riel (2015) states experts estimate unwanted events and their effects based on expertise and common sense judgement. In addition, control measures and fall back scenarios are qualitatively reasoned and assessed. No quantitative risks analysis or comparison of scenarios is currently carried out. Van Riel states the following needs:

- The effect of unwanted events needs a better evaluation. A quantitative analysis for delay propagation through a planning must be possible.
- The effectiveness of different control measures must be computable and comparable. Both in the planning and construction phase.
- The effectiveness of different fall back scenarios must be computable and comparable. Both in the planning and construction phase.

3.2 Stakeholder analysis

Stakeholders influence the processes and relations of the system. To understand the system and its influencing factors, a stakeholder analysis is carried out. In this part different stakeholders are first identified together with their objective. Combining the interests, attitudes and power results in an interest-attitude-power matrix, which is presented in Appendix E.

Identification of stakeholders

First, the different stakeholders related to the 9-day TVP are identified. For the identification, only the stakeholders relevant for the TVP-system are taken into account. This means stakeholders involved in the planning and construction during the 9-day TVP over the different working locations are considered. Stakeholders can be external, which means they act from outside BAM Combinatie Amstelspoor. Internal stakeholders are part of BAM Combinatie Amstelspoor.

For each of the stakeholders, their type and task is presented. Two different types can be identified:

- Contributors: Stakeholders inside the system boundary that actively participate in the 9-day TVP.
- Influencers: Stakeholders that influence the system from either outside or inside the system boundary

Table 3: Identification of stakeholders

Stakeholder	Type	Internal/ external	Task regarding the TVP
Design team	Influencer	Internal	To answer design related questions resulting from activities in the TVP.
Project planner	Influencer	Internal	To monitor the progress and planning of the overall OV SAAL Zuidtak Oost project.
Planner Rail department	Contributor	Internal	To plan and prepare the work for the rail aspects of the system during the TVP, including the top layer of the ballast

			layer, the sleepers, rails, overhead line and safety aspects. This include necessary materials, machinery and working shifts. Planning departments from <i>all</i> departments communicate with each other to present a feasible planning for each work location.
Planner Track foundation department	Contributor	Internal	To plan and prepare the work for the track foundation aspects of the system during the TVP. Usually the track foundation is finished up front. However, for the locations close to a track in operation a foundation has yet to be constructed in the TVP. To guarantee sufficient building site accessibility by constructing temporary roads for building traffic.
Planner K&L department	Contributor	Internal	To plan and prepare the work for all underground cables and pipes necessary for rail safety and power supply.
Planner Civil department	Contributor	Internal	To plan and prepare the work for all necessary work for the engineering structures. Most construction works regarding the civil structures have already been finished during earlier phases. However, some additional work is sometimes necessary.
TVP coordinator	Contributor	Internal	To ensure a consistent, feasible logistic plan between the different departments per working location. Also on between working locations a feasible logistic plan must be created.
Coordinating construction site manager (BCU)	Contributor	Internal	To coordinate the logistic movements between the different work locations during the construction works. Monitoring the schedule and reacting to disturbances and delays in the time schedule.
Chief construction site manager	Contributor	Internal	To assist the BCU, while travelling between the work locations, with solving non-technical essential problems. Depending on the size of the work locations, there can be multiple chief construction site managers per TVP.
Construction site manager	Contributor	Internal	To coordinate and overview the planned construction works for a specific department and work location.
Foremen	Contributor	Internal	To follow the construction site managers instruction and providing directions for the construction site workers per work location.
Construction workers	Contributor	Internal	To build and construct according to the foreman's instructions.
Emergency decision team	Contributor	Internal/ External	To decide which choices are made when emergencies arise or unsolvable delays occur. Both BAM and ProRail have high placed team members in this team.
ProRail	Influencer	External	To test whether all delivered parts are completed within the acceptance margins of the contract. To guarantee a safe railway track at the end of the TVP, allowing train traffic to run safely at normal operations.
Third party contractors	Influencer	External	To use the TVP to complete construction works in the possessed railway tracks inside or outside of the spatial scope

			of this system.
Integral script meeting	Influencer	External	To integrate the work schedules for all construction companies performing activities inside the OV SAAL project.
Rail safety organization (NVWO)	Contributor	Internal	To guarantee a safe railway track during the TVP. This means making sure regular train traffic can no longer access the work locations. To provide safety instructions for all persons on the construction site.
Neighbouring authorities (GVB, RWS, TenneT, Municipality, Schiphol, NS)	Influencer	External	To keep the nuisance of the TVP as low as possible for their own network and facilities.
Supplier	Contributor	External	To supply deliveries for the construction works. Deliveries can as planned or emergency deliveries.

Appendix E presents the interest-attitude-power attitude matrix for all stakeholders. The output of this matrix is used in Chapter 3.4, where a priority list of risks and efficiencies is determined.

3.3 Information flows

In this section, the information flows between all relevant stakeholders related to a TVP are presented. The design, planning and construction phases as defined in Figure 5 are applicable for any TVP. As this figure presents the just different *phases* related to a TVP, corresponding stakeholders have not yet been defined in this figure. For each of the stakeholders as defined in Table 3, the relations and information flows in the system are defined in Figure 12. This diagram is constructed based on the set of interviews and verified by Van Riel. A clarification of this figure is provided below.

First of all, the system boundary can be observed. Internal stakeholders are located inside the system boundary. External stakeholders are presented outside the system boundaries, but information can flow between internal and external stakeholders. Furthermore, the different phases can be distinguished by a colour difference.

Regular and emergency information

A very clear distinction can be made between two types of information flows. There are *regular TVP information flows*, for which a TVP goes exactly as planned and prepared for. For this type of operations, no emergency decisions are necessary. Once delayed activities cause milestones to be in danger (Figure 11), some regular operations are no longer applicable. Then, *calamity TVP information* is included as information flows during the construction phase.

First, the different information flows between stakeholders are described. Second, for both the planning phase and construction phase a more elaborate description of the different information flows are presented.

The red numbers in Figure 12 explains the 6 most important *regular information flows*. Table 4 presents the regular information flows.

Table 4: Information flow during regular operations

Flow number (Figure 12)	Type of information
1	CAD-models and drawings, 2D and 3D
2	Material and machinery orders, delivery times requests
3	The general project planning, including milestones
4	Gantt-charts per planning department
5	Feasible Gantt-charts, logistical plan, control measures, predefined fall-back scenarios
6	Gantt-chart and drawing per work location per department

The blue letters in Figure 12 present the most important information flows once a calamity occurs. Note, this calamity can *only* occur during the construction phase. Up to number 5 of the regular situation, no calamity can occur as calamities occur during the construction phase.

Table 5: Information flow during calamity operations

Flow number (Figure 12)	Type of information
a	Adjustments to the planning if clashes with 3 th party contractors occur
b	Extra resources orders, changes in orders or special delivery requests.
c	Requests to implement or change measures or timetable.
d	Notification of incidents, state of the system and expected time of completion of construction works
e	Expected time of completion of construction works
f	Updated schedules and priority activities

Design phase

The design team represents the start of the information flow in preparation of a TVP. The client presents a set of design requirements to the design team. The design team creates a design in CAD-drawings and 3D models based on the design requirement. Feedback from the planning phase may result in changes in the design (Bodegom, 2015a).

Planning phase

The planning phase starts with a set of CAD-drawings or 3D models that are transferred from the design department to the planning departments (**flow 1**). In addition, the overall project planner presents the global project milestones to the planning departments (**flow 3**). The first step is determining whether a TVP is necessary to complete the construction works. Once this is decided, each of the different departments constructs a feasible internal planning and synchronizes this per working location with the other planning departments. These feasible plans, presented as Gantt-charts, are transferred to the TVP-coordinator (**flow 4**) (Thole, 2015). In addition, the planning departments order and schedule material deliveries with (external) suppliers (**flow 2**). Internal and external machinery availability is assessed to match to the proposed schedule as well.

The TVP-coordinator checks whether the charts *per working location* are indeed non-conflicting. Simultaneously the TVP-coordinator checks the feasibility of the planning between *all* BAM working locations. This includes manual checking of the Gantt-charts and if transportation of materials and machinery can be done without conflicts.

The TVP-coordinator regularly meets with the integral script meeting, which are external contractors also planning to perform construction works. During this meeting the different construction schedules are synchronized to eliminate any possible interfaces, e.g. working trains or material deliveries traveling through the site when it is occupied by a different activity. In addition, the TVP-coordinator agrees with neighbouring authorities as Rijkswaterstaat (RWS), Schiphol and the Gemeentevervoerbedrijf (GVB) to eliminate conflicts with these parties (De Groot, 2015). During the planning phase, the chief construction site manager assists the TVP-coordinator with expert judgement on feasibility of the planning schedules.

The TVP-coordinator presents a feasible time schedule as well as a construction logistics plan to the BCU.

Construction phase

During the construction phase, the BCU is the link between the different construction site managers working at the construction site at different location. In addition, the BCU monitors the overall planning during a TVP. First, the regular operations are discussed. Then, for calamity situations the operations are discussed.

Regular operations

'If a TVP goes as planned, a BCU can sit back and relax for a full shift' (Immers, 2015). During regular operations, the information flow from the TVP-coordinator (**flow 5**) provides sufficient information for the BCU to prepare each of the construction site managers with a planning and drawing per discipline

(flow 6). Every 2-4 hours, the BCU calls the construction site managers to obtain information about the state of the construction works and if the project is still on schedule.

The NVWO is the organization responsible for the track safety during the construction site. The BCU and NVWO are physically in the same location during the TVP (Site visit TVP 12 April, 2015), which allows fast communication.

Calamity operations

If a delay occurs and the information flowchart of Figure 11 show there is a danger to a milestone, a calamity situation occurs. In addition to the regular operations, extra calamity operations are started to prevent failing the final deadline. In Figure 12 the blue numbers represent the calamity information flows. As the BCU is the building coordinator, he organises the initial start-up of a calamity scenario.

First, a BCU decides with the construction site manager if the delay can be settled by ordering more resources (flow b). If this is not the case, predefined fall-back scenarios are investigated for effectiveness by the BCU, based on expertise. The Emergency Decision Team is notified if the delay cannot be settled within the buffer time (flow d, flow f). This team decides what measures must be taken to achieve the best solution for that specific situation. If the decision affects the scheduled deadline, ProRail is notified (flow e). If a delayed activity or a corresponding affects 3th party contractors or neighbouring authorities, the BCU contacts the corresponding stakeholders with relevant information or requests (flow a, flow c).

3.4 Risks and inefficiencies

With the activities and stakeholders identified in the current situation, causes for risks and inefficiencies are identified. During each of the 18 interviews, interviewees were given the opportunity to name risks and possible inefficiencies that occur because of the use of the current planning methods. After combining similar answers, a set of resulting causes of risks and inefficiencies is presented in Table 6. This table presents the number of times a cause is named. Different stakeholders, depending on their role in the system, emphasise different risks and inefficiencies. The 6 highest ranked risks and inefficiencies are clarified after the presentation of the table.

Table 6: Identified risks and inefficiencies

Risk / inefficiency	Number of times names
Early clash detection (state-based)	10
Overall overview	9
Early clash detection (activity-based)	6
Plans become unclear as complexity increases	5
Scenario analysis limitations	4
Construction logistics	3
Spatial dimensions of environment	2
Unclear effects delay propagation	2
Accessibility on-site construction manager	1
Link geometrical dimensions vs. planning	1
On-site conflict solving (via BCU)	1

Clash detection (state-based and activity-based)

Clash detection concerns the interfaces during the planning construction phase of the TVP. Location and time within the scope of the system can be common boundary between multiple departments. The principle of clash detection is to identify possible conflicts of interest between different planned activities (Vuist, 2015). These conflicts or clashes can be state-based, where the sequence of construction steps causes clashes. Clashes can be activity-based as well, which describes multiple activities simultaneously occupying a location. Figure 13 presents a graphical representation of an activity clash. Figure I and II present non-problematic situations, as there is a clash-free dimension. However, figure III clashes in both in the spatial and temporal dimension, and thus results in a possible operational problem. Using only Gantt-charts, clashes (as presented in Figure 13.III) are not detected in an early stage or not detected at all (Bodegom, 2015a). An in-depth study in the different types of clashes is conducted in section 7.1.

Risk: Clashes get detected during the construction phase of the project, which results in high failure.

Inefficiency: Departments individually include spare time in the construction planning, as they are unable to correctly detect clashes and thus make a conservative estimation.

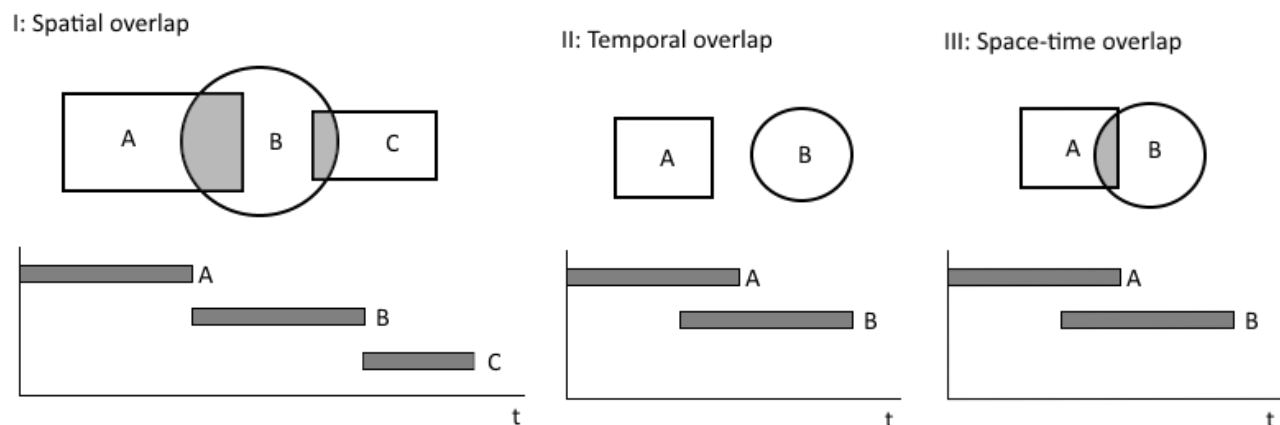


Figure 13: Different types of overlap

Complexity

The planning schedule becomes unclear as the project complexity increases. With increasing complexity of the project, the amount of tasks in the Gantt-chart results in a loss of overview for the complete plan. In addition, the critical path can become less visible (Aerts, 2015). The dependencies between different activities can become hard to identify as the planning becomes too complex. Reducing the size of the Gantt-chart by grouping certain activities can result in omitting important information.

The principle of *optimism bias* causes planners to underestimate project risks when these are hard to identify (Flyvbjerg, Glenting, & Ronnet, 2004). Flyvbjerg et al. found that reducing project complexity allows decision makers to make a well-considered decision and reduce the optimism bias.

Risk: Planners and construction site managers cannot deduct the correct information from the Gantt-chart resulting in faulty risk estimation and thus in failure costs.

Overall project overview

An integral overall overview for all stakeholders in the project is currently absent. The separate departments know their precise planning schedule but are unaware of the other departments' schedules (De Groot, 2015). Stakeholders which are not involved in the planning departments (MT, BCU) are insufficiently able to understand the overall overview of the construction works. A connection between the planning and the geometrical dimensions is missing, which makes it even more difficult to get a good overview. Especially for users not deeply involved in the extensive coding system, the link between the planning and spatial component is difficult to make.

Risk: Decision makers in the system are unable to make fast and substantiate decisions as the overall overview is absent. Bad and late decisions can lead to failure costs.

Inefficiency: Conservative estimations result in unnecessary time buffers in the planning.

Scenario analysis limitations

A scenario analysis assists in testing different possible scenarios and the consequences for the feasibility of the planned schedule. Currently, this analysis is carried out qualitatively (Van Riel, 2015). A group of experts analyse the different possible scenarios during a TVP, and discuss if control measures are necessary to reduce the risks. The qualitative scenario assessment relies fully on expert knowledge and not on decision-making assisting software. The effect of the delays caused by the occurrence of incidents is currently causing a risk. The propagation of the delay through the system is considered in a qualitative manner.

Risk: Failure costs can be high if a risk occurs and resulting delays are inadequately accounted for beforehand.

Real-time construction logistics

During the construction phase of a TVP, most heavy machinery is transported by rail. Transport over rail is dependent on the state of the construction works, so delays in activities may result in unavailable tracks for the transport of materials or machinery (De Groot, 2015). A BCU must determine logistic problems and decide on train priority if unexpected events disrupt the planning. Currently, the BCU has limited information about the both the track availability as well as the exact location of trains within the scope.

Risk: The BCU makes a bad decision regarding train routing and priority, resulting in delays in the critical path of construction works and thus failure costs.

Inefficiency: The BCU chooses a non-optimal solution, resulting in inefficient operations.

Real-time delay propagations

During the construction phase of a TVP, activities can deviate from the scheduled time. Depending on the location in the planning, there can be major consequences of any delayed activity. In the current

situation, the BCU decides for small deviations from the schedule what actions must be taken to avoid further delays. If severe delays occur on the critical path or severe disruptions are expected, the Emergency Decision Team decides what measures must be taken to avoid further delay propagation. Both the BCU and the Emergency Decision Team base their decision on expert opinion.

The difference with the aforementioned *scenario analysis limitation* is the moment in time when the risk can be avoided. The scenario analysis can be conducted during the *planning phase* to detect possible scenarios and prepare control measures if necessary. The real-time delay decision-making is related to the *construction phase* in which delayed activities threaten the deadline. The objective of this decision is minimize failure costs (Aerts, 2015).

Risk: Bad expert decisions about delayed activities during high pressure phases of the TVP can cause high failure costs.

Summary Dym & Little Stage 1

The first part of this research defines the problem as initially stated by BAM Rail. A set of 18 interviews with different stakeholders provides the basis for this stage.

OV SAAL is a major rail construction site for which BAM executes a rail extension from 2 to 4 railway tracks over section between Amsterdam Zuid and Duivendrecht. Rail possessions (TVPs) are necessary to facilitate a safe working environment for the construction workers. TVPs are time critical and require a well prepared, unique type of planning. The planning methods problem owner BAM Rail currently uses are primarily Gantt-charts and time-distance diagrams. Insufficient insight in the planning is obtained from these methods. The problem statement of this research is defined as:

The planning methods BAM Rail currently uses provide insufficient insight into the state of the line system at each time user defined step during the construction phase. Also the interdependency of activities and how delays propagate spatially and temporally across the system is essential but currently not available in high detail. In addition, the construction related logistics cannot be visualized in the current situation.

The main research question for this research is defined as following:

How can BAM Rail get insight into the state of the construction works at a line construction site at each time step?

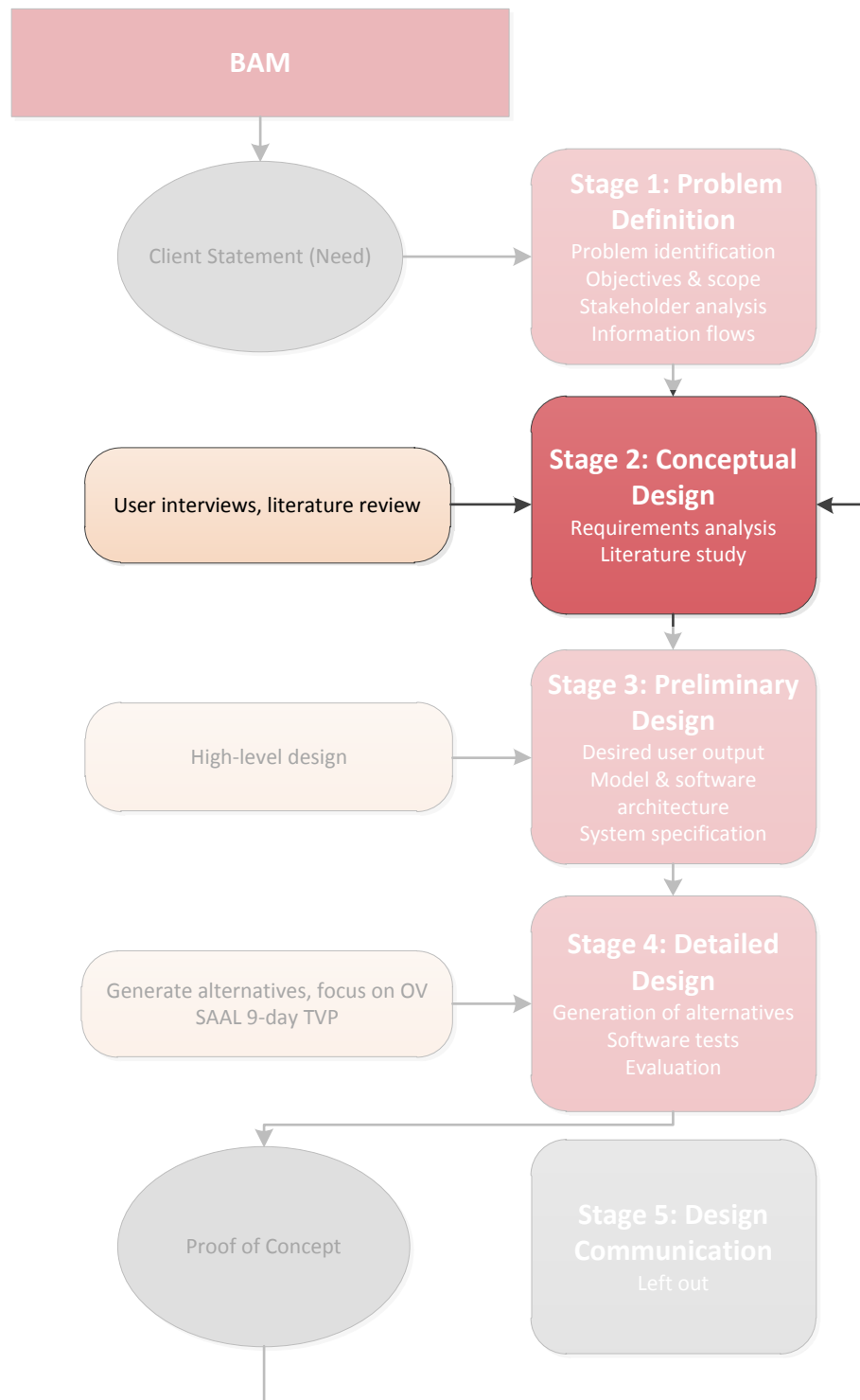
Dym & Little (Dym & Little, 2008) present a five-stage descriptive design model which is used to give structure to the design process in this research.

Following, the current situation is researched. Three phases can be distinguished to a TVP: design phase, planning phase and construction phase. The construction works are planned during the planning phase and executed in the construction phase. In a Gantt-chart, planners define the activities. A stakeholder analysis is conducted to identify tasks of types of the stakeholders during the TVP preparation. The TVP-coordinator and BCU are considered as key stakeholders. After the stakeholder analysis and presentation of the information flows through the TVP preparations, a more thorough identification of the risks is presented. A set of 6 main causes of risks and inefficiencies are identified resulting from the current situation in the TVP planning process:

1. *Absence of clash detection*: clashing activities or invalid state sequences are left unidentified in the planning phase, resulting in failure costs during the construction phase.
2. *High project complexity*: Gantt-charts become too complex to comprehend, resulting in experts making mistakes when creating planning schedules.
3. *Missing project overview*: no basic site overview is available, resulting in non-expert decision makers making wrong decisions.
4. *The impossibility to perform a scenario analysis*: this results in failure costs as no control measures and fall back scenarios can be quantitatively analysed.
5. *The impossibility to show construction logistics real-time*: train paths and machinery locations are unknown, resulting in failure costs when making operational decisions.

6. *The impossibility to determine delay propagations real-time:* measures to settle delayed activities cannot be quantitatively analysed real-time, resulting in failure costs when making operational decisions.

DYM & LITTLE STAGE 2: CONCEPTUAL DESIGN



4. Requirements analysis

Risks and inefficiencies were identified in previous chapters. During the next step, a set of requirements and wishes can be constructed. First, user requirements are formed by combining information derived from the stakeholder analysis and the identified risks & efficiencies. During the requirements analysis the wishes and requirements are analysed, transformed and weighted with help of the stakeholder analysis.

The transformation into system specifications is conducted in a later stage of this research: Chapter 9.

Definition

Many interpretations of the concepts *requirement* and *wish* exist. During this research, a requirement is defined as a functional need a particular design must be able to perform. If the functional or physical need is preferred in a system, it is referred to as a wish (Systems Engineering Working Group, 2009). Even though wishes are often organised as a type of requirement, the function of a wish is different. This difference is applied in this thesis as well.

Abran, Moore, Bourque, & Dupuis (2004) present a suitable framework which assists in the process of transforming from a first set of stakeholder requirements to system requirements. The framework focusses on the transformation, classification and prioritization of requirements. The three main goals of this method are as following:

- Detect and resolve conflicts between requirements.
- Discover the boundary of the end product and how it must interact with its environment.
- Elaborate system requirements to derive software specifications (Chapter 9).

4.1 Transformation of requirements

First of all, the concepts of *user* and *customer* need to be defined to allow a requirements classification for this research. Abran et al. (2004) present the following definitions:

- *Users*: This group comprises those who will operate the software. It is often a heterogeneous group comprising people with different roles and requirements.
- *Customers*: This group comprises those who consult the output of the software.

Both the BCU and TVP-coordinator can be identified as *users* of the new visualization method. The *customers* of the new visualization method are the different planning departments, chief construction site managers and the emergency decision team. The other stakeholders in the stakeholder analysis which can neither be identified as user or customer are identified as *miscellaneous stakeholders*.

The transformation of requirements consists of two subsequent activities:

1. *Eliciting requirements* is the practice of collecting the requirements from users, customers and other stakeholders. For this research, the sources of this step are stakeholder interviews, user observations and brainstorming. The result of this step is a first unorganised set of requirements.

2. *Analysing requirements* is the process of transforming the stated requirements to be clear, complete, consistent and unambiguous, and resolving any apparent conflicts. A categorization is part of this step as well.

4.2 Requirements

The first step in the requirements analysis is the *elicitation* of requirements. During the interviews, site visit and brain storming a first set of requirements is conducted and presented in Appendix F. This unorganised set is still yet to be classified, made conflict free and prioritised.

The second step in the transformation of requirements consists of an analysis of the requirements. Requirements can be categorized in different categories (Abran et al., 2004). The requirements are categorized depending on the type of requirement and the stakeholder that has stated the requirement. The *first* step in categorization of requirements is the type of requirement. Three types can be distinguished:

- *Functional* requirements describe the functions that the visualization method has to perform.
- *Non-functional* requirements regard the quality of the system performance and output.
- *Interface* requirements are requirements that allow the system to interact with its surroundings, including software packages.
- *Wishes* are included as a type of requirement, however they have a different function. The line between a wish and a requirement is vague when developing a new concept. Stakeholders name requirements in many different fields and are aware of the possibility not all requirements are included in the visualization method. Wishes therefore present the low priority requirements.
- *Institutional* requirements refer to legal institutes or authorities.

The *second* step is prioritizing the requirements based on the weights resulting from the Stakeholder Power-Attitude-Interest matrix as presented in Appendix E. Then, for each of the requirements the phase in which the requirement is applicable is determined, which can be either the planning phase, construction phase or a combination. The final step in the categorization is to determine from which higher-level requirement each requirement is derived. There are 6 higher-level requirement classes identified: Clashes, construction logistics, delays, spatial overview, user interface and miscellaneous.

The process of transforming all requirements is presented in Appendix G. The final set of processed requirements are presented in Table 7.

Table 7: Set of requirements

#	Requirement	Type of owner	Type label	Class label
Top	<i>The model must present a spatial representation of a Gantt chart</i>	<i>Customer/ user</i>	<i>Functional</i>	<i>TOP</i>
1	<u>Clashes must become visible</u>	<u>Customer</u>	<u>Non-functional</u>	<u>Clashes</u>
1.1	Activity-related clashes must become visible	Customer	Non-functional	Clashes
1.2	State-related clashes must become visible	Customer	Non-functional	Clashes
1.3	A planning projected as feasible must actually be feasible	User	Non-functional	Clashes
1.4	Clashes defined by institutions (ProRail, municipality) must be included.	Customer	Institutional	Clashes
1.5	It must be possible to include user-defined spatial and temporal activity margins	Customer	Functional	Clashes
1.6	All clashes must be detected automatically	Customer	Functional	Clashes
2	<u>Construction logistics must be become visible</u>	<u>User</u>	<u>Non-functional</u>	<u>Construction logistics</u>
2.1	Train route availability must be visible	User	Functional	Construction logistics
2.2	Track occupation must be visible for each spatially decomposed rail section	User	Functional	Construction logistics
2.3	The availability to perform activities at each location must be visible	User	Functional	Construction logistics
2.4	Train routes must be visible	User	Functional	Construction logistics
3	<u>Risk scenarios must be implementable and tested beforehand</u>	<u>Customer</u>	<u>Functional</u>	<u>Delays</u>
3.1	Generated scenarios can either be deterministic or probabilistic	Customer	Functional	Delays
3.2	It must be possible to compare different scenarios on performance indicators, both in planning and construction phase	Customer	Non-functional	Delays
3.3	Fall-back scenarios must be tested and compared in the visualization model	User	Functional	Delays
3.4	Delays resulting from an occurring risk must be visible	Customer	Functional	Delays
3.5	When alterations in the planning are done, availability of resources (real time) must be included	User	Functional	Delays
3.6	Activities on the critical path must always be visible in the model	Misc.	Non-functional	Delays
4	<u>The lengths of the spatial overview should be on scale</u>	<u>User</u>	<u>Non-functional</u>	<u>Spatial overview</u>
4.1	A user must be able to insert a spatial decomposition of the system	User	Functional	Spatial overview
4.2	Spatially complex situations must be made understandable (e.g. by using colours)	Customer	Non-functional	Spatial overview

4.3	The lengths of all items, including material, machinery, tracks and work locations must be on scale	User	Functional	Spatial overview
4.4	The surrounding environment (roads, water, infrastructure) must become visible and spatially on scale	Customer	Functional	Spatial overview
4.5	There must be a zoom function in the spatial overview	User	Functional	Spatial overview
4.6	An implementation of CAD drawings from the design department must be implementable	Customer	Interface	Spatial overview
5	<u>The output of the model must be understandable by stakeholders without the knowledge of all planning encoding</u>	<u>Customer</u>	<u>Non-functional</u>	<u>User interface</u>
5.1	The output of the model must be understandable by stakeholders without the knowledge of all spatial encoding	Customer	Non-functional	User interface
5.2	The existing planning and CAD software must be integrated so no 'double work' is necessary	User	Interface	User interface
5.3	A simulated time visualization must be possible, both in <i>helicopter view</i> as well in zoomed view.	User	Non-functional	User interface
5.4	A simulated state representation of each track section in time must be presented	User	Non-functional	User interface
5.5	Gantt-charts with many bars must be visualised clearly, so the spatial overview per section can be guaranteed	Customer	Non-functional	User interface
6	<u>The spatial decomposition must be defined in the design phase of the project</u>	<u>Customer</u>	<u>Interface</u>	<u>Miscellaneous</u>
6.1	A protocol must be included so there can be no confusion about the most actual version	Customer	Non-functional	Miscellaneous
6.2	The model must be robust and redundant, to make sure it is always functional during a TVP.	Misc.	Non-functional	Miscellaneous
6.3	It must be possible to link resources to activities	Misc.	Functional	Miscellaneous

Furthermore, a set of wishes is defined based on the low priority requirements. These wishes do not span an initial solution space as the requirements do, but can be used in a later stadium when comparing design alternatives.

Table 8: Set of wishes

#	Wish	Type of owner	Type label	Class label
W2.1	The model must be able to keep track of resource information for the current situation as well as the short future.	User	Functional	Construction logistics
W2.2	Cranes, trucks and heavy machinery should be real-time visible	User	Functional	Construction logistics
W2.3	Road access routes and RIP must be visible	Customer	Functional	Construction logistics
W2.4	Logistical operations must be visible for complex time windows	User	Functional	Construction logistics
W2.5	Potential locations of access roads and RIPs must be	Customer	Functional	Construction

	analysable			logistics
W3.1	Re-planning must be possible and made visible in the model	Miscellaneous	Functional	Delays
W5.1	Incidents must be easy to register for construction site managers	Miscellaneous	Functional	User interface
W5.2	Safety checks must be easy to register for safety testers	Miscellaneous	Functional	User interface
W5.3	Activities must be completed with a single checkbox in field to monitor progress	Miscellaneous	Functional	User interface
W5.4	Object coding agreements must be implemented when spatial and temporal dimensions are connected via a unique coding system	Miscellaneous	Interface	User interface
W5.5	A work protocol must be included in the visualization model	Miscellaneous	Non-functional	User interface

The functional requirements can be sorted by five high-level system functions: *clash detection*, *moving activities*, *state representation*, *scenario analysis* and *software integration*. During the implementation in Dym & Little phase 4, these functions are referred to.

Conclusion

A first set of user requirements as presented in Appendix G is transformed into a set of system requirements as presented in this chapter. Six classes of requirements are defined: Clashes, construction logistics, delays, spatial overview, user interface and miscellaneous. The complete set of requirements spans a solution space for a high-level design. The literature review presented in the next chapter researches for state of the art solutions in the spanned solution space.

5. Literature review

Key search words: construction logistics, linear projects, construction planning software, construction site planning, workplace management, construction scheduling, construction site visualisation, BIM, GIS, concurrent engineering, Gantt-chart spatial visualization

Now a set of requirements is presented, literature can be consulted as the final step before the high-level design. The identified problem statement is not only recognised by BAM. Planners in the global construction industry rely on their experience, judgement, intuition and imagination to make planning and construction decisions. It is often noted in literature that support tools can be of practical help to planners and site management. This chapter presents a literature study which explores the current state of construction management related visualisation methods. First, the traditionally used methods and tool are described and discussed. Then, trends in the application of new methods is discussed. In addition, a preliminary step towards analogue industries is taken, to observe expertise from a different work field. Finally, a conclusion of the literature review is presented.

5.1 Traditional planning methods

First mentioned in 1985, Karima, Sadhal and McNeil (1985) pointed out the large potential of CAD-drawings for the architectural, engineering and construction industry. With CAD systems focussing on

geometrical dimensions, complex interfaces could be detected in an early stage. No integration between CAD-drawings and planning tools existed yet, as the design phase of a project was separate from the planning and construction phases.

Traditionally-used construction planning methods are Gantt-charts, Program Evaluation and Review Technique (PERT) and the Critical Path Method (CPM) networks. These methods describe and analyse the schedule of a construction project (Koo & Fischer, 2000). However, these tools do not provide any information regarding the spatial context and complexities of project's components. Therefore, users must use 2D and 3D drawings or models to conceptually associate the components with the project planning. Because CPM or PERT networks are an abstract representation of the project schedule, users need to interpret the activities to comprehend the sequence they convey. This presents two practical limitations of the methods (Koo & Fischer, 2000):

- First, there may be hundreds of activities in a planning (Vuist, 2015) which makes it difficult to comprehend and identify relations between different activities or groups of activities. In addition, checks for correctness of the schedule and clashes are difficult.
- Second, different project members may develop inconsistent interpretations of the planning when viewing the CPM-network and Gantt-charts.

Tory et al. (2013) identify two additional limitations related to complex scheduling.

- First, traditional methods graphically represent the timing of constraints but not their type. Consequently, when reviewing a schedule, it is difficult to understand why a constraint exists and when it is applicable. Incomprehension often leads to misuse and failure costs.
- Second, there is no possibility of comparing schedule alternatives. Current tools focus on one schedule at a time, making it difficult to create and compare alternate versions to see which is most suitable. However, there is little visual support for exploring and comparing different alternatives. This includes the beforehand evaluation of pre-defined fall back scenarios.

The integration of three-dimensional geometrical models with a construction schedule proved to be a useful alternative for the traditional project scheduling methods (Chau, Anson, & Zhang, 2004; Koo & Fischer, 2000; Heesom & Mahjoubi, 2003). Each of these researches coupled a 3D model with a time dimension. The resulting four-dimensional (4D) models enable more people to understand a schedule more quickly and identify potential problems. By designing a 4D model, the state of the construction site at any user-specified moment in time can be generated. Chau, Anson & De Saram (2005) showed: "4D visualisation could be strategically used by site management for progress visualisation and presentation, locating equipment, analysing craneage times, checking access/openings for equipment, storage visualization, co-ordination of subcontractors and possible clashes of trade."

5.2 BIM

More recently, the concept of Building Information Modelling (BIM) is rapidly gaining more popularity. First introduced by Van Nederveen and Tolman (1992), BIM facilitates different participants to have a specific view on a building project. With help of the use of *aspect models*, specific information could be stored in a building model. Nowadays it can be described as an accurate visual digital model, which

supports the design and construction through its phases, allowing better analysis and control than separate, manual processes (Eastman, Teicholz, Sacks, & Liston, 2011).

BIM is an object-oriented method in which attributes as cost, building time or failure rate can be assigned as metadata to different objects in a system (Eastman, Teicholz, Sacks, & Liston, 2011). BIM is considered to be a general principle to assist different actors in the process of building and construction. 4D models as described by Koo and Fischer (2000) and Kamat and Martinez (2001) are early adaptations of the present day BIM trend. An *example* of a BIM model is a 3D building model built from objects. Objects can be grouped, and each of the (group of) objects can have meta information enclosed in its properties.

An application as BIM is by most authors considered as early clash- and conflict detection in the geometrical dimensions. A link towards planning, cost and construction logistics is rarely present. The implementation of using BIM for planning and logistics is best presented by Chau, Anson, & Zhang (2004). They present a 4D visualization model that is intended to help construction managers plan day-to-day activities more efficiently in a broader and more practical site management context. MS Project and AutoCAD are used for respectively the planning and geometrical visualisation.

When a time dimension is added to a 3D geometrical model, additional problems arise. Four problems are listed based on Koo and Fischer (2000), Eastman, Teicholz, Sacks, & Liston (2011) and Chau, Anson, & De Saram (2005):

1. *Consistency of Level of Detail (LoD) of schedule.* For each planning a different level of detail is desirable. An overall master schedule should not describe every small activity, but should have only primary activities related to the milestones. As each object in the model will be linked to an activity in the schedule, the level of detail should be similar. However, the *desired* LoD can be different for both planning and geographical model.
2. *Errors in activities in the schedule.* It is critical for planners that each object in the geographical model is associated with an activity. Confirming whether all associations exist can be a time consuming process. If objects are not linked to an activity, they may not appear and thus giving a false state of the system. BAM BIM-modeller Erik Alink (2015) emphasized this problem.
3. *Problems related to time-space conflicts.* When creating or evaluating the planning, the planning department must ensure construction workers have sufficient space to execute their work. In addition, material and machinery can cause problems.
4. *BIM tools are difficult to difficult use.* Tool complexity is an issue when using BIM models, as the input data and the time involved for preparing that data is usually short (high pressure decisions). Extensive 3D models can have 4000+ elements in 100+ layers, which requires time to link to activities.

5.3 GIS

Since difficulties in railway construction works are usually in the 2D surface (Kardux, 2015), a 2D plane of the surface of the construction area is sufficient to comprehend BAM's construction works. Literature states object oriented 2D geometrical BIM can be applied when a 2D overview is used. However,

additional schools of thought exist. Geographical Information System (GIS) is a different discipline suitable for this research.

GIS was originally designed as a system to capture, store, analyse, manage, and present all types of spatial or geographical data. Data is stored in databases, and can be projected as layers in the presentation context. GIS can consider buildings and construction as information in a geospatial context (De Laat & Van Berlo, 2011). In addition, GIS uses different layers, all calibrated at defined coordinates. Figure 14 presents an example of a GIS representation.

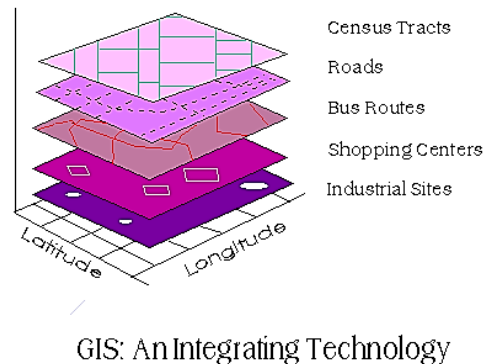


Figure 14: Representation of a GIS system (Foote, 1995)

ProRail, RWS and other authorities use GIS to keep a central database to manage their infrastructure networks (Moons, 2015). Each of them preserves different layers of their network, specified to a certain location. As GIS data focusses on a 2D geo-location, the only link with the object oriented BIM is based on the coordinates (De Laat & Van Berlo, 2011). They state that especially when the surrounding area of a construction is of importance, integrating GIS models in BIM can be a solution. Irizarry, Karan, & Jalaei (2013) integrated BIM and GIS to improve the visual monitoring of construction supply chain management. They present a model used for combining locations for material storage (GIS) on linking all elements in the CAD model.

It is possible for users to implement extra layers in a GIS model. The objects in the layer are either vertices, edges or polygons and are all described by a coordinate system. In addition, a time dimension can be implemented in a certain layer to make objects appear, disappear or change status at a certain moment in time. The implementation of a time dimension has been applied before (Bansal & Pal, 2008). The focus of this research was on the implementation of the 3th geometrical dimension in a GIS system, but proved a layer based approach provided a solution for planning visualization problems. This makes the application of GIS with an additional time dimension for these problems a possible solution.

5.4 Miscellaneous methods

Apart from focussing on the aspect to enhance the visualization of construction schedules, presenting a different type of Gantt-chart can be done as well. Tory et al. (2013) present the *TASM* tool (Tool for Advance Schedule Management), which is designed to address the limitations of Gantt charts. TASM uses line colour, line style and different icons to represent different constraints in the schedule. In

addition, extra highlighting is implemented to represent network chains in the schedules. Dependencies per activity can be easily observed with different colour lines (Figure 15). However, the TASM method does not incorporate a spatial component. The requirements state a spatial component must be included in the visualization method. Thus, the TASM method is not included in this section.

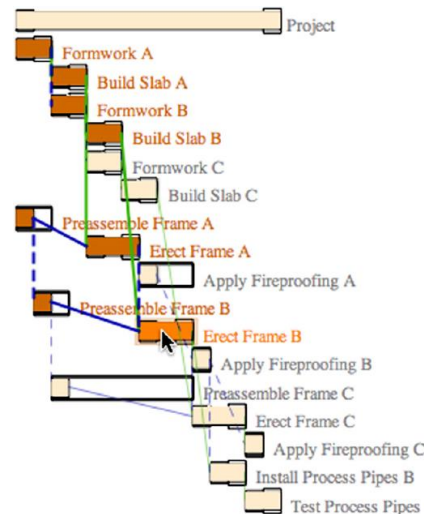


Figure 15: Highlighting network chains to reveal that an activity's timing is flexible. (Tory, et al., 2013)

5.5 Construction logistics

Construction logistics is a general principle in literature. For this research, the aspect of workplace planning and management is reviewed in literature. Workplace planning focusses on how construction site managers can make optimal use of the workplace of the construction site. In literature a construction site is often considered as a 2D plane in which multiple objects (cranes, storage, etc.) need a location. The optimal layout is computed by an object function and a set of constraints (sources). The linear characteristics of a rail focussed project are not yet published in literature. However, useful aspects can be observed in existing researches.

Within the workplace planning and management a two way division can be made: workplace *optimization* and workplace *visualization*. Most studies in optimization often present an algorithm where an object function is solved, while constraints are implemented to represent the different set of dimensions. This can include budget, maximum time for available machinery, construction workers or shift. The field of optimization is different from the field in visualization. In visualization the main objective is not to solve an optimization algorithm, but to present an oversight of the workplace in order to assist decision makers in making the schedule. As the objective of this research is *increasing the planning overview*, the focus of this chapter is on the visualization papers rather than on workplace optimization literature.

Dawood & Mallasi (2006) developed a critical space-time analysis (CSA) approach that was to model and quantify workspace congestion. A tool called PECASO (patterns execution and critical analysis of site space organization) is developed to assist site managers in the assignment and identification of workspace clashes. A new concept of “visualizing workspace competition” between the construction

activities is presented based on a unique representation of the dynamic nature of activities within the construction site, in 3D space and time. PECASO is able to use 4D visualization and highlights the critical space control aspect to formulate an innovative 4D space planning and visualization tool.

5.6 Analogue industries

The railway construction industry differs from other industries for reasons presented in Chapter 1.1. However, there are analogue industries with similar characteristics. This section presents solutions for similar problems in highway construction. In addition, the principle of concurrent engineering is researched.

Highway construction

The highway industry can be considered as a layer-based, linear construction industry as well. Furthermore, road construction possessions are used to guarantee no traffic is allowed for a limited time span to allow a safe working environment for construction workers. The need for a 3D visualization in highway construction originates at the geometrical complexity of highways (Liapi, 2003). However, the implementation of a time dimension (4D) for a highway construction project is little referred to in literature (Hassanein and Moselhi, 2004; Zanen, Hartmann, Al-Jibouri, Heijmans, 2013). Reasons there is no demand for a planning visualization model can be:

- The logistical operations for highway construction industry is not as complex as for rail construction sites. There is sufficient space for heavy machinery to pass and turn. In addition, machinery can use the unfinished product to move. This is impossible for rail-bound machines during railway construction sites.
- Highway possessions only occur on rare occasions for highway construction work, and thus the demand for a better visualization is low.
- Contractors are considered pragmatic and often make no record of activities or best practices.

Hassanein and Moselhi (2004) present a planning optimization algorithm for highway construction planning. Their model automatically generates the work breakdown structure (WBS) and corresponding network, while respecting both job logic and stores a list of construction operations typically encountered in highway projects. As this model is focused on optimization, a database with resource availability is at the core of this model. One interesting aspect in this paper is the application of weather influences in the model. The proposed weather model considers precipitation, temperature and wind speed as independent variables to compute the duration of an activity.

More recently, Zanen, Hartmann, Al-Jibouri, Heijmans, (2013) present a visualization method to show the impact of delays in highway construction. In order to manage these impacts, gaining an in-depth understanding about the space and time dimensions of a project is crucial. To support planners with understanding a highway construction project's impacts upfront, a 4D modelling method is developed that visualizes important attributes and the effect on different stakeholders. The spatial dimensions and the progression over time are included in the model.

Concurrent engineering

Concurrent engineering is a methodology based on the parallelization of operations. Instead of sequentially executing a series of operations on a complete object, concurrent engineering integrates different sequential operations to reduce throughput time. A formal definition is presented by Winner et al. (1988): “Concurrent Engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including, manufacturing and support.”

Concurrent engineering can either be applied on the design concurrency or on the operational concurrency. This review focusses on the operational concurrency. Essentially, construction works during a TVP can already be classified as concurrent processes. Swink, Sandvig & Mabert (1996) investigated for five large construction companies how concurrent engineering is applied. They found for all five companies, including Boeing and Texas Instruments, concurrent engineering was applied during the *design* process of new products. However, no information about the concurrent *operations* is available. In addition, it is noted concurrent engineering can save costs for non-unique products (airplanes, calculators, e.g.). As each TVP is considered unique, no specific focus on concurrent engineering is done.

The pipeline construction industry and the coal mining industry share characteristics as linearity and repetitive segments. However, no similar problems were identified in literature which lead to new insights for this research.

5.7 Gap in literature

The literature review suggests no ready-to-use software package is available for the objective for this research. Planning software packages as MS Project and Primavera P6 allow users to create and optimize complex planning schedules. BIM and GIS software can link these schedules to spatial components up to a certain level. However, neither of the two can directly be used for TVP planning schedules. A gap in both literature and software exists. This section focusses on the reason for this gap.

Many software packages are available on different aspects of project management. ProCore, Primavera P6, Relatics and SYNCHRO are examples of packages focusing on information management, data management, resources planning or document control. These software packages have a wide application scope. When focusing on operational planning software, almost without any exceptions software packages present Gantt-charts as an output. Only one software package can produce time location diagrams as an output: TILOS. However, as explained in section 3.1 TILOS supports one spatial dimension and thus makes it infeasible for this project (TILOS, 2015) .

Two reasons are suggested for the absence of suitable planning visualization software.

Low supplier push incentive

In section 1.1 TVPs were identified as unique construction projects. The combination of a time driven, brownfield situation project with unique linear and logistic characteristics result in a small niche market for software engineers. Also it can be considered as a complex situation to model, in-field expertise is necessary to fulfill user requirements. The specific user requirements result in a small area of distribution for software companies. Additionally, software companies are unaware of the defined problem statement in this research. Three software companies were consulted whether they were aware of the stated problem:

- Esri (ArcGIS): unaware of the problem. A solution Esri can offer relates to a set of toolboxes to connect planning schedules to a geospatial component. These toolboxes allow the computation of state-based output and moving objects as well.
- Autodesk (Navisworks, AutoCAD, Revit): unaware of the problem. Autodesk suggests Navisworks is suitable to create a 4D BIM model. Activities cannot be visualized unless these are manually modelled.
- Oracle (Primavera P6): unaware of the problem. A solution Oracle can offer is the *MapViewer* plugin. This plugin integrates project data into geospatial data. Activities can be projected on a map, however it is currently not possible to present states without external software.

Concluding, when referring to the market push/pull strategies software developers are unaware of the stated problems and have no incentive in ‘pushing’ products to customers.

Low customer pull incentive

The conservative attitude of contractors results in a lack of innovation in software engineering. During interviews it is often mentioned the current planning methods have been used for many years already and always work in the end. This conservative attitude is further elaborated.

An explanation of the underlying cause of this conservative attitude is explained by Van Riel (2015). It can be found in the low need to reduce failure cost. Profits in the Dutch construction industry were high up to the year 2008 (Cobouw, 2014). Failure cost were around 15%, very high profit margins resulted in a lack of focus in reduction of failure costs. Only once profit margins decreased, contractors started focusing on failure cost reduction. This was only several years ago, and only slowly contractors start initiatives to reduce failure costs.

Concluding, the incentive to reduce failure cost was low from a contractors’ perspective and only recently they started to gain more attention for innovations. Up until now, no software packages are used assisting contractors in failure cost reduction.

5.8 Conclusions

A literature study confirms that the defined problem statement is recognised in scientific literature as well. Different authors identify similar planning and logistics issues in the construction industry. As hardly any literature on railway construction is available, a wider search scope is applied to find literature useful for this research. Based on a literature review, several conclusions can be taken:

1. Many authors state current planning tools and methods give insufficient insight at construction sites. Network diagrams, Gantt-charts and time-distance diagrams cannot assist planners to identify risks and inefficiencies. The resulting failure costs are high and there is a need to increase the insight.
2. BIM is an object-oriented method to get insight in a construction site system. It can be used to link meta-information to objects in the geometrical dimensions. The implementation of a 4D planning is possible if time based information is added to a 3D model. A 4D planning can be used as a method to visualize construction scheduling and site utilization. BIM is considered as a possible solution and will be considered as a design alternative.
3. GIS is a location-oriented, layer based method used to present and analyse geographical data. GIS software has the possibility to project 1D/2D objects on a background layer. GIS can be

applied for planning visualization purposes and will therefore be considered as a design alternative.

4. The railway construction industry shares characteristics with the highway construction, pipeline construction and coal mining construction industries. However, the specific planning visualization problems for the railway industry cannot be identified in these analogue fields. The specific logistic operations regarding the transport of machinery and track availability makes railway construction unique. Additionally the field of concurrent engineering is researched. Major companies use concurrent engineering primarily in their design process instead of operational processes.
5. A gap in literature and software availability can be detected regarding the stated problem. Two reasons are suggested. First of all, suppliers have a low incentive to push new products into the contractor market, they are unaware of the defined problems. Second, contractors only very recently gained the incentive to reduce failure costs. Only since then, innovative measures are taken to reduce failure costs. Planning visualization has not yet been in their scope.

Summary Dym & Little Stage 2

The second stage of this research first presents a requirements analysis. The method to transform first-hand requirements into a clear, consistent and unambiguous set of requirements is presented by Abran et al. (2004). A categorization is part of this requirements analysis as well.

The first step is collecting a first set of requirements from users, customers and other stakeholders. Interviews, user observations and site visits are used to collect requirements from users. The second step is the analysis of the requirements, which transforms the stated requirements to be clear, complete, consistent and unambiguous, and resolving apparent conflicts. A categorization based on stakeholder weight is part of this step as well. The lowest priority requirements are considered as wishes.

Six categories are presented, for each of the categories the top requirement is presented in Table 9.

Table 9: Six top requirements

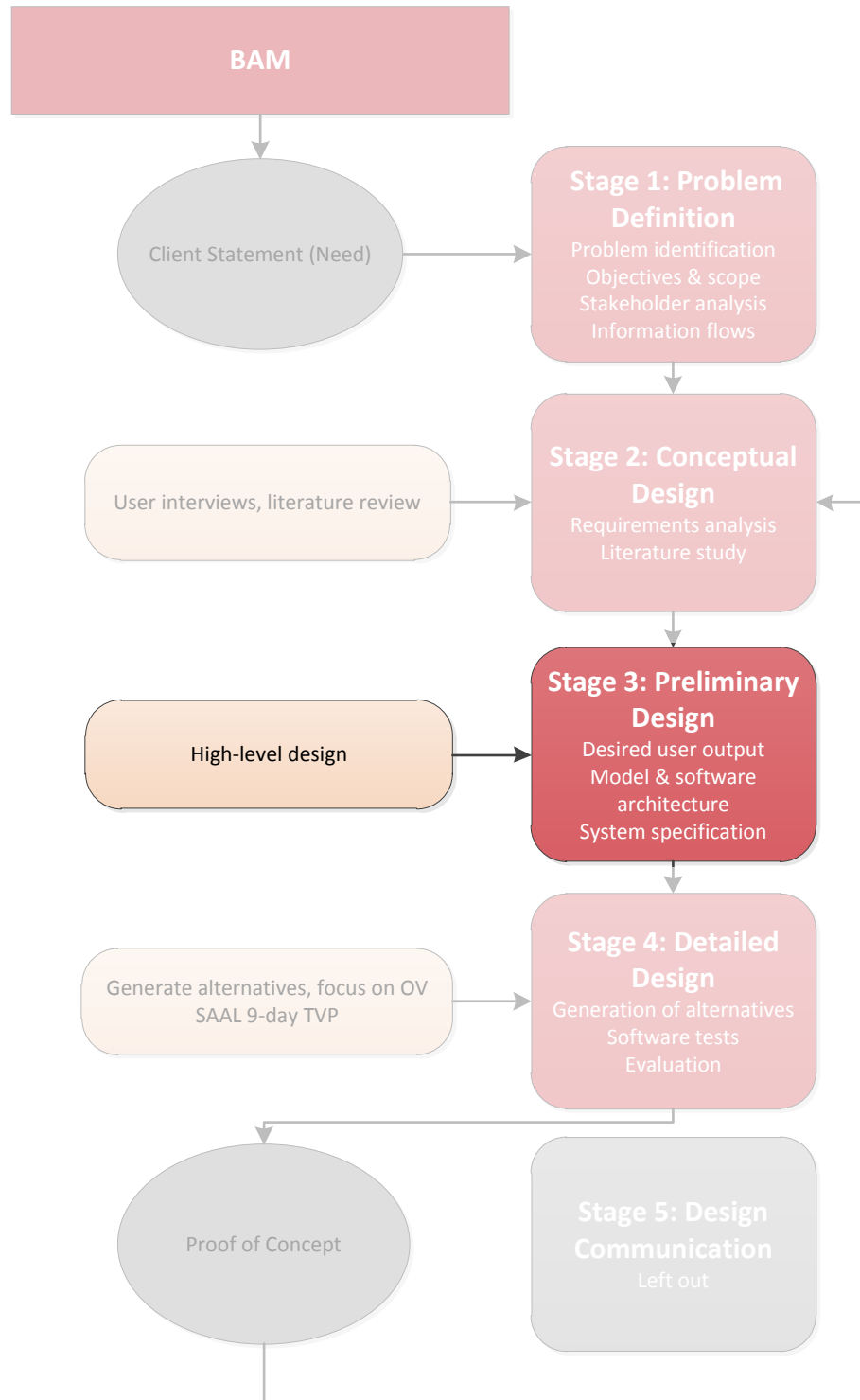
#	Top requirement	Category
1	Clashes must become visible	Clashes
2	Construction logistics must be become visible	Construction logistics
3	Risk scenarios must be implemented and tested beforehand	Delays
4	The lengths of the spatial overview should be on scale	Spatial overview
5	The output of the model must be understandable by stakeholders without the knowledge of all planning encoding	User interface
6	The planning grid must be defined in the design phase of the project	Miscellaneous

The requirements analysis spans a solution space for the design process. Before starting the high-level design, a literature review is conducted to assist in designing the solution concept. The literature first researches traditional planning methods. Gantt-charts, critical path networks and time-distance diagrams are often used by contractors to create a planning schedule. Literature identifies several issues related to the use of the previously presented planning methods. Issues identified in literature were very similar as identified during the problem definition, and regarded planning overview, clash detection and ease of use.

Literature mentioned two possible solution methods. The principle of *building information modelling* (BIM) can be used to link meta information to objects in the geometrical dimensions. The application of a 4D planning is possible if a time dimension is added to a 3D model. A 4D planning can be used as a method to visualize construction scheduling and site utilization. *Geo information systems* (GIS) is a layer-based method used to present and analyse geographical data. GIS has the possibility to create location-based 2D objects projected on a background layer.

A review into analogue industries resulted in no useful insights for this research. The unique characteristics related to linearity, time-driven and logistical operations cannot be identified in literature.

DYM & LITTLE STAGE 3: PRELIMINARY DESIGN



6. High-level design

Before a specific implementation of the requirements can be done, a high-level design presents the functional aspects, software architecture and system specifications. This chapter presents the objectives and structure of a high-level design (HLD) for a planning visualization method.

6.1 Objective

The objective of a high-level design is to define a software structure that is able to fulfil the requirements. The high-level design defines the architectural patterns and interfaces of the system and is independent of a specific implementation method or programming language. It can be described as the transitional step between what the system must do (based on requirements) and how the system can be implemented to meet these requirements (U.S. Department of Transportation, 2015).

The first two stages of the Dym & Little framework form the base of the high-level design.

6.2 Structure

The designing procedure of a HLD is important to guarantee that a complete and unambiguous design is presented. Different methodologies can be found to come to a high-level software design. Microsoft presents a sequence of steps to design an architecture for a software system in Visual Studio 2013. Analogies can be detected with this research, and thus the guideline is used to design an implementation-independent HLD for this research (Microsoft, 2013).

Mind, some steps in the guideline already are implementation oriented. Therefore, several alterations in the Microsoft guideline to ensure a solid application for this research can be done. The steps are executed as following:

1. *Desired user output.* First, the desired user output is defined. A clear desired output is necessary to structure the follow-up steps. (Chapter 7.1)
2. *Model architecture.* Then the architecture of the model is presented. (Chapter 7.2)
3. *Software architecture.* The architectural pattern of the software illustrates a high-level overview of the systems' components and their interfaces. The desired output assists in the steps from a black box to a clearly defined system. (Chapter 7.3)
4. *Components.* With the help of pseudo code and illustrations, a high-level description of several components and functionalities for the visualization method is presented (Chapter 8).
5. *System specifications.* The final aspect of a HLD is a system specification. All system specifications can be traced back to requirements or the previously defined architectural pattern. (Chapter 9)

7. Architectural structure

This chapter presents an architectural structure for the visualization method. First, the desired user output is explained. Then, the architecture diagram of the model is presented. Following, the architectural diagram of the software system is presented. During the desired user output, examples are presented in a 2-dimensional overview.

7.1 Desired user output

Users of the visualization method desire a certain type of output and visualization concept. Several requirements (4.0, 4.2, 4.3, 4.5) state the importance of scalability of the spatial overview. To address these requirements, the use of a geographical overview with different types of underlays must be embedded in the visualization model. Other user specified data must be located in separate viewing layers which a user can view or hide (requirement 5.4).

Activity-based output

Vuist (2015) states that for planners, it is necessary to see which activity is performed at what location at each time instant. A detection whether a certain area is still available to execute activities can be done with that output. In addition, space-time clashes between activities can be detected. The relation with activities is strong, as for *each* activity as scheduled in the planning a location exists. The related output is defined as activity-based output. Figure 16 presents a mock-up illustration of desired activity-based output. Two static activities and one moving activity can be identified. The arrow next to the blue activity represents the train path (requirement 2.5).

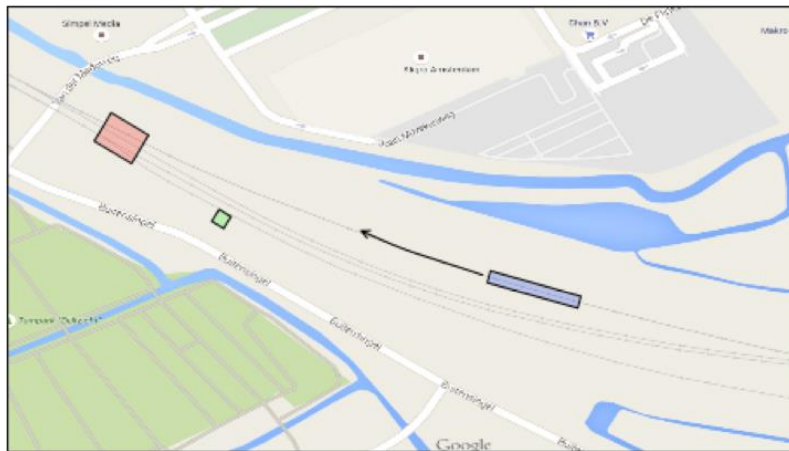


Figure 16: Example of activity-based output

Two requirements (Chapter 4.2) state additional information about the desired user output and must be included in the visualization method. However these are not presented in Figure 16:

- An AutoCAD drawing must always be the basis of the model to allow scalability (requirement 4.5)
- A simulated time visualization must be possible, both in helicopter view as well in zoomed view. (requirement 5.3)

From activity-based output, activity clashes can be detected. The high-level design of this type of clash detection is explained in Chapter 8. For the current research objective, the output from an automatic clash detection model must visualize rather than optimize. Two reports must be presented for the temporal clash detection:

- De Groot (2015) and Vuist (2015) state that a spread sheet which presents all temporal clashes would be most helpful in gaining insight. Table 10 presents an example of the desired output.

More columns can be added if more than two activities clash. The *From* and *To* columns define the timespan for which the clash occurs.

Table 10: Desired temporal clash report

Clash	From	To	Activity 1	LocationID1	Activity 2	LocationID2	Critical path
T.1	30-05-2015 16:00	30-05-2015 17:30	Inbrengen dubbele ES-Las sp VS km 153.783	WL1.5:LAS:06	Onderstoppen lassen t.p.v sp VS km 153.783	WL1.5:LAS:04	No

- In addition, each clash must be made visible in the geographical view of the model. Figure 17 presents a graphical representation of two activities clashing. When two activities overlap a bright, red colour must be projected (Vuist, 2015). Clicking this overlapping object must toggle a window as projected in Table 10.

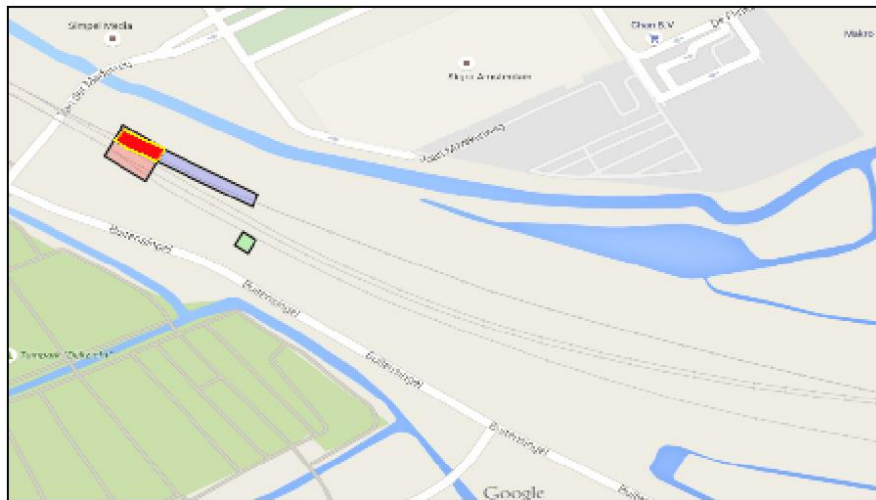


Figure 17: Geographical representation of a temporal clash: bright red notification

State-based output

Apart from activity-based output, it is very useful to obtain information about the state of the railway tracks (Van Riel, 2015).

This state-based output provides information for two identified risks:

- First, *state priority clashes* can be identified. A user-defined sequence of states (first state A, then state B) must be satisfied. If a section undergoes invalid state transitions, a state priority clash occurs and the user must be notified the planning is infeasible.
- Second, it allows a planner to detect whether a certain track section is available for the execution of certain activities (requirement 2.2, 2.3). For example, if a tamping machine is scheduled to pass railway section while no track is available, a clash occurs. This type of clash is defined as a *track availability clash*, and regards only the track availability.

These two types of clashes require a different set of states. For the spatial priority clashes, a subset of all possible spatial states must be defined for the clash detection to be useful. For each section, a valid state sequence must be defined to make optimal use of the spatial priority clash detection.

For the track availability clashes, only a *track available (spoor)* state and *track not available (geen spoor)* state are necessary, as that information is by far most critical (Van Riel, 2015):

- *Spoor* indicates the railway track is physically accessible for rail-bound material
- *Geen spoor* indicates there is physically no track located for a location.

As an example, 7 sequential states can be identified during a TVP (De Groot, 2015). These states are: (1) oud spoor, (2) oude ballast, (3) zandlaag, (4) fijne ballast, (5) grove ballast, (6) dwarsligger, (7) spoorstaaf. Table 11 presents the states, preconditions and corresponding track availability. In addition, Figure 18 presents a graphical overview of the state transitions. The colour of the icons represents track availability.

Table 11: Example set of states

Number	State	Precondition state	Track availability
1	Oud spoor	<i>Initial state</i>	Spoor
2	Oude ballast	Oud spoor	Geen spoor
3	Zandlaag	Oude ballast	Geen spoor
4	Fijne ballast	Zandlaag	Geen spoor
5	Grove ballast	Fijne ballast	Geen spoor
6	Dwarsliggers	Grove ballast	Geen spoor
7	Spoorstaven	Dwarsliggers	Spoor

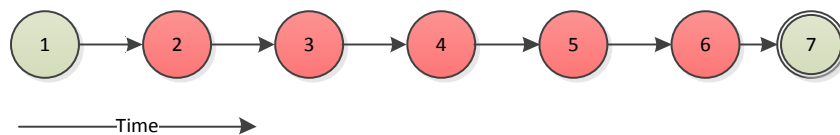


Figure 18: Visual representation of state changes

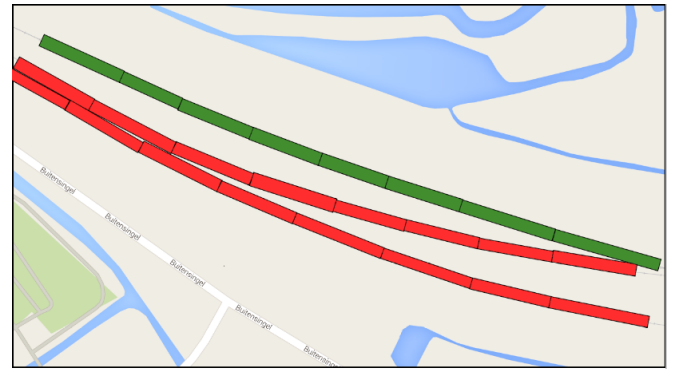
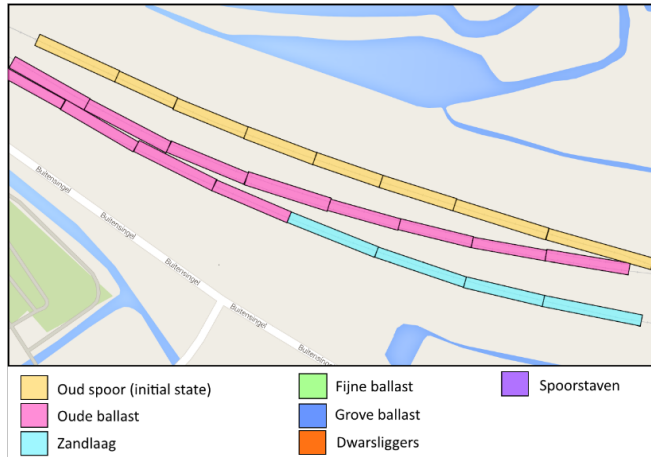
The state-based output presents a (time) stepwise overview of the line system which is discretized in space. The spatial decomposition and temporal visualization step size depend on the situation at the construction site. For construction logistics and heavy machinery the application of a state-based output is valuable when planning or re-planning logistical decisions.

Figure 19 presents a mock-up output for two time instances of construction works at a switch. The two left figures present the states of the system at 12.00h and 16.00h. In addition, the two corresponding track availability information is projected on the two right figures. The figure is based on Table 11.

State of the system

Track availability

12:00h



16:00h

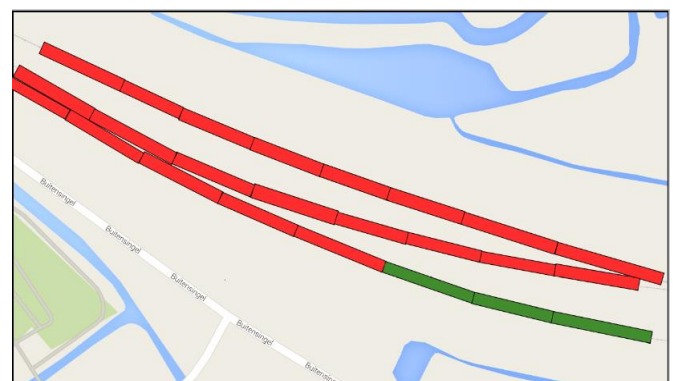
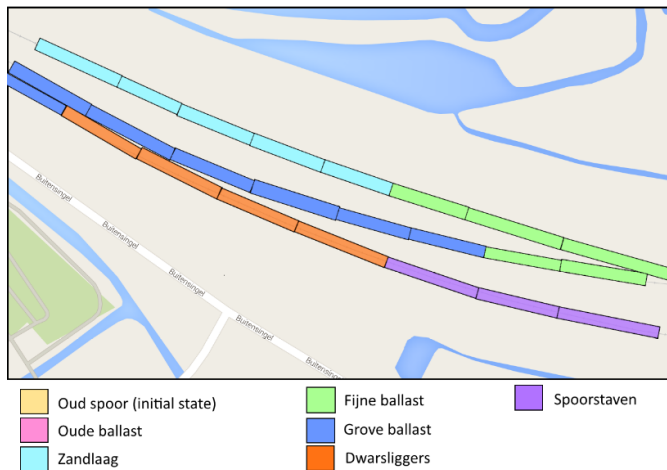


Figure 19: Mock-up state-based output of an example section, both at 12.00h and 16.00h

In addition, a list of spatial priority clashes must be provided (requirement 1.2). Table 12 presents an example output for a detected spatial clash. In this clash, the state 'Spoorstaven' is planned to be reached before the section is in the state 'Dwarsliggers'. In reality this is impossible, as 'Spoorstaven' are always placed after 'Dwarsliggers'. Hence, the model notifies the user for the spatial priority clash.

Table 12: Desired spatial priority clash output

Clash	From	To	LocationID	Clashing state 1	Clashing state 2	Critical path
SP.3	31-05-2015 12:00	31-05-2015 13:00	151.68:151.94RT	Spoorstaven	Dwarsliggers	No

The second type of state-based output must also be provided as a list. Each time a planned activity cannot be executed because the underlying track is not available, a clash occurs. Table 13 presents the desired output for a state-availability clash: the activity 'Inbrengen dubbele ES-Las' is planned to be executed at a certain location during a certain time. This activity is rail-bound. However, during that time the derived state of the underlying block is set to 'No track'. Thus, a state availability clash is detected.

Table 13: Desired state-availability clash output

Clash	From	To	LocationID	Activity	Availability	Critical path
TA.2	31-05-2015 12:00	31-05-2015 13:00	151.68:151.94RT	Inbrengen dubbele ES-Las sp VS km 153.783	Geen spoor	Yes

This section considered a spatially decomposed railway system. This is done to facilitate an easy input mechanism for planners: per section the invalid state transitions are imported. However, it is also possible to approach the railway system as a continuous system. This would make the clash detection even more efficient, as no partially unavailable sections would be presented as fully unavailable. Primarily for long track sections with sequential moving activities inefficiencies can be reduced when either the system is considered continuous or spatially decomposed track sections are small.

Relation activity-based output and state-based output

A relation exists between activity-based output and state-based output. Before going into detail of the system architecture, a more detailed explanation of the activity-state relation is presented.

A state change is caused by the start or completion of an activity. This means first the activity-based output must be generated before any state-based output can be computed. In addition, a sub-set of activities initializing a state change and a sub-set of activities requiring a certain state must be provided as user-input.

Consider the following situation: Figure 20 shows an overview of area for which a TVP is planned to execute several activities. A spatial decomposition is executed and presented as a set of blocks. The initial state for all railway sections is defined as *oud spoor* (old track) as defined in Table 11.

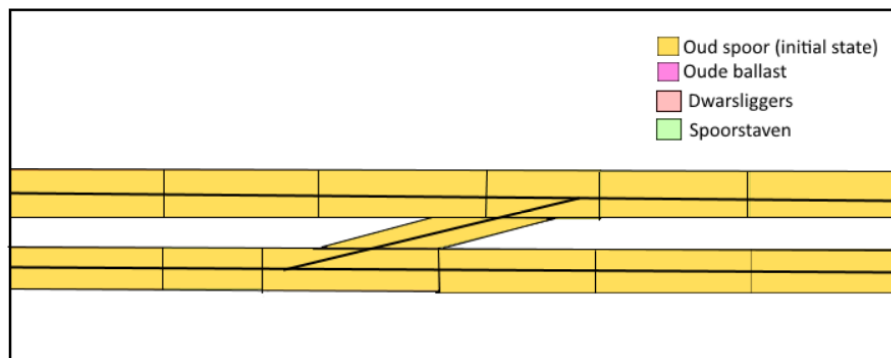


Figure 20: Initial state all railway sections

A set of 9 different activities are executed during the TVP. Table 14 illustrates the mock-up activities. Several activities initialize a certain area to change state. All activities require a track availability state in the underlying grid in order to commence.

Table 14: Mock-up activities

Activity	<u>Initializes</u> state of underlying grid	<u>Requires</u> derived track availability of underlying grid
Opbouw tijdelijke rail-inzet-plaats	-	Spoor
Verwijderen bevestigingsmiddelen rail	Oude ballast	Geen spoor
Verwijderen ballastlaag	Zandlaag	Geen spoor
Verwijderen bovenleidingmast 52/1N	-	Spoor, geen spoor
Aanbrengen fijne ballast	Fijne ballast	Geen spoor
Aanbrengen grove ballast	Grove ballast	Geen spoor
Aanbrengen dwarsliggers	Dwarsliggers	Geen spoor
Bevestigen nieuw spoor	Spoorstaven	Geen spoor
Afvoer stopmachine	Spoor gereed	Spoor

Each state-initializing activity ‘fills up’ at least one spatial grid cell. A method to determine the overlap between the activities and location grid cells must be implemented in the software. Figure 21 presents two activities from Table 14 being spatially implemented in the overview. The ‘verwijderen bevestigingsmaatregelen’ activity initiates a state-change for the underlying state-based output.

The previously defined Table 11 provided the track availability for all states as defined for this example.

Figure 22 presents the ‘Afvoer stopmachine’ activity, which is a moving activity. Once the moving activity enters or leaves a spatial block, the state of that block changes if the activity initializes a new state.

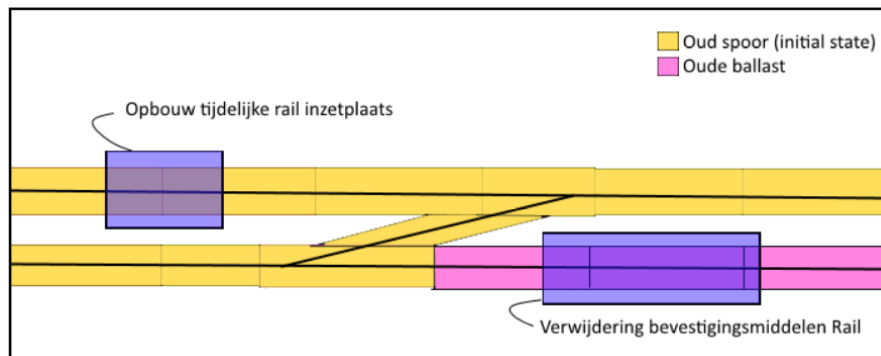


Figure 21: Two activities of which one initiates state-changes

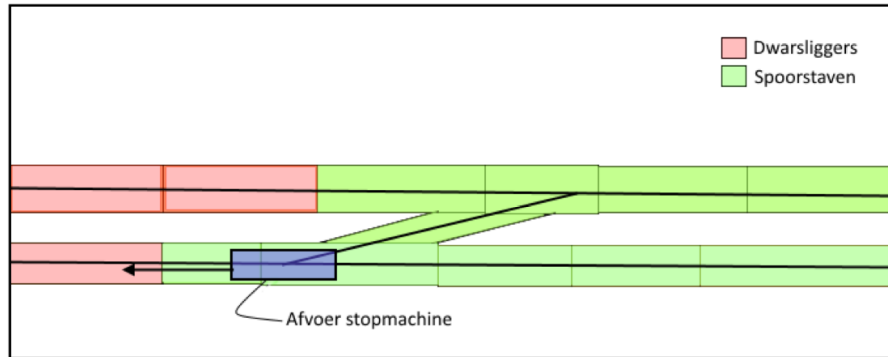


Figure 22: A moving activity that initiates a state-change

A pseudo code is presented for the algorithm for the detection of spatial clashes. The pseudo code describes the algorithm without committing to a platform. This algorithm must be executed each time an activity starts.

For the start/end of each activity, check state of all underlying spatial grid cells (do this as well for moving activities entering/leaving grid cells)

For all underlying spatial grid cells

If activity requires certain state

If required state does not meet actual state

 Notify user with warning;

Else required state meets actual state

 Do nothing;

Else activity does not require certain state

 Do nothing;

If activity initializes new state

 Change state of all underlying grid cells to new state;

Else

 Do nothing;

Visual representation

The objective of this research states that a better insight in the state of a linear construction system must be gained. The visual representation of activities, constraints and the system state is therefore discussed. Activities and constraints occupy a certain area, for which for that time interval it is not accessible for other activities. This area can best be represented by polygons projected on a background layer.

The linear characteristics of the rail system can be used when the system is spatially decomposed. Instead of using polygons to represent rail sections, the 'line' representing the rail system can be given a certain thickness and colour instead.

Scenario analysis

Users do not only require a clash free initial planning, additionally a scenario analysis must be executed to detect clashes for different input scenarios. Appendix I describes how the scenario analysis must be executed to fulfil the user requirement. Note: only a deterministic scenario analysis is conducted in this research.

7.2 Model architecture diagram

Before addressing the software architecture and specifications, the model architecture is described. During the first stage of the Dym & Little approach, two types of clashes were identified as risks: activity-based clashes and state-based clashes. However, these can be defined in more detail.

Figure 23 describes the relation between time, activities, states and the static infrastructure. Five types of sub-clashes can be determined. This chapter describes the diagram in more detail. Note: Figure 23 *only* refers to input necessary for clash detection. Additional necessary input is presented in section 7.4.

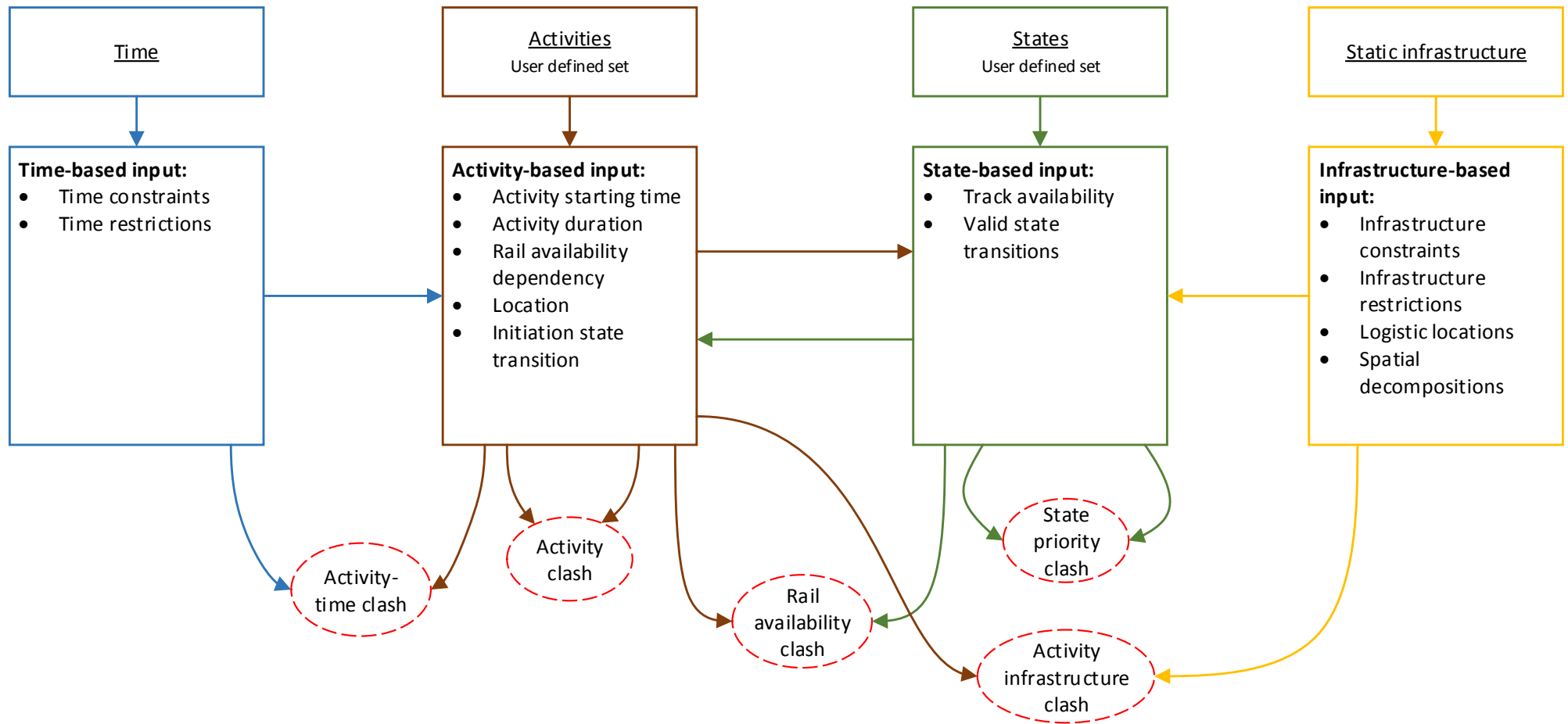


Figure 23: Relation between different types of output

Time

The time component in the model describes all time related components. In essence, regular planning software as MS Project or Primavera P6 can process the time component. It is therefore included in the planning visualization model with the following aspects:

- *Time constraints* are set times in the planning: milestones and project deadlines that must be met and are therefore considered constraints.
- *Time restrictions* are based on regulations and can be local or project wide. These regard restrictions during the night, traffic peak time or weather forecasts.
- The *time step size* defines the frequency of model output presentations. A step size of 5 minutes would present output every 5 minutes. Note: if the step size is too large, clashes with fast moving activities can be left visually unidentified. The clash detection model is capable of detecting these in-between clashes, since the clash detection model recognises activities as discrete events (see: algorithm p.64).

Activities

Activities are user defined and are presented as a set. The following aspects are included:

- *Activity starting time and duration* are defined for each activity.
- *Precedence relations*, to define the dependencies between sequential activities.
- *Track availability dependency* defines for each activity whether it is rail-bound or not.
- The *location* can be defined as a time dependent function describing the location an activity occupies. A location can change over time both in shape and geographical location.
- The *initiation for a state transition* defines whether an activity initiates a state transition.

States

States are user defined and triggered by activities. The following aspects are included in Figure 23:

- *Track availability per state* defines for each state whether the rails allow rail-bound vehicles.
- *Allowed state transitions* defines the sequence in state transitions. Deviations from this sequence must notify a user. Since state transitions only depend on preconditions and are independent from time, these are located under state-based input.
- The *initial state* is defined per spatially decomposed cell.

Static infrastructure

The static infrastructure describes all infrastructure related components. The geographic situation as used as background or underlay forms the base of this component. For this research, a static infrastructure is assumed. When situations with longer time-periods are studied, the infrastructure can also be dynamic. Clashes can occur with the static infrastructure. Included aspects:

- *Infrastructure constraints* are areas physically defined as impossible to perform certain activities. For example: water, slopes or other infrastructure.

- *Infrastructure restrictions* are based on regulations and can be temporal or permanent. Examples are noise restrictions, height restrictions, pile driving ('heien') restrictions or safety restrictions regarding train and car traffic.
- *Logistic locations* are areas where rail-bound vehicles can enter the tracks. Including material access locations on land.
- *A spatial decomposition* must be implemented in the static infrastructure. The decomposition defines the spatial breakdown used for state-based output.

Clashes

Of the five different types of clashes as illustrated in Figure 23 only 3 of 5 types of clashes were acknowledged by stakeholders during the interviews the 9 day TVP at OV SAAL. For all 5 clashes an example is provided to illustrate the type of clash:

- *Activity clash*: two or more activities occupy an area during the same time span. Example: connecting the overhead wire while at the same moment a welding van occupies the same area.
- *Activity-time clash*: an activity is planned to be executed during a restricted time. Example: noisy activities cannot be executed at night when nearby a residential area.
- *Activity-infrastructure clash*: an activity is planned to be executed on a location where it is impossible to execute that activity. Example: pile driving is not permitted when working next to offices with high-end computer servers in the basement.
- *State priority clash*: the state sequence per cell must be valid. Example: it is impossible to first remove the ballast and later the tracks.
- *Track availability clash*: a rail-bound activity is planned during a moment no rail is currently on the tracks. Example: connecting the overhead line to the portal requires a rail-bound crane. However, when the tracks are not yet constructed, a clash occurs.

7.3 Software architecture diagram

An architecture diagram provides an overview of an entire system. Main components and interfaces are included in a high-level architecture diagram. The previous section presented the desired output, which can be used as a guideline when designing the software. This section focusses on the high-level structure necessary to provide the output. After presentation of the architecture diagram (Figure 24), each of the defined blocks is elaborated in more detail.

To construct the high-level diagram, two frameworks are combined. First of all, the previously mentioned Microsoft framework (Microsoft, 2013) suggests a division in input, model, output, database and user interface. However, a more specific description of the user interface is preferred for this research. Thus, in addition to Microsoft, a second framework is applied.

Krasner and Pope (1988) introduced a description to view architectural patterns of user interface. The model-view-controller (MVC) divides software applications into three high-level interconnected parts. The objective of the MVC method is to separate internal representations of information from how that information is presented to the user. The MVC is incorporated in the architecture diagram as presented in Figure 22 to make a distinction in user input (control) and output (view):

- A *controller* (user input) can send commands to the model to update the state of the model (e.g. state updates, activity information). In addition, a user can send commands to the *view* (output) to change the view's presentation of the model (e.g. changing the viewport).
- A *view* (screen output) requests information from the model to generate a representation of the output to the user.
- A *model* stores the data that is send to the controller and displayed in the view. Changes to the data are done in the model (e.g. state updates, activity information).

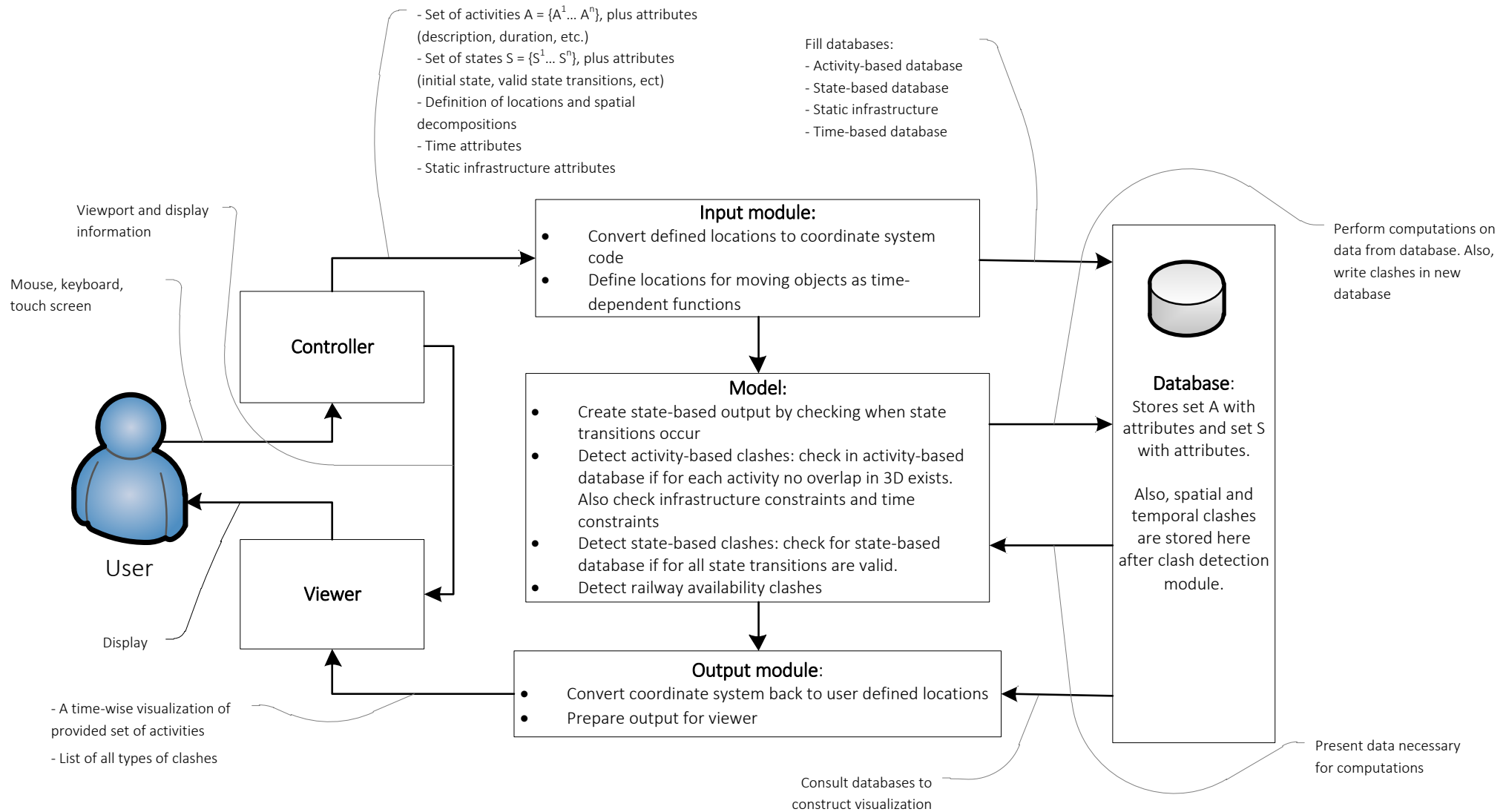


Figure 24: High-level architectural structure

User interface

The user interface is split up in a viewer and controller part as described by the MVC principle (Krasner & Pope, 1988). The viewer is considered as the screen the user is looking at to retrieve information from the model. The controller either controls the viewport or asks for a certain output from the output module from the model.

Input module

The input module must convert user specified attributes to a specific, generic format which can be used to perform clash computations. All input data is stored in the database module of the model. Initially, 4 databases can be filled according to Figure 23: time information, activity information, state information and the static infrastructure information.

For the attributes representing date and time formats, a formal time format must be used. The input module must convert locations to functions in time. By expressing a user-defined location in a formal coordinate system (for example, Rijksdriehoekstelsel), computations with other formally defined locations can be executed. When considering each activity location as a polygon, each vertex is a location within the coordinate system. For each step in a stepwise movement, all vertices must be defined for each time step.

Figure 25 presents an example. The left polygon is the initial location of an activity). The user defines the final location and shape as presented as in the right figure. The input module must compute the path how the polygon 'moves' in time. For each time-step, an output must be generated: both for visualization as for clash detection purposes.

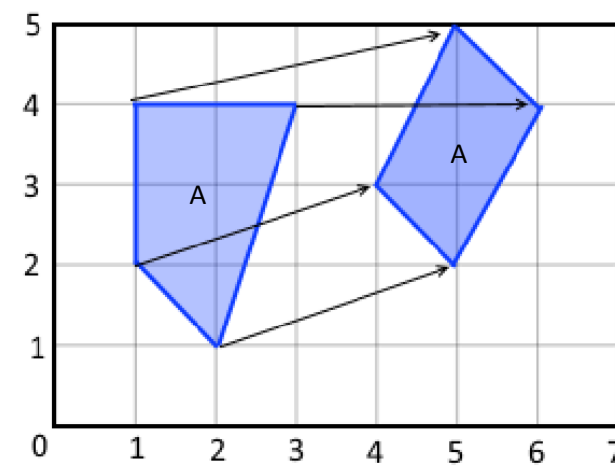


Figure 25: Moving polygon

Table 15 presents the location for 3 time steps. Mind, this table presents how location information can be saved in the database. Both locations as illustrated in Figure 25 are noted in the columns t_1 and t_3 . The input module computes the in-between location, based on the user defined time-step. In the table, the location for t_2 must be computed by the input module.

Table 15: Description of the location of the polygons

Object	t ₁ (user defined)	t ₂ (computed by model)	t ₃ (user defined)
A	(1;4)(3;4)(2;1)(1;2)	(3;4,5)(4,5;4)(3,5;1,5)(2,5;2,5)	(5;5)(6;4)(5;2)(4;3)

As an alternative, the user may also define a path which an object moves along. Especially if an activity moves along railway lines, it may be represented by defining its path along the railway line. An expression for location (along railway line), shape and rotation must be included, all dependent on time.

Database

The database stores all permanent or temporary information used to operate the planning visualization model. All constraints and restrictions regarding time information, activity information, state information and the static geometry are stored initially. When clash-detection computations are executed, these are saved in the database as well. The output module requests data from the database to generate user output.

Model

The computational model of the visualization method detects the five different types of output based on the information in the database. Per type of clash, data from the database is checked for overlap. Clashes are stored in the database, based on the information as presented in Chapter 7.1. Chapter 8 elaborates the inner working of the clash detection model.

Output module

The output modules processes output requested by the user. It consults the database for the requested information and transform it so it can be transferred to the viewer. The formal location representation must be presented as a geographical object for users to comprehend. In addition, the output module includes a module which allows movies to be played with user defined time-steps.

7.4 Verification user input

Desired user output can be generated by using the model architecture and software architecture. Input is necessary before the output can be generated. For each mock-up screenshot of desired user output in section 7.1 (including all types of clash detection), a back trace is executed to determine what input is necessary. The back trace is executed and presented in Appendix M. The resulting list of all required user input is presented below. Additionally, whether the information is currently available is presented in **red**. Chapter 8 proposes for the non-available input how it can be created.

The division of four types of input as presented in Figure 23 is used in this section as well: Time-based input, activity-based input, state-based input and finally static infrastructure-based input.

Time-based input consists of the following attributes. **All time attributes are available**, however they are not made explicit in any document. Thus, a process change is necessary.

- **Time constraints** are set times in the planning: milestones and project deadlines that must be met and therefore are considered constraints.
- **Time restrictions** are based on regulations and can be local or project wide.

- **The time-steps** must be defined to determine the time between model updates. Based on the precision the planning is created, a time-step of 5-10 minutes is advised.

The activity-related attributes required as input are presented.

- **Description:** a description of the activity as it can be understood by all users and customers. The description must be clear, concise and unambiguous. **Yes, available without process adaptations.**
- **Expected duration to complete:** the estimated time for completion. For now, this time is deterministic. In the *recommendations* chapter, a probabilistic planning is recommended. **Yes, available without process adaptations.**
- **Starting time:** as only a visualization model rather than an optimization model is presented. **Yes, available without process adaptations.**
- **Location:** the space the activity occupies must be an attribute. The location must refer to a user defined coordinate system, either national (Rijksdriehoekstelsel) or a local project coordinate system. In addition, the location of an activity must be presented as a function of the simulated time to include moving activities. **No, currently not documented for all activities. Changes in planning process are necessary.**
- **Dependency relations other activities:** dependency relations must be implemented for the model to visualize a planning. **Yes, available without process adaptations.**
- **Unique ID:** allows a quick reference when dependency relations exist. **No, currently not available. Appendix H proposes a encoding system for activities and spatial decomposition.**
- **Department:** the department that executes the activity. **Yes, available without process adaptations.**
- **State information** (requires or initiates): the link with state-based output must be presented as in Table 14. **No, currently not documented for activities.**

The state-related attributes required as input are presented. For the state-related attributes, **no information is currently available** to be used by the proposed model.

- **Initial state of the system:** for each spatial cell, an initial state must be defined.
- **Valid and invalid state transitions:** a list of valid and invalid state transitions must be provided to detect spatial clashes.
- **Track availability:** must be included per state.

Static infrastructure-based input consists of the following attributes.

- **Geographical layout:** represents the ‘underlay’ of the model and must be defined by the user. **Yes, available without process adaptations.**
- **Infrastructure constraints** are areas physically defined as impossible to perform certain activities. **No, currently not made explicit. Process adaptations are necessary.**
- **Infrastructure restrictions** are based on regulations and can be temporal or permanent. **No, currently not made explicit. Process adaptations are necessary.**
- **A spatial decomposition of the area:** the area relevant for the TVP must be spatially decomposed as presented in Figure 20. **No, currently not available.**

- **Logistic access areas:** RIPs (rail inzetplaatsen) must be implemented in the model to show access locations for machinery. **Yes, available without process adaptations.**

8. Components

This chapter specifies a high-level description of the clash detection component of the visualization model. First, a high-level description of clash detection is presented. Then, an elaboration of currently existing techniques is presented. Finally, a pseudo code is presented for the clash detection module.

8.1 High level clash detection

Before focusing on the specifications a definition distinction between *clash* and *conflict* must be made. During this chapter, a clash is defined as a 3 dimensional overlap between two or more objects. A conflict is defined as the acknowledgement by a planner of the clash actually appearing.

Figure 23 defines specific types of clashes. In essence, these two can be reduced to two concepts:

1. 3-Dimensional polyhedron clashes
2. State transition clashes

3-Dimensional polyhedron clashes

For this concept each activity, constraint or restriction is simplified to a 3-dimensional (2 geographical, 1 spatial dimension) polyhedron. This principle can be applied to more dimensions as well. A clash is considered as an overlap between two or more polyhedrons in the multi-dimensional space. A polyhedron can be either concave or convex, depending on the shape of the corresponding activity and whether it moves in time.

Figure 26 presents a description of three polyhedrons in a 3-dimensional space. When translating this abstract figure to a realistic example, the green and yellow polyhedrons represent static activities planned, with the green activity starting first. The orange polyhedron represents a working train, moving with a constant speed in a straight line. Two clashes can be detected: the green and yellow activity first, later the orange and yellow activity.

Mind, the definition of a polyhedron states only a flat polygonal faces, straight edges and vertices can describe a polyhedron. However, curved edges as described in the yellow cylinder below can be described with a rough straight edges approximation of the curved edges.

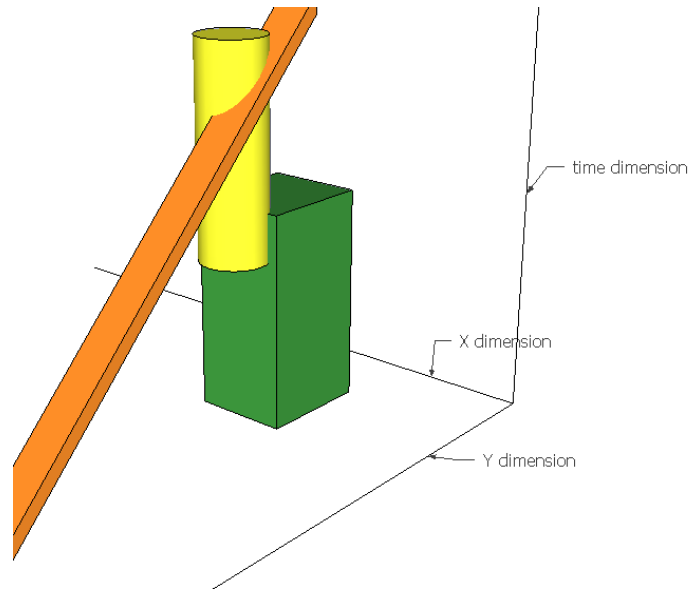


Figure 26: Graphical representation of a space-time clash

State transition clashes

For the conceptual explanation of the state transition clash, activities are for now referred to as a set of events. The start of an activity is an event, the end of an activity is an event as well. For example; the activity 'Lassen spoorstaaf' is for now represented as 2 events: 'Begin lassen spoorstaaf' and 'End lassen spoorstaaf'. Some events may initialize a state transition, others may not.

After the spatial decomposition is executed, a number of cells represent the underlying infrastructure. Each cell consists of different planned events which are executed in a certain sequence. Thus, in theory each cell can have a unique sequence of states.

Two aspects must be determined:

- Per cell, the valid sequence of states must be determined. Depending on the construction works, there can be many differences per cell. For example, one cell may need a switch replaced, while an adjacent cell does not. This information can be stored in a state transition table. Table 16 presents a state transition table. It can be seen parallel sequences can be valid state transitions as well. The most right column defines whether the cell is accessible for rail-bound machinery.

Table 16: State transition validity table

State	Valid state transitions	Track availability
S_0	S_1	No track
S_1	S_2	No track
S_2	$S_3 ; S_4$	Track
S_3	S_4	No track

S_4	S_5	Track
...	...	No track
S_n	S_{n+1}	No track

- For all events, it must be defined whether a state transition is initiated by that event. A state transition table is presented in Table 17. If event E_2 would occur at a cell with any other state, the state would change to state S_2 . If the state transition is invalid (Table 16) a clash would be detected.

Table 17: State transition table

Event	Initiates state
E_1	S_1
E_2	S_2
...	...
E_{n-1}	S_m
E_n	-

Not for every event a state transition is defined. If a planning consists of 300 activities, an estimated 50-100 states would be necessary considering the variety of activities. To ensure a good balance between the model's ability to detect clashes and the user's overview, roughly 12 states for rail and 4 for the overhead line are necessary (Immers, 2015). The set of states is user-defined and can be different for each TVP, working location and cell.

8.2 Existing techniques

The literature review as presented in Chapter 5 presents both the object oriented BIM principle and location oriented GIS principle as possible solutions for the this researches' problem statement. This subchapter focusses on available techniques to implement the high-level clash detection models within either a BIM or GIS software package.

Polyhedron collisions

A common method used by many software packages (BIM software, GIS software) consists of an efficient algorithm to detect clashes between activities. For this algorithm to work, the input must be presented as defined in section 7.3. The algorithm is based on a spatial overlay of activities. A stepwise approach of this type of clash detection is as following:

1. First, the time dimension is hidden from all activities. This results in a 2D grid presenting many spatial objects without a starting or ending time.
2. Then, a spatial overlap detection is done for the grid. Every area for which at least 2 activities overlap is written to the database as a separate object. In this object, the time dimension of corresponding activities is saved as metadata in the database.

3. For each detected geographical clash, the algorithm checks if the spatial component clashes as well. If no temporal overlap exists, the object is discarded from the list of spatial clashes. The final product considers only clashes in three dimensions.

This algorithm is efficient for static activities. The location of moving activities varies over time, which makes the first step of the previously presented algorithm impossible to execute. Either moving activities are not included, or the complete area they occupy over a time span is included. Moving activities are of key importance for the visualization method. Therefore, a different algorithm must be used to detect activity-based clashes.

The set of activities, constraints and restrictions can be considered as a Euclidean 3-space. Several methods can be found which suggest a method of detecting overlap between polyhedrons. Two promising methods are presented to provide direction for further research:

The *first* method considers 3-dimensional objects in a Euclidean space. Baker (2004) presents a theory for which overlap in convex shapes can be computed. Each shape can be surrounded by an imaginary rectangular boundary (box). All boxes must have their axes aligned. Only if these boundaries overlap the internal shapes may or may not overlap, and thus additional computations are necessary. If the boundaries do not overlap, the inner shapes do not overlap. This reduces CPU intensive clash detection for complex shapes.

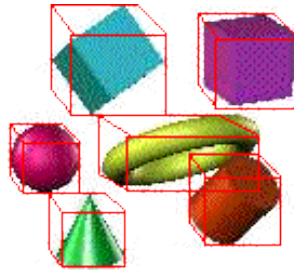


Figure 27: Imaginary boundaries bounding the 3-dimensional objects (Baker, 2004)

Testing whether these 'boxes' overlap can be done by comparison of the minimum and maximum of all three dimensions. Consider 2 objects, A and B. For each dimension, the following statements must be true for a clash to occur: $A_{x \min} < B_{x \max}$ and $A_{x \max} < B_{x \min}$. Figure 28 shows all four situations possible per dimension. Only if in all dimensions overlap exists between shapes, a clash is detected. Mind, the presented algorithm for detecting collision between shapes requires the shapes to be convex. If concave shapes are included, these must be decomposed in number of convex shapes.

The presented method if there are n objects, there are $n!$ possible combinations. For each of these combinations, 3 dimensions must be computed. The combination of these factors makes this algorithm inefficient. The next section presents a different method to detect clashes.

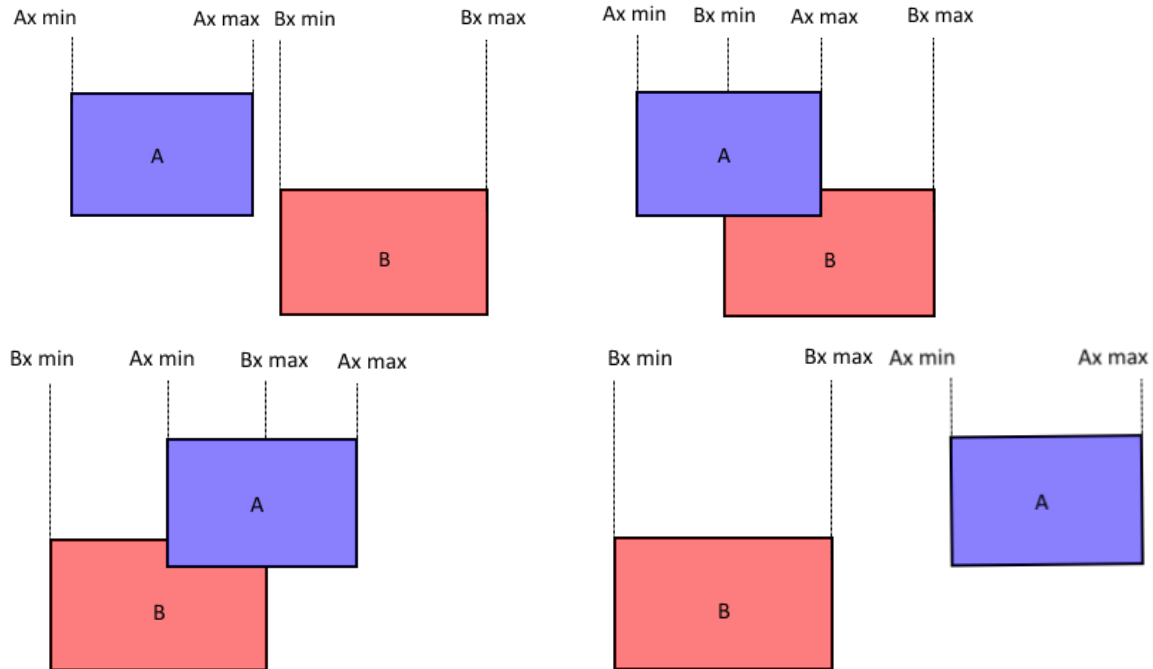


Figure 28: Overlap detection polyhedron (x-axis horizontal)

A *second* method described by Cozic (2006) focusses on 2D polygons in time, rather than considering these as 3D polyhedrons. The Separating Axis Theorem, also referred to as the Hyperplane Separation Theorem (Samelson, Thrall, & Wesler, 1958), is used. The method Cozic defines tries to find a line that separates both polygons. If such a line exists the polygons are not intersecting. Figure 29 illustrates the Separating axis theorem.

The implementation of this theorem results in the following algorithm. For each edge of both polygons:

1. Find the axis perpendicular to the selected edge
2. Project both polygons on that axis
3. If these projections do not overlap, neither do the polygons.

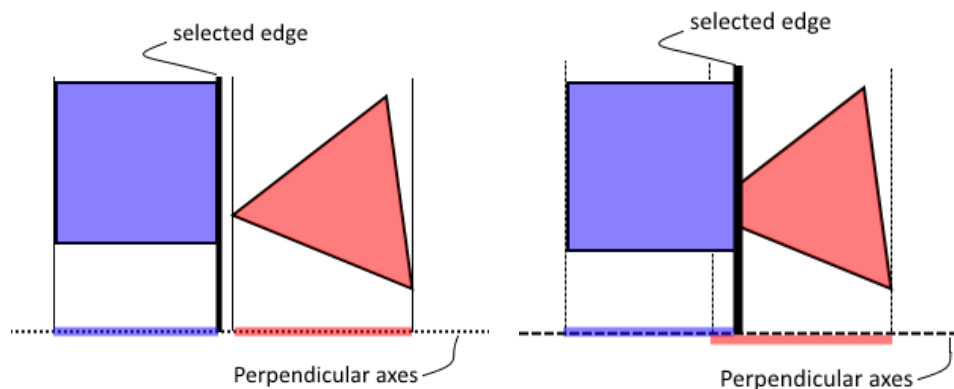


Figure 29: Application of the Separating Axis Theorem

Only two dimensions were considered so far. Implementing time is done by projecting the displacement of the polygons for the next time step on the axes. By repeating this for each time step, all overlapping polygon clashes are detected.

When a user needs an *additional dimension* implemented within a visualization model, a different solution can be interesting. A clash detection model with 3 geometrical dimensions and a time dimension can be imagined as moving polyhedrons within a space. Canny (1986) describes a method for describing collision detecting for moving polyhedrons, and thus suggesting a solution for a 4D clash detection. Instead of expressing each vertex in a coordinate system over time, he suggests a separate description of the shape, rotation and path of the polygon. In addition, he describes three types of interactions: a vertex can touch a plane, an edge can touch a plane and an edge can touch another edge. With a set of equations the collisions are described. For this thesis, no further investigation in 4D clash detection is executed.

State transition clashes

Per cell, all state transition must be logged. For each transition as recorded in the log, a validation can be done by checking for each transition if it is defined as valid. For a small set of possible states, the algorithm can be executed quickly. For a large set of possible states, an efficient algorithm must be developed.

The state sequence is retrieved from the time-based input as defined by the user. The actual state of the system changes under influence of activities.

8.3 Pseudo code

This section presents a high-level pseudo code. Structural conventions of a programming language are implemented, however the purpose is human reading rather than machine reading.

Section 8.2 suggests the requirement of moving objects in the planning visualization method requires a clash detection per time step. Based on the knowledge gained in this research, a pseudo code is presented which structurally performs a clash detection per time step. Further research might develop different, more efficient algorithms by changing the way moving objects are regarded.

1. START PROGRAM

Define variables

Create database

2. INPUT & INITIALIZATION

Define time-based input

Define activity-based input

Define state-based input

Define infrastructure-based input

3. DEFINE STATE OF THE SYSTEM

For all time-steps

For all activities per time-step

If an activity initializes a state transition

Change state of underlying cells, write to database

Check rail availability of underlying cell, write to database

4. ACTIVITY CLASH DETECTION

For all time-steps

For all activities per time-step

If an activity overlaps with another activity

Write clash information (activities, location, time) to database

If an activity overlaps with a time-related constraint

Write clash information (activity, constraint, location, time) to database

If an activity overlaps with with an infrastructure-related constraint

Write clash information (activity, constraint, location, time) to database

If an activity is executed and the underlying rail availability is not as required

Write clash information (activity, state, location, time) to database

5. STATE CLASH DETECTION

For each spatially decomposed cell

For each state transition as logged in step 3,

If a state transition is invalid according to list of valid state transitions for that cell (from time-related input)

Write clash information to database

6. OUTPUT PRESENTATION

Retrieve all activities, states and clashes from database

Play movie with activities, states or clashes projected as a layer on the infrastructure

Present clashes in a list, per type of clash

9. System specification

This chapter presents a set of high-level system specifications for the new visualization method. For this chapter, the requirements as defined by the user in Chapter 4 are transformed to high-level system specifications. The methodology as described in the *Guideline for Systems Engineering within the civil engineering sector* (Systems Engineering Working Group, 2009) is used for. Each system specification specifies the functionality or output a system shall perform. In addition, the high-level design and specification of the components as described in Chapter 7 and Chapter 8 provide extra system specifications. A back trace for requirements (Chapter 4.2) is presented in Appendix K. This appendix traces each requirement to a specific system specification. This ensures all requirements can be traced back.

The customer for the high-level system specification is a software expert from any software company to implement the high-level design in a software package.

The set of high-level system specifications is as following:

1. The structure of the mode shall be as presented in Figure 24.
 - 1.1. The objective of the model is the implementation of a spatial component in a Gantt-chart.
2. The model shall have an input module which can process the input as presented by the user.
 - 2.1. For all non-location based input, a module shall be included to implement spread sheets, work schedules and CAD drawings.
 - 2.2. For all input that requires a geographical location, a module shall be included to draw shapes referring to the specific location of an activity/boundary/constraint/geographical decomposition
 - 2.2.1. There shall be an option for which the user can discretize the length of each railway section into smaller locations. The model automatically discretizes each section according to the users input
 - 2.2.2. A user-defined list of sequential states per location is input for the model to defining a correct, conflict-free sequences of states.
 - 2.2.3. A user must be able to zoom in and out on the projected area's and background layer.
3. The main function of the model shall be 'providing planners insight in the planning and clashes'
 - 3.1. Two types of output shall exist
 - 3.1.1. Activity-based output shall be represented in a separate layer.
 - 3.1.2. State-based output shall be represented in a separate layer.
4. Output shall be presented in two different manners.
 - 4.1. A visual representation of the output presents all output as a movie.
 - 4.2. A textual representation of the output presents output in tables and databases.
 - 4.3. Activities on the critical path shall be always distinguishable from other activities.
5. Clashes shall be made explicit to the user by the visualization model.
 - 5.1. The user shall be presented a list of identified clashes of the types defined in Figure 23 once the clash detection sub-system has been run.
 - 5.2. The model shall give a textual output notifying the user when no clashes are detected.

6. Clashes are detected by detecting overlap between activities, constraints and states as presented in Figure 23.
 - 6.1. The model shall be able to cooperate with a user definable margin for which clashes are not detected (in all dimensions).
 - 6.2. The model shall be able to incorporate both static as well as dynamic objects.
 - 6.3. Either the first moment of overlap or the final moment of overlap of an activity over a spatial cell can change the state of that cell.
 - 6.4. For each state, the track availability is defined. The 'track available' and 'track not available' are possible states for this type of output.
 - 6.5. A method to determine the overlap between the activities and location grid cells shall be implemented in the software. An algorithm is included to determine the state of a track section of 'half overlapping cell'.
7. The model shall represent construction logistics.
 - 7.1. The model shall represent the movement of trains and other heavy machinery, both over regular surface and over rail
 - 7.1.1. Moving objects shall be shown as regular activities and move, either continuously or in small steps, through the system in time. The time step shall be no longer than 5 minutes.
 - 7.1.2. For each moving object, the exact route as scheduled must be projected as a thin line. The user shall be able to select a colour.
8. The model shall incorporate the performance of a scenario analysis as presented in Appendix I.
 - 8.1. Both a deterministic scenario analysis as well as a probabilistic scenario analysis shall be possible.
 - 8.2. An easy connection with planning software must exist.
 - 8.3. A comparison between different scenarios shall be possible, both visually as well as by KPI's.
9. An implementation with GPS trackers to track real-time information shall not be made impossible.
10. A version control function shall be incorporated to always notify the user if the most up-to-date version is currently operated.
11. A user manual and help-function shall be incorporated in the model.

Summary Dym & Little stage 3

During the third stage of the Dym & Little framework a high-level design of the planning visualization model is presented. This high-level design is platform-independent and focusses on functional aspects rather than on the actual implementation in a software package.

First, the desired user output is presented. The user requirements combined with reviewed mock-up screenshots present for both activity-based and state-based output how a desired user output must be presented. Both visual output (presented as a time simulation) as well as written clash reports are part of the desired user output.

The input for the visualization model is consists of four aspects:

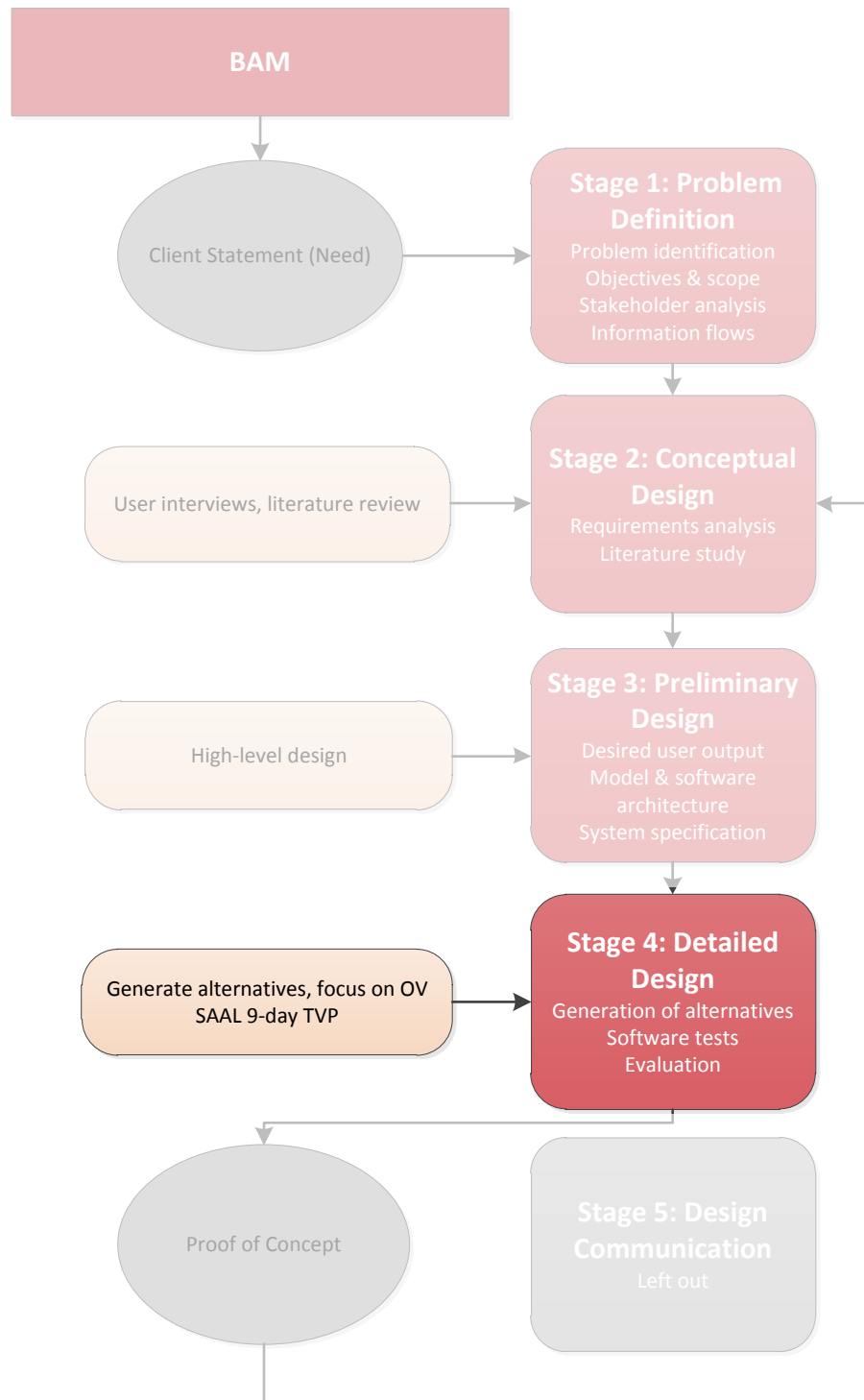
1. A set of planned activities, including duration, starting time, location and interaction with the state of the system.
2. A set of states of the underlying infrastructure is presented.
3. Time constraints and restrictions (e.g. noise restriction during the night) are presented
4. Infrastructure-related constraints and restrictions (e.g. slopes or ditches for which no activities can be executed). This input includes a spatial decomposition of the underlying infrastructure.

Then the model infrastructure identifies five high-level types of clashes. Activities can clash mutually or with space-related or time-related constraints. In addition, invalid state transitions or state preconditions can cause clashes as well. The user is notified - either visually or by a list – about clashes existing in the schedule used as input.

Following, the high-level software architecture diagram is presented. Each component as defined in the model architecture is located in the software diagram. An interaction between the user, input module, database, clash detection model and output module can be observed. For the clash detection model, two main types of clashes are identified: 3-dimensional polyhedron clashes and state transition clashes. Several techniques are presented currently used in literature to efficiently detect clashes.

In addition, a step-wise pseudo code is presented as a suggestion for further research. The pseudo code defines a structured algorithm able to detect all types of identified clashes. Finally, a functional system specification is presented. Both the user requirements as well as the model- and software architecture are used to define a system specification. The set of specifications combined with the software architecture can be presented to a software developer to initiate the implementation of the high-level design.

DYM & LITTLE STAGE 4: DETAILED DESIGN



11. Generation of implementation alternatives

Stage 4 of Dym & Little steps into the implementation of the high-level design in existing software packages. This chapter presents two implementation alternatives. Both alternatives are identified by literature as methods theoretically feasible to meet the high-level design. This chapter elaborates on the two design alternatives: the object-oriented BIM and location-oriented GIS. For both alternatives the characteristics and a software review is executed to test the feasibility of the software.

11.1 BIM: Navisworks

Building Information Modelling (BIM) is a broad concept. It can be described as an accurate visual digital model, which supports the design and construction through its phases, allowing better analysis and control than separate, manual processes (Eastman, Teicholz, Sacks, & Liston, 2011). In a more pragmatic description it can be described as the *coupling of information to objects in a building model*. This information consists of many different subjects. BIM can be used throughout the complete building life cycle, from design to demolition.

Azhar (2001) defined multiple purposes for the application of BIM for a complete lifecycle. As for the objective of this research, three relevant purposes are highlighted.

- *Visualization*: 3D renderings can be generated. A time dimension can be added.
- *Construction sequencing*: A building information model can be effectively used to create material ordering, fabrication, and delivery schedules for all building components.
- *Conflict, interference and conflict detection*: BIM models are created to scale, all major systems can be visually checked for interferences. This process can verify that overhead line does not intersect with steel beams, ducts or walls.

The base of a multi-dimensional BIM model is often a *3D CAD model*. The 3D model is composed from physical objects. A single 3D model does not yet meet the previously presented description of BIM. Once a 3D model is linked to different information models a BIM model is created (Van der Hoek, 2015). For this research, a combination of geometrical information and temporal information is linked. Azhar's (2001) and Van der Hoek's (2015) definition of BIM purposes suggests BIM is suitable for the implementation of a construction visualization model.

Software

When combining geometrical dimensions with a schedule, dedicated BIM software is necessary. BIM software cannot be used for the creation of models. It can only be used to combine different building information models and link objects. There are multiple software packages used in the industry. Berber & Reicik (2010) showed the U.S. market shares for all BIM software packages in 2010 is majorly dominated by Autodesk's Navisworks. In addition, BAM currently uses Navisworks as a BIM software package. Therefore, Navisworks is chosen as a BIM software package as an alternative solution for the high-level implementation.

Figure 30 presents the schematic representation of the construction of a 4D BIM model, based on the software packages BAM currently uses during a TVP.

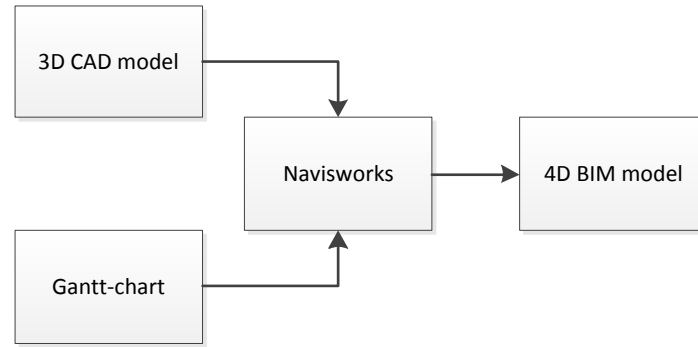


Figure 30: Construction of a BIM model

Figure 31 presents two Navisworks screenshots presenting 3D models for a train overpass for OV SAAL. The left figure presents the overview, with one object selected (blue). The right figure presents a lower-level sub-object of the high-level object. Objects are coded using agreements defined in a Leaflet object coding (Werkgroep Infra Codering, 2014).

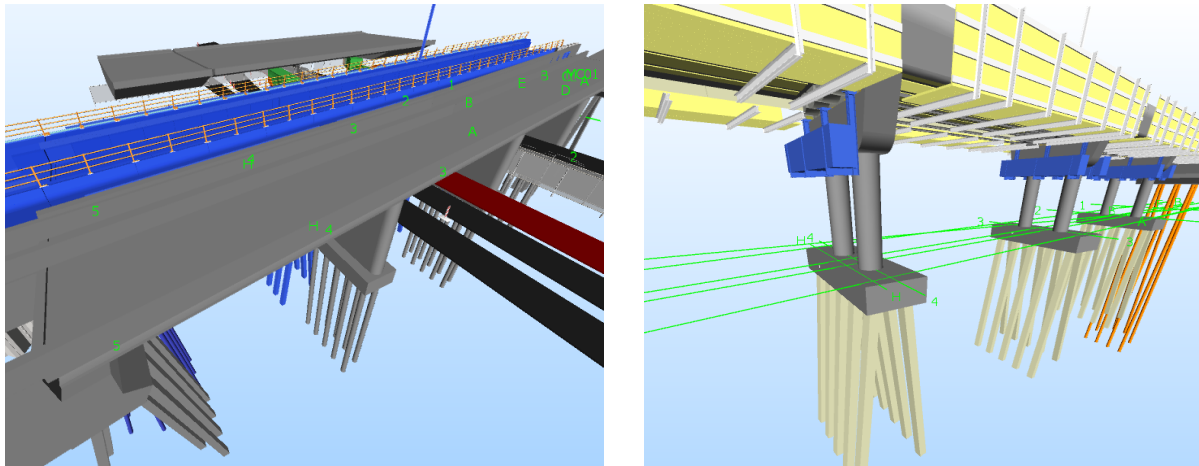


Figure 31: Example of an object breakdown for an existing 3D model (OV SAAL KW15)

It can be noted currently only physical objects are inserted in the BIM procedure. No activities, states or logistic operations are currently visualized in Navisworks.

Advantages Navisworks

The use of Navisworks to achieve this research' objective has three key advantages:

- A very high *level of spatial detail* is possible. If the 3D model is of high detail, which is up to the designer's preference, the planning can be linked in a high level of detail as well. As for the TVP detailed planning schedules are necessary, the level of detail is considered as an advantage for the BIM design alternative.
- *All geometrical dimensions* can be observed, including the corresponding clashes.
- Several departments within BAM recently *started with the implementation* of new projects in 3D models. With the Rail department included in this group, a complete 3D model can be constructed which can assist in physical clash detection in an early phase.

Disadvantages Navisworks

The use of Navisworks to achieve this research' objective has several disadvantages as well:

- A *dichotomy* exists between the output Navisworks presents and the output necessary for this research. Navisworks is designed to show physical objects and clashes between these objects, while the user desires user activities and state as output. This difference can be overcome by implementing (2D or 3D) activities in Navisworks as physical objects. Additionally, a spatial decomposition to realise state-based output must be included.
- The high level of detail in Revit models is *redundant* for showing activities and states. Working locations are planned with a level of detail for about 2-3 meter (Aerts, 2015).
- A 3D model must be available for all *intermediate situations*. The state of the system right before and after the TVP must be implemented in the model. However, often neither of the two states is available in 3D. Extra 3D models must be created to link to a TVP planning.
- Navisworks is considered a *difficult software package* and requires experienced modellers to create and edit models. Navisworks consists of a 'viewer only' package, which allows for a more user-friendly interface (Van der Hoek, 2015)

11.2 GIS: ArcGIS

The location-oriented principle of GIS can be applied in many different industries. Problems regarding social geography, network maintenance, architecture, planning and engineering are often solved with the help of GIS. GIS software is unique in its ability to capture, store, and manage spatially referenced data such as points, lines, and polygons. Simply used as a spatial database, GIS assists in modelling applications through handling a special form of data that would otherwise be compromised or impossible to store in a spatial databases (Miles & Ho, 1999).

The application of GIS to visualize a TVP requires the implementation of a planning schedule in the model. Each of the activities in a planning schedule can be linked to an object in the GIS model. Unlike in a 3D CAD model, no physical objects exist in a GIS model. In a GIS system the activities instead of physical objects are modelled.

A TVP visualization created in GIS can be described as a 2-dimensional layer model with polygons representing different activities. Each of the polygons is linked with an activity in the planning schedule which dictates the state and time of the polygon. Additionally, a spatial decomposition of the system is necessary to present state-based output.

Software

Many GIS software programs are available and may be suitable for this research (Moons, 2015). Currently BAM currently uses Esri's ArcGIS as GIS software. Esri is market leader in GIS software in different industries (Directions Magazine, 2011).

BAM's GIS department demonstrated the use ArcGIS for planning purposes. Figure 32 presents a screenshot of the possibilities of the implementation of a planning schedule of an example project. The project is divided in work locations, and each colour represents a different state of the system. As BAM

is currently licenced to ArcGIS and the package is available for this research, ArcGIS is an design alternative for the implementation of the high-level design.

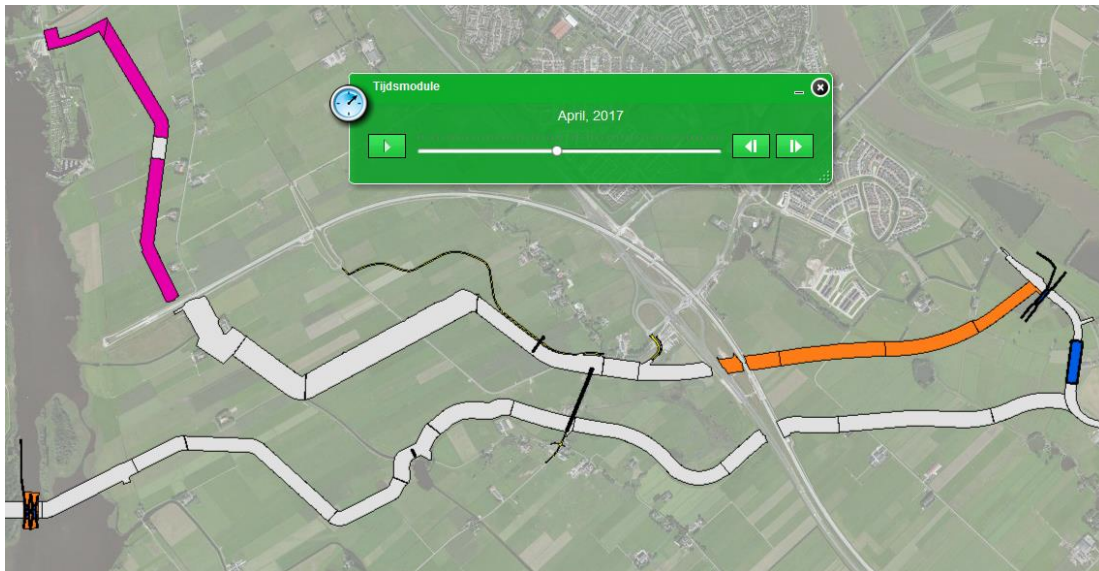


Figure 32: Screenshot from ArcGIS, with different work locations marked in a different construction phase

Advantages

The use of GIS to achieve this research' objective has several advantages:

- *Activities and states rather than physical objects* can be modelled in GIS. This results in clash detection for activities instead of physical objects.
- *Different background layers* can be projected as a base layer. High-resolution aerial views, land registry maps and satellite images are available as background layers. In addition, ProRail has an additional layer of all railway lines projected in the GIS environment.
- *Multiple interfaces* exist in ArcGIS. For the users, a desktop application exists which allows the extensive features, including the creation of polygons and connection with planning schedules. For customers, a simplified web interface exists which allows viewing and consulting of the beforehand created GIS environment.

Disadvantages

The use of GIS to achieve this research' objective has several disadvantages as well:

- The *absence of physical objects* may result in a defect in the link between the planning and physical objects. For each activity in the planning must be defined which work location is occupied for that activity. The size and exact location of each work location per activity is difficult to predict.
- The *absence of a height component* results in the projection of clashing activities. However, in reality these activities can be executed at the same time. For example, removing a train safety cabinet and constructing an overhead line are activities which can be executed at the same time at the same location.

11.3 Conclusion

Based on the literature study and the high-level design Navisworks and ArcGIS are presented as design alternatives. Both Navisworks and ArcGIS are reviewed for suitability for a planning visualization model as presented in the high-level design. For both software packages tests were conducted to determine the feasibility for this research.

Navisworks is a BIM software packages focussing on connecting different building information models. Navisworks focusses on spatial dimensions and corresponding. Navisworks is very suitable for geographical dimensions, however for activities as defined in this research no application has yet been done. A dichotomy exists between the current way of planning design in BAM Rail and how Navisworks represents objects. Despite this dichotomy, Navisworks is considered suitable to implement a planning visualization model.

ArcGIS is location-based and can model activities and states rather than physical objects. Aerial photos and land registry maps are available as separate layers. No physical objects are represented in ArcGIS. It is however possible to use CAD drawings as an underlay. Concluded, ArcGIS is considered a suitable option to implement a planning visualization model as present in the high-level design.

Navisworks as well as ArcGIS is, based on this chapter, suitable for the implementation of a planning visualization model. In order to make a decision which software to use, a more elaborate evaluation of the design alternatives is necessary.

12. Evaluation of design alternatives

This chapter describes the process of comparing the BIM (Navisworks) and GIS (ArcGIS) design alternatives. First, the method to perform an evaluation is explained based on the available information and test runs of both software packages. Then, the evaluation criteria and corresponding weights are defined based on the wishes from the requirements analysis. Furthermore, the alternatives are scored and a sensitivity analysis of the evaluation result is executed. Finally, a conclusion presents the software package that is used for the implementation of the visualization method.

12.1 Evaluation method

When comparing different alternatives, several qualitative and quantitative characteristics are scored. Multi-Criteria Decision Analysis is a general term for methods providing a quantitative approach to support decision making in problems involving several criteria and choices. A Weighted Sum Model (WSM) is not applicable for this evaluation, as all data compared must be in the exact same unit. As this is not the case, this method is not applicable for this research.

To evaluate and compare the alternatives, the ELECTRE method (Roy, 1991) for Multi-Criteria Decision Analysis (MCDA) is used. As the defined criteria are measured both quantitatively and qualitatively, this method seems to be most appropriate because it can consider criteria in all categories. The ELECTRE method compares the two software alternatives and for each criterion it is determined which of the designs outperforms the other(s).

Botti & Peypoch (2013) identify an important pitfall of ELECTRE method: the need for precise measurement of performance of alternatives on each criterion and its weight. The main limit of ELECTRE

methods is that both rank and weight may rely on subjective inputs from the decision-maker (when weights and performance of alternatives on each criterion are directly assigned by the decision-maker). For this research, this pitfall is covered by a validation of weights by an expert interview with Martjan Bodegom (Bodegom, 2015b)

12.2 Evaluation criteria

This section presents the evaluation criteria and weights. The set of evaluation criteria is derived from the wishes resulting from the requirements analysis and additional specifications from the high-level design. Four categories are identified in which the evaluation criteria are divided. The four categories are technical criteria, project criteria management criteria, user interface criteria and configuration criteria.

Appendix J describes the generation of evaluation criteria and the determination of associated weights as appointed by Bodegom. Table 18 presents the resulting evaluation criteria and weights

12.3 Scores of alternatives

Each of the two alternatives is evaluated and scored with one of the pre-defined evaluation options. In addition to the ELECTRE MCDA method, the current situation is included as a reference situation. Both the weighted as the unweighted scores are represented in Table 18, Appendix J provides the description of the appointed scores by Vuist and de Groot.

Table 18: Scores and weighted scores of the MCA

Main criteria	Sub criteria	Weights	Sub-weights	Current situation		BIM: Navisworks		GIS: ArcGIS	
				Score	Weighted	Score	Weighted	Score	Weighted
Functional	State representation	0,23	0,06	0	0	1	0,06	1	0,06
	Link-ability with external software		0,05	0,5	0,02	1	0,05	0,5	0,02
	Environment on scale		0,06	0	0	0	0	1	0,06
	Moving activities		0,01	0	0	0	0	1	0,01
	Activities instead of physical objects modelled		0,06	1	0,06	0	0	1	0,06
Project management	Investment cost	0,08	0,01	0	0	0,5	0,00	0,5	0,00
	Operational cost		0,03	0	0	0	0	1	0,02
	Scenario analysis comparison		0,04	0	0	1	0,04	1	0,04
	Adaptation in process		0,03	1	0,01	0,5	0,01	1	0,01
User interface	Ease of implementation	0,46	0,19	0	0	0	0	1	0,19
	Ease of use		0,19	0	0	0	0	0,5	0,10
	Time to achieve result		0,04	1	0,04	0	0	1	0,04
	Overall insight		0,04	0	0	1	0,04	1	0,04
Configuration	Changes in planning	0,23	0,08	0	0	1	0,08	1	0,08
	Changes in design		0,15	0	0	1	0,15	0,5	0,08
TOTAL		1,00	1,00	3,5	0,13	7	0,42	13	0,80

Table 18 shows the result of the ELECTRE MCDA, in which the ArcGIS design alternative scores highest both unweighted and weighted with a weighted score of 0.80 out of 1. It can be observed the distinguishing aspects between ArcGIS and Navisworks are mainly in the Functional and User interface criteria. A sensitivity analysis is conducted in the next section to illustrate the sensitivity of this result.

12.4 Sensitivity of evaluation results

Both assigning of the weights and the and ranking the alternatives are sensitive for subjectivity by the stakeholders assigning the scores. To map the effect of this subjectivity, a sensitivity analysis is executed. This analysis explains how robust the result for changes in the assumed scores and weights. Two types of parameters are evaluated in the sensitivity, as these are the only types for which values have been assumed. These are the values of the weights and related sub-weights, and the values of the appointed scores.

Sensitivity of weights

When inspecting the unweighted scores for the four main criteria, it can be seen that only for the *Configuration* criterion the unweighted score of Navisworks over ArcGIS is higher. When increasing the weight of *Configuration* main criterion to a maximum of 0.62 (to 0.23 now), the ArcGIS alternative still performs best based on the same scores.

Sensitivity of appointed scores

During the assignment of the scores, subjectivity and different perspectives may result in different types of scores. Even though opinions are underpinned, a sensitivity study discusses the heaviest weighing scores. When inspecting the sub-weights, it can be seen three heaviest weighing criteria have a combined weight of 0.53. These categories are: *Ease of implementation*, *Ease of use* and *Changes in design*.

Appendix J presents for each of these three categories an opposite score situation, in which all scores are changed to the most extreme opposite situation. For all individual sensitivity tests, the ArcGIS alternative stays first in the ranking with a small difference in weighted score. A combination of opposite scores may completely switch the ranking order.

3D CAD model availability

Even though Bodegom (2015b) stated clear no 3D models will be used in the near future by BAM Rail in preparation of a TVP, it is interesting to investigate the outcome of the MCDA. Thus, for the sensitivity analysis a check is done if the availability of a 3D CAD model would make the Navisworks alternative score higher.

If a fully operational 3D model would be available, the *Ease of implementation* would score a 1 instead of 0. The total score would 0.61 instead of 0.42. Thus, still the ArcGIS alternative would outperform the Navisworks' score. Additionally, users require the visualization model to show activities and states rather than physical objects, which strongly suggests ArcGIS best suits the high-level design.

12.5 Conclusion

An MCDA is executed in order to compare both implementation alternatives. The criteria are generated with help of the manager design (Bodegom, 2015b). Test models are created and scores are awarded by two users, Vuist and De Groot. The result of the MCDA can be concluded in three aspects:

- For the functional criteria ArcGIS scores higher than Navisworks. Being location oriented with a map or aerial photo as underlay ArcGIS matches the functional aspects of the desired user output. Furthermore, activities and states rather than physical objects are modelled which matches the requirements stated by planners to detect time-space clashes.
- Based on project management criteria, ArcGIS scores slightly better in the MCDA. The investment costs are estimated to be similar, however the operational costs of ArcGIS are estimated to be lower. In addition, no major changes in the planning process are necessary when implementing ArcGIS.
- The most noticeable difference in scores can be found in the user interface criteria where ArcGIS outperforms Navisworks in 3 out of 4 sub criteria. The intuitive, click-based character ("Google

Maps feeling”, Vuist) of ArcGIS makes using it easy for non-specialists and guarantees fast results. Therefore, ArcGIS scores high on user interface criteria.

A sensitivity analysis proves the ArcGIS outcome as consistent as both weights and scores are tested for sensitivity. The outcome order resulting from the original MCDA does not change in single alterations in weights and scores. In certain combinations of scores and weights, the ranking of the results may change. Furthermore, if a fully operational 3D model would be available, still ArcGIS would be preferable as activities rather than physical objects must be modelled.

It can be concluded the MCDA presents a robust solution, however subjectivity of stakeholders must be acknowledged. ArcGIS scores highest and is therefore chosen to implement the high-level design in.

13. Implementation in ArcGIS

This chapter presents the implementation of the previously presented high-level design in ArcGIS. First of all, the structure of ArcGIS is presented. Then, the feasible specified desired user output is presented. Additionally, a verification of the implementation of ArcGIS is done. Finally, all detected shortcomings based on the presentation of the desired output and verification are presented. Recommendations for further development are presented in Chapter 14.

13.1 ArcGIS structure

The software used for this research is ArcGIS Desktop 10.2. The Esri ArcGIS online support centre (Esri, 2012) is used as a reference in writing this section.

ArcGIS connects maps to other (non-spatial) data. ArcGIS is location-based, using spatial information as maps or aerial photos as a base layer. Connected datasets are projected as separate layers over the base layer. Layers can be defined as the mechanism used to display geographic datasets, they contain additional visualization information. Each layer refers to a dataset and specifies how that dataset is portrayed using symbols and text labels. Layers consist of objects recorded in the corresponding layer database. For example, infrastructure information can be projected as a separate layer on top of a base layer.

The background layer, usually a topological map or aerial photo, is calibrated on a coordinate system by ArcGIS. For this research, the national Dutch coordinate system (Rijksdriehoekstelsel) is used. Layers consist of objects, also referred to as *features*. Objects can be either points, lines or polygons. Information about objects is saved in underlying databases, accessible for the user. Objects can have multiple attributes, both spatial and non-spatial. Figure 33 presents a screenshot of the underlying dataset of a set of objects. Both spatial information (Shape, Location) as well as non-spatial data (Activity, Dates, Department) is registered.

OBJECTID	Shape	Shap	Shap	Activity	StartDate	EndDate	Department
9	Polygon	50.40	150.4	Inpakken telekraan	24-1-2015 20:20:00	24-1-2015 21:20:00	Kraan
47	Polygon	66.14	239.4	Leggen dwarsliggers aansluiting ak w/ sp	24-1-2015 19:50:00	24-1-2015 20:20:00	Spoer
49	Polygon	112.9	695.6	Maken 16 termietlassen in wissel en sporen	24-1-2015 18:35:00	25-1-2015 2:35:00	Spoer
69	Polygon	250.0	1746	Aanbrengen onderlaag en vlakken cunet	24-1-2015 19:40:00	24-1-2015 20:40:00	Spoer
74	Polygon	130.8	769.5	Leggen 800 dwarsliggers	24-1-2015 19:40:00	24-1-2015 20:40:00	Spoer
78	Polygon	130.8	769.5	Leggen 800 dwarsliggers	24-1-2015 19:40:00	24-1-2015 20:40:00	Spoer

Figure 33: Objects with different attributes in an ArcGIS database

Objects can be created by users by defining them in a certain layer, which is projected over the base layer. An ObjectID automatically assigned to the object in the database once an object is created. Additionally, the corresponding shape and location information are automatically linked to the object by ArcGIS.

Feature classes are collections of similar features, each having the same spatial representation, such as points, lines, or polygons. An example of a feature class is a polygon feature class for representing working locations during a TVP. The four most commonly used feature classes are points, lines, polygons, and map text.

A *geodatabase* is a collection of geographic datasets of various types, held in a common system folder. The geodatabase storage model is based on a series of essential relational database concepts. Tables and well-defined attribute types are used to store the spatial, activity and temporal attribute data for each geographic dataset. This approach provides a formal model for storing and working with data. Through this approach, structured query language (SQL) can be used to create, modify, and query tables and their data elements.

Figure 34 presents a graphical representation of the structure of ArcGIS.

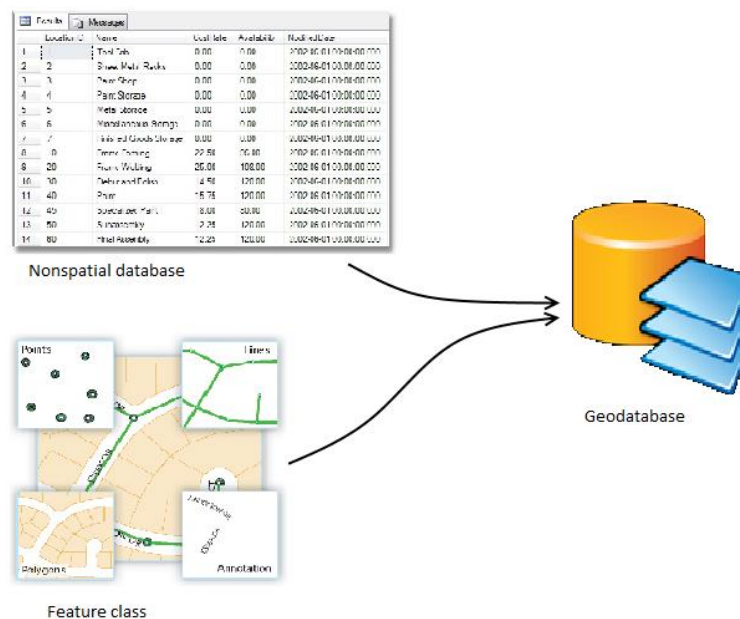


Figure 34: ArcGIS Geodatabase

Spatial information from feature classes can be linked to non-spatial databases by implementing a mutual attribute field. Either with one-to-one relations or a one-to-many relations datasets can be linked:

- *One-to-one relations* allow each row in a feature class dataset to be linked to exactly one row of in a non-spatial database, based on a mutual attribute field.

- *One-to-many relations* allow each row in a feature class dataset to be linked to multiple rows of a non-spatial database, based on a mutual attribute field.

Geoprocessing

Apart from just viewing and consulting the maps and databases, ArcGIS consists of a feature to analyse data. *Geoprocessing* provides a large set of tools for performing a different types of GIS tasks. Examples of tasks are polygon overlays, image classifications and regression analysis. Geoprocessing is based on a framework of data transformation. Geoprocessing allows users to create a sequences of tools, feeding the output of one tool into another. Users can use geoprocessing to compose a number of tool sequences that help a user automate work and solve complex problems.

13.2 User-desired output in ArcGIS

This section presents to what level the desired user output as defined in the high-level design can be generated in ArcGIS. During the high-level design, all system specifications are presented. The system specification is a specific description for which ArcGIS satisfies only a part. Detected shortcomings in the desired user output in the ArcGIS output are explained in more detail in section 13.4.

Activity-based output

Activity-based information originates from a Gantt-chart in which all activities and their attributes are saved. Currently, MS Project is used to generate a Gantt-chart. Each activity consists of the following attributes: *MutualID*, *Activity description*, *Start time*, *Duration*, *End time*, *Department*, *Critical path*. This information is exported into a spread sheet, before importing in ArcGIS can be done.

With the input attributes described as presented, for each *MutualID* a location can be defined in ArcGIS. Based on expert knowledge, a polygon represents the occupied space for each activity. Each polygon can be assigned to an activity by joining the spread sheet to the set of polygons. Table 19 presents two joined datasets. The two blue columns originate from drawn polygons in ArcGIS, the three green columns are joined non-spatial datasets.

Table 19: Mock-up joined datasets

MutualID	Location and shape description	Mutual ID	Activity description	Additional attributes
WL1.8:BVL:02	[location description]	WL1.8:BVL:02	Draad vastzetten mast 52N/150	Start time, end time, etc.
WL1.8:BVL:05	[location description]	WL1.8:BVL:05	Draad vastzetten mast 61N/110	Start time, end time, etc.
WL1.8:WSL:01	[location description]	WL1.8:WSL:01	Uithijzen wisseltong 6B	Start time, end time, etc.
WL1.8:KRAAN:03	[location description]	WL1.8:KRAAN:03	Torenkraan afbreken	Start time, end time, etc.

ArcGIS can detect time formats in data cells, which allows each activity to appear and disappear at the start and end time. An ArcGIS screenshot of activities active at 13:40:00 during a TVP is presented in Figure 35.



Figure 35: Activities represented in ArcGIS as polygons. The colour represents the department.

Time-related and infrastructure-related constraints can be implemented as well. In essence, these constraints can be seen as polygons (selectively) occupying certain locations. Similar attributes (description, location, starting time, ending time, etc.) can be defined for constraints as for activities. The result is an oversight of the constraints and restrictions, for which clash detection can be executed.

State-based output

State-based output can potentially be generated with ArcGIS (Esri, 2012). First, a spatial decomposition must be defined. ArcGIS can detect overlapping polygons by using geoprocessing models. In addition, polygons can potentially change of value (state) after overlap is detected. Partial overlap can be detected as well, priority rules can be set defining which state a certain location gets. Figure 36 presents an example how state-based output can be presented in ArcGIS.

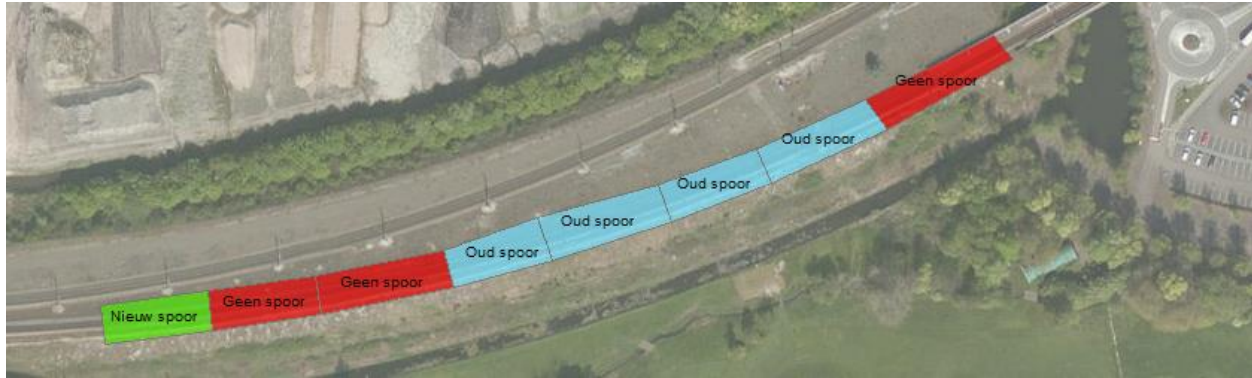


Figure 36: Spatial decomposition and state-based output in ArcGIS. The colour describes the state of a cell.

For this thesis, a functioning model producing state-based output could not be produced. However, a description of the underlying difficulties are presented in Section 13.4. Furthermore, section 14.2 presents recommendations to solve identified difficulties.

Clashes

Automatic clash detection is possible for three out of five types of clashes by the currently available version of ArcGIS. Activity clashes, activity-time clash and activity-infrastructure clashes can be detected. Users desire visual output, as presented in ArcGIS in Figure 37. Several activities are presented in this figure. Space-time clashes are shown in bright red. In addition, a list of clashes is desired. ArcGIS presents the output in a separate spread sheet. Appendix N presents an example of this detected clash.

Mind, moving activities are currently not possible to implement, thus cannot be used in this clash detection. Appendix N presents the geoprocessing model to generate the presented output.

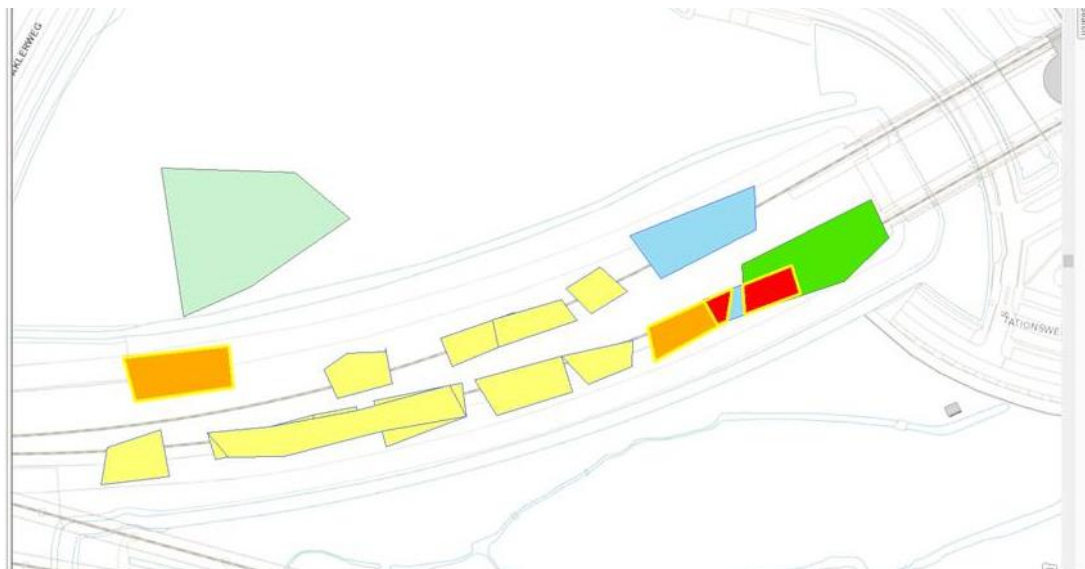


Figure 37: Automatically detected time-space clashes in red

13.3 Verification

The previous section presented if the desired user output could be presented. This section verifies if ArcGIS satisfies the requirements stated in Chapter 4. The requirement verification is conducted with Henri Vuist, potential user of the visualization method. The verification is executed based on a section of the actual planning of the 9 day TVP at OV SAAL. For 2km railway track, roughly 60 activities in a 20 hour time-span are planned in MS Project. ArcGIS is used to visualise these activities and identify mistakes.

Appendix L presents a description of the activities and a screenshot of the model. Furthermore, it describes for all requirements if they are satisfied by the ArcGIS visualization model. An explanation is included if necessary. Note, many requirements are only partially satisfied. Appendix L elaborates on these requirements as well.

Conclusion

Several requirements can be satisfied by the test run in the ArcGIS model.

- The spatial overview presents exactly what is required by users. An overview on scale including all surroundings, restrictions and distances. The zoom function is considered as a major benefit. Additionally, the implementation of an AutoCAD drawing is considered as a benefit as well.
- The test model demonstrates that activity clashes can automatically be detected. In fact, during the test runs several actual clashes were detected. The symbology and list of clashes are considered as a benefit as well.

Other requirements can only be partially satisfied during the ArcGIS test run.

- Clash detection for activities exists, however the system is not robust. Automatic clash detection is implemented by a specifically designed clash detection model. A slight change in planning makes it unusable. In addition, no moving activities are included in this clash detection.
- Time and infrastructure constraints can be manually implemented and thus used for clash detection. However, there is no input module for which these constraints can be implemented. Thus, for now these are represented as activities.

Finally, several requirements cannot be satisfied by the ArcGIS test run.

- States are currently not possible to implement. For each spatially decomposed cell only manually a state transition can be assigned. State changes cannot be initiated by activities.
- Track availability can only be drawn manually. No link with the system state can be implemented.
- Moving activities can be visualized, however no clash detection for moving activities exists.
- The ArcGIS model is cumbersome in use. Apparent easy steps require difficult processes to execute. The stability of these processes is vulnerable for input changes.
- A scenario analysis including the comparison of scenarios is currently not included.

13.4 Shortcomings and recommendations ArcGIS

Based on the verification and presentation of the desired output, a complete set of shortcomings is presented. Note, these shortcomings are based on the main functional aspects of the visualization model. The main functional aspects are defined as *clash detection*, *moving activities*, *state representation*, *scenario analysis* and *software integration*.

Recommendations proving a direction to solve the shortcomings are presented in section 14.2. Section 14.1 presents a validation of the shortcomings and recommendations by the ArcGIS software developer, Esri.

Clash detection

In the current ArcGIS model, only clashing activities can be detected. States and track availability are not included. For the activity clashes, no robust method of activity clash detection is implemented yet. For each TVP a specific process model describes the algorithm to detect (static) activity clashes. Each process model is currently specially designed for a single TVP. A more robust method to detect clashes is currently missing in ArcGIS.

In addition, no system for inserting the time constraints and infrastructure constraints exists. The current model can only manage these constraints if these are manually inserted as activities.

Clash detection of activities and constraints can be done relatively easily with adaptations of the input module of the data, as they can both be represented as polygons. State-based clash detection is a fundamental problem in ArcGIS, as no similar method of output generation yet exists in ArcGIS.

Moving activities

Moving activities currently cannot be checked for clash detection. The implementation of this functional aspect is impaired by the addition of the time dimension. When implementing static activities, each activity simply has an 'appearing time' and 'disappearing time' for which the location does not change over time. The location of an activity is inserted as a description of the coordinates in its attributes. When implementing moving activities including clash detection in the current model, the location of an activity must be explicitly defined for each time step. This results in splitting up a single activity of moving from location A to B in many different 'sub-activities' to represent the movement.

This manner of describing locations is a fundamental problem in ArcGIS, impairing the implementation of moving activities. The requirements state *an easy use must be possible*, which implies a different method to describe the location is necessary in ArcGIS.

State representation

States as described in the high-level design are currently not implemented in the ArcGIS visualization model. The absence of states is a fundamental problem in ArcGIS. Especially the interaction between activities and states requires changes in ArcGIS, as no similar function yet exists. State priority clashes to detect invalid state transitions is a unique type of clash detection, not yet implemented in ArcGIS.

Scenario analysis

No possibility to compare scenarios exist in the current ArcGIS model yet. Currently, for each scenario, a separate, independent model run must be done. Only a manual comparison can currently be executed. During the verification the absence of this functionality is identified.

No fundamental ArcGIS changes are necessary for performing a scenario analysis. The presented software architecture facilitates a scenario analysis, however a parallel structure is necessary when a comparison is executed.

Software integration

Currently, a planning schedule created in MS Project is exported in an XLS file. Via MS Excel, the data formats are prepared for the ArcGIS model. Even within ArcGIS, several operations must be done before the MS Project data can be used for the model. A robust and quick software integration is missing from the ArcGIS model.

14. Feasibility ArcGIS model

This chapter presents recommendations regarding the implementation of the high-level design by ArcGIS software company Esri. An interview with Maarten van Hulzen (Hulzen, 2015), ArcGIS software engineer for Esri Nederland, is done to validate the identified shortcomings for implementing the high-level design in ArcGIS. After the validation of the shortcomings the feasibility of implementation is discussed. In addition a time and cost indication is presented as estimated by Maarten van Hulzen.

Note: this chapter has no legal value, it cannot be interpreted as an official offer. Only indications are presented.

14.1 Validation of shortcomings

This section presents the validation of the shortcomings by Esri software engineer Maarten van Hulzen (Hulzen, 2015). In addition for each shortcoming functional aspect an implementation advice is given. Appendix A presents the full interview.

Maarten validates the shortcomings as identified in the presented model. However, he notes these are shortcomings of the *model* rather than the *software package*. With the knowledge gained in this research, these shortcomings are in line with what can be expected from an advanced ArcGIS user. Python programming language knowledge and editor access in ArcGIS is necessary to implement all functional aspects. For each functional aspects, an implementation advice is provided.

Moving activities

Van Hulzen recognizes the *moving activities* functional aspect as an administrative challenge rather than a computational. Filling the database for each time step requires two assumptions:

- All moving activities move with a constant speed in time. If a start location A is defined and a finish location B, it is assumed the speed between A and B is constant, based on the start and finish times.
- Moving activities can *only* move over rail. This assumption can be justified by the observation that currently only rail related moving activities are inserted in Gantt-charts.

The two assumptions allow a user friendly implementation of moving activities. ProRail currently has a very accurate ArcGIS plugin (ProRail Basis Beheerkaart) representing all railway lines. Van Hulzen advises the following approach:

1. Each moving activity is marked in the Gantt-chart in a special column.
2. For each moving activity, a user defines a begin location and end location, both click-based on the ProRail railway layer.
3. A width of the activity is inserted, for example 4 meter.

4. The model computes the location of the moving activity for each time step, based on the starting location, ending location, starting time, ending time and in-between path. ArcGIS automatically fills the attribute table for further clash detection operations.

Clash detection

Clash detection is recognized by Van Hulzen as "simple administrative work". Computations based on database attribute fields are considered easy to implement. It is suggested to first leave the time dimension out of account. All spatial clashes are then written to a temporary database. Then, all overlapping activities are checked for overlap in time.

The path of moving activities is discretized by the visualization model, which means the location of each moving activity is written as a separate row for each time step. This approach facilitates the clash detection model is able to detect clashes for moving activities.

State representation

States can be implemented in the ArcGIS model. By implementing overlapping rules for activities over decomposed sections, state transitions can be initiated. Van Hulzen suggests the following algorithm for state transitions.

```
For each activity
    If activity overlaps with a spatially decomposed section
        If activity initiates a state transitions
            Change state underlying decomposed section
        Else do nothing
    Else do nothing
End
```

In addition spatial clash detection can be implemented as well. If all state transitions are saved in a separate database, all can be checked for validity of state transitions by comparing them with user defined valid and invalid state transitions.

Scenario analysis

Van Hulzen states a scenario analysis is repeating the same computation with different input data. Most important aspect for conducting a valuable scenario analysis is the presentation of important information to users. Van Hulzen suggests a split-screen option is inserted, so either two scenarios, control measures or fallback scenarios can be compared. In addition, he suggests the output consists of a spreadsheet comparing different user defined KPI's to assist the user in choosing.

Software integration

Van Hulzen suggests all software integrations should be 'only one button'. A single 'import from MS Project' click should be theoretically possible to implement. Both MS Project and ArcGIS have a database structure and thus can exchange data.

14.2 Implementation feasibility

This section presents the result of a feasibility study for the implementation of the high-level design in ArcGIS. Note that both cost and time indications are rough estimations and present an order of magnitude instead of an exact figure.

It is estimated a total of 6 weeks are necessary for Esri Nederland to implement the high-level design. Mind, this is only after the official order from BAM is presented to Esri. It is estimated the financial investment is roughly [CONFIDENTIAL]. Maarten expects roughly half time is necessary to the technical implementation and functional aspects. The other half is spend in creating a clear user interface. Appendix A (Interview Maarten van Hulzen) presents a specification of the implementation times.

Given the 9-day TVP is executed in August 2016, the implementation of a visualization model in ArcGIS is considered feasible.

14.3 Advice to BAM Rail

This section presents an advice to BAM Rail regarding the implementation of the visualization model.

It is advised to start with the implementation of the high-level design in ArcGIS as soon as possible. Esri estimated they require roughly 6 weeks to implement all functional aspects in the model. As the 9-day TVP starts the 29th of July 2016, sufficient time is left for test runs and training planners to use the model. The first users to train are the TVP-coordinator, BCU and planners from the Rail department.

It is advised to implement a redundant system during the 9-day TVP, especially to reassure sceptical users. In practice the visualization model is an 'extra' step in the planning process and thus redundant. It is designed to test Gantt-charts for clashes so it can be considered as a sequential process. First, a Gantt-chart is created, then the visualization model visualizes and tests the Gantt-chart for clashes.

Generally, internal stakeholders are enthusiastic to cooperate in the implementation of the high-level design. It is expected once the visualization method shows results and detects previously unnoticed clashes, sceptical stakeholders will be convinced of the model as well. Presenting the estimated saved failure cost per TVP can help in showing the value.

Two aspects of the current planning process need extra attention when the visualization method is implemented:

- Locations must be already considered and referred to in the planning software when creating the planning schedule. This can be achieved by making this an attribute field mandatory to fill in MS Project, or directly drawing the polygons representing the location in ArcGIS.
- Dependency relations between activities and states must be inserted with extra care. Incorrect relations or mistakes can leave clashes undetected and thus result to high failure costs.

Plan for implementation

Apart from a financial investment, an implementation plan is necessary. This section describes the next steps for BAM Rail.

First of all, a project team should be created. This team should have authority to make implementation and financial decisions. It is recommended to assign only enthusiastic, open-minded team members. The following team member backgrounds are recommended:

- ArcGIS expert from BAM Infraconsult, to assist in the clash detection and visualization method.
- BAM TVP-coordinator or planner rail, to fully understand the contents and user requirements of the visualization method.
- Building process expert, to assist in the correct of implementation of the visualization method in current processes.

It is advised for the team to keep regular contact with the Esri software design team. Regular meetings (roughly once every 2 weeks) should be scheduled to monitor the progress. This design team should have at least the following tasks:

- *Monitor progress.* The primary task of the project team should be the monitoring of the projects' process.
- *Set deadlines.* Clear deadlines are necessary, as the program must be finished before the 9-day TVP. Deadlines should not only be set for the final product, but also for the completion of functional aspects. A planning including deadlines should be made together with Esri, and evaluated every meeting.
- *Organize test runs* with potential users. These in-between validations make sure throughout the complete implementation phase the objective of the visualization method is considered. Also users can comment on the half-finished product.
- Define '*showstoppers*' for the implementation of the visualization method. Showstoppers should refer at least to the most important functional aspects: *clash detection, moving activities, state representation, scenario analysis* and *software integration*. If one of these aspects cannot be realised within ArcGIS, the project team should reconsider the implementation in ArcGIS. Alternatives as Navisworks and Primavera should be studied in more detail then for possible implementation.
- *Organize training sessions* for users once first prototypes are operating. Additional user feedback can lead to additional requirements or wishes.

Summary Dym & Little stage 4

Stage 4 of Dym & Little presents the implementation of the high-level design.

Based on the literature research and high-level design, two design alternatives are generated. Autodesk's Navisworks and Esri's ArcGIS are presented as design alternatives. Both software packages are tested and reviewed for suitability for implementation of the high-level design. A multi-criteria decision analysis is executed. The four main categories of evaluation criteria are defined as functional, project management, user interface and configuration. Preliminary tests could be conducted for both packages as a basis for the MCDA, the performance of missing features is estimated.

The MCDA presented ArcGIS as highest scoring option. Two main reasons for this outcome are as following:

- ArcGIS matches the functional aspects of the desired user output by using maps or aerial photos as an underlay. Furthermore, activities and states rather than physical objects are modelled which matches the requirements stated by planners to detect time-space clashes.
- The intuitive, click-based character of ArcGIS makes using it easy for non-specialists and generates fast results.

ArcGIS connects maps to other (non-spatial) data. Connected datasets are projected as separate layers over the base layer. Each layer refers to a dataset and specifies how that dataset is portrayed using symbols and text labels.

During the process of generating and validating the desired user output in ArcGIS several shortcomings were detected. These shortcomings are listed based on the main functional aspects of the visualization model. The main functional aspects are defined as *clash detection*, *moving activities*, *state representation*, *scenario analysis* and *software integration*.

Software manufacturer Esri is consulted for two aspects. First, the identified shortcomings are confirmed for correctness. Esri recognised all shortcomings, and had several suggestions and ideas for the implementation of the high-level design were presented. In addition, Esri estimates an investment of [CONFIDENTIAL] is necessary before delivery of the software model. Mind that a legal offer still has to be made. BAM is advised to further investigate the implementation in ArcGIS.

Finally, an implementation advice for to BAM Rail is presented. The advice consists of several aspects:

- Using the ArcGIS visualization model requires two adjustments in the current planning process. First, a description of the location must be inserted in an attribute field when creating the Gantt-chart. Second, dependency relations between activities and states must be inserted with extra care to avoid undetected clashes.
- It is advised to implement a redundant system during the 9-day TVP, especially to reassure sceptical users of the success of the visualization model.
- It is advised to form a project team leading the implementation in ArcGIS. This team is responsible for the monitoring the progress and deadlines, organizing test runs and defining milestones and showstoppers.

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

15. Discussion

This chapter uses the knowledge gained throughout the research to discuss the potential for BAM Rail to implement a planning visualization method. First, a critical examination of the results is done. During this section, the presented deliverables are critically evaluated and interpreted. Then, the strengths and limitations of the research are discussed. Furthermore, a financial feasibility is presented. Finally this research is placed into perspective by presenting a bird's eye view.

This study presents primarily qualitative, non-numerical results. These results are grouped under three deliverables:

1. A set of requirements. This deliverable contains a problem analysis, stakeholder analysis and final set of requirements for the visualization method.
2. A high-level, platform independent design. This deliverable contains desired user output, model architecture, software architecture and a system specification.
3. An advice to BAM Rail for the implementation of a planning visualization method in the software package ArcGIS. This deliverable consists of an evaluation of software packages, test runs in ArcGIS and recommended developments in ArcGIS.

15.1 Discussion of the results

For each of the three deliverables a discussion is done. First, the results are interpreted and explained. Then, a critical evaluation is done. This evaluation consists of a literature comparison to investigate if the results in any way conflict or agree with existing literature or theories. Finally, new or unexpected insights are discussed.

Requirements

In the process of defining the causes of risks and efficiencies, interviews and construction site visits were the main information sources. Some stakeholders were strongly biased and provided subjective descriptions during the interviews. Many stakeholders had different interests and roles, which resulted in a wide scope of identified problems, of which some were irrelevant for this research. The presented set of requirements can be interpreted as a well-considered version of users' perspective combined with input from literature and software tests.

The planning related problems as identified during this research had many similarities with problems as identified in scientific literature. Lack of geospatial overview, lack of clash detection and no possibility to conduct a scenario analysis were identified in both literature and interviews. When researching the specific logistic characteristics of a railway system, a gap in scientific literature was identified. Especially the presented state-based output and related clashes are considered as extensions in current literature.

High-level design

The resulting high-level design can be interpreted as a platform independent description method to satisfy the user requirements. The model architecture presents an interpretation of the different types of desired user output, including clash detection. During the design of the high-level model, the focus was on a 2-dimensional geospatial representation. It is possible that the results of the first test runs in ArcGIS biased several stakeholders when describing their desired output.

Two parts of this high-level design resulted in new insights. Both resulted in a more complete design:

- When designing the model architecture, at first only state-based input and activity-based input were considered. Time and infrastructure constraints were not included, as these were implicitly accounted for. However, activities can also clash with these constraints. Only by drawing the model architecture, this was noticed.
- When creating the required input, at first an incomplete list resulted from the first analysis. Only when reasoning stepwise for each of the mock-up screenshots of the desired user output, missing input aspects were detected.

Advice to BAM Rail

The implementation in ArcGIS can be interpreted as *a* solution to satisfy the system specifications as presented in the high-level design. It is expected more software programs can meet the system specifications. ArcGIS turned out to be the best alternative during the evaluation of alternatives.

No similar studies have yet been performed in scientific literature, thus no literature comparison can be made. However, in the literature study a theory is presented which describes limitations of current planning methods (Koo & Fischer, 2000). A first verification with Vuist (2015) indicated a fully functional ArcGIS visualization model would resolve the defined problems as stated in literature.

No substantive unexpected results were found during the implementation of the high-level design in ArcGIS. Only the poor software integration between ArcGIS and MS Project unexpectedly resulted in difficulties when a connection between the packages was attempted. This difficulty was presented to Esri to further investigate.

15.2 Strengths and limitations

This section discusses the strengths and limitations for the research methodology and input sources.

Research methodology

The Dym and Little framework proved to be a suitable methodology for this research. From the start it was clear this research could be approached as a design assignment. The framework provided structure and guidance through this thesis. Primarily stage 1 and stage 2, in which stakeholder involvement is common, the framework proved its value. Minor modifications were done to form the methodology more towards this specific research.

A limitation of the application of the Dym and Little framework for this result can be found in the inflexibility for changes in the research outline. During this thesis the initial planned outline changed after a full implementation in ArcGIS proved to be infeasible for this research. In order to execute this outline change, modifications to the original Dym and Little framework had to be done. The *detailed design* stage was not executed during this research. Instead, an *implementation* stage was added.

Information sources

The following information sources were used as input for this research:

- Stakeholder interviews and site observations,
- Literature and industry specific information,
- Output of test runs.

All information sources were necessary to answer the research questions. The stakeholder analysis was necessary to identify information flows between stakeholders and understand their perspective on the

defined problem statement. The site observations assisted in experiencing first handed how operations, processes and information flows run during a TVP. Limitations in stakeholder interviews can be described as subjectivity and biased opinions. Some stakeholders stated the need for a new visualization method was non-existent, while others were enthusiastic. This resulted in two aspects: a wide set of identified problems, and myself being influenced by sceptic stakeholder opinions. By regularly checking for awareness of scepticism, these opinions were neutralized.

Scientific literature proved to be a valuable information source. Primarily when stated hypotheses and identified problems were confirmed by different researches. Additionally industry specific information sources were consulted to gather software related questions. User manuals and example case studies provided information and suggestions regarding implementation of software packages.

Limitations could be identified during the literature research. Planning visualization as specifically described in this research has not yet been described in literature. Alternative methods provided insight and suggested directions, but no similar study was yet available. Furthermore ArcGIS has not yet been applied for this objective. Necessary modifications were often impossible to be created with existing user manuals and literature. Esri confirmed this statement (Van Hulzen, 2015).

Assumptions

At the start of this research, several assumptions were presented as preconditions for a visualization method to become functional. This section presents the importance of the assumptions. Table 20 presents for each assumption the when the assumption is removed.

Table 20: Assumptions and result when removed

Assumption	Result when removing assumption
<i>All dependency relations between activities are correctly inserted in the Gantt chart for all clashes to be detected by the model.</i>	Strictly seen, if the dependency relations between activities are either omitted or invalid, the visualization model would still be functional if the starting times are correct. However, the automatic generation of the Gantt-chart would be impossible. It is therefore important that the initial generation of the dependency relations in the Gantt-chart are done carefully, to avoid clashes in the visualization stage.
<i>For all activities the state transition relation and state dependency relation are correctly inserted in the visualization model.</i>	If the activity-state dependency relations are omitted or invalid, no corresponding clashes can be detected.
<i>The expected duration of each activity is determined by an expert and therefore assumed deterministic.</i>	If the duration of activities are no longer assumed deterministic, the duration can be described by a function or distribution. If, for a random seed, a planning would be generated a visualization would still be possible. However if the advantages of a probabilistic planning would be fully used, an optimization algorithm should be added to the visualization model. For this optimization algorithm to work an extra assumption is necessary: the starting time of each activity should be expressed in ending time of the previous activity.

Miscellaneous notes

During this thesis the initial outline did not have a high-level design included. Directly from user requirements a MCDA (multi criteria decision analysis) would be executed as a first step into implementation. Later it was decided a high-level design was necessary to avoid a premature, incomplete software design. However, several test runs were already executed in ArcGIS before creating the desired user output. This reverse order may have resulted in biased stakeholders, stating their desired model output how it was already presented to them in ArcGIS test runs. This possible bias is not considered as a disadvantage, however it might have limited the imagination of users while describing desired model output.

15.3 Financial feasibility

[CONFIDENTIAL]

15.4 Validation BAM Rail

This section presents a validation by BAM Rail of the model Esri suggested to implement. Van Riel states that the implementation of the high-level design proposed by Esri looks promising. Van Riel makes the following remarks:

- For simple, linear operations, the model looks very promising. Operations can be visualized and clashes can be detected. Simple TVPs usually have small, relatively easy planning schedules. Implementation in the model looks relatively easy and visualization with the suggested model would be a valuable addition.
- For complex operations, Van Riel foresees a potential pitfall. Complex operations usually have Gantt-charts with a dynamic character. Stakeholders often request planning adaptations during the planning phase. The model that Esri suggests does not fully integrate a planning and visualization model. If test runs show this lack of integration is a major, time-consuming obstacle, success cannot be guaranteed.
- The *ideal* planning visualization model still doesn't exist, but it is expected this model is a good start. The most important missing aspect is the robust integration between a planning model and visualization model.

Concluding, BAM Rail states the visualization model solves the stated visualization problem up to a certain level of complexity. However only a very user-friendly user interface will lead to success. This will be evaluated by BAM Rail with Esri.

15.5 Bird's eye perspective

This section considers this research from a bird's eye perspective. A discussion of the fundamental position of the results is presented, to identify if the stated problems are really solved.

The requirements and the high-level design presented the need for a sophisticated and extensive software package. During the implementation phase, two software packages were evaluated. ArcGIS scored highest as a solution. Unexpectedly, as the core business of the ArcGIS lies the furthest from planning related aspects. However the verification (Chapter 13.3, Appendix L) showed still many functional aspects were missing during the test runs. Thus, Esri was asked to design a functional planning visualization model.

Esri suggested the design of a custom designed extension, based on toolboxes and custom macros searching the limits of ArcGIS. Since the investment in the implementation is expected to be profitable, BAM Rail is advised to purchase the suggested tool. The extension satisfies the system requirements, which solves BAM's initial problem. However, the suggested ArcGIS patch does not fundamentally solve planning visualization problems.

A fundamental, long term solution is not yet available in any existing package. Different functional aspects can be found in a range of software packages, however no integration exists. For each of the three schools of thought useful functional aspects can be identified:

- BIM's object-oriented perspective, linking all types of information to user defined objects, including a solid integrated time dimension.
- Project management software facilitates both deterministic and stochastic planning and re-planning, critical path analysis and scenario analysis.
- GIS's location-oriented perspective, intuitive navigation (Google Maps 'feeling'), real-time tracking and choice of back-ground layer (aerial photo, CAD drawing, ect).

A package combining the best of all functional aspects would be ideal to solve the defined problems. An ideal software package would have the object-oriented characteristics from BIM, the layer, real-time tracking and location characteristics of GIS combined with stochastic and re-planning options from a project management software. In addition, a package as described would strongly simplify the upgrade to a planning optimization package.

Concluding, the implementation can be seen as a step in the right direction for a fundamental solution. Test runs should be recorded carefully to really understand users' requirements and wishes for the design of a complete, fully integrated solution for further research.

16. Conclusion and recommendations

This chapter describes the conclusions and recommendations for this research project. At the end of the chapter, this graduation research project is reflected upon.

16.1 Conclusion

First, this section gives an answer to the six sub-questions from Section 2.1. Then, the main research question is answered.

Each of the following research sub questions were stated to provide structure to answer the main research question:

1. What planning methods and tools are currently used at construction sites?
2. What are the risks and inefficiencies resulting from these currently used methods?
3. What are user requirements for a method to provide extra insight?
4. What high-level model design and software design describes a method to provide extra insight?
5. What planning related software packages are currently available?
6. Which design options can be distinguished for the method to visualize the 9-day TVP at OV SAAL?

Planning methods and risks in current situation (sub question 1 and 2)

Currently, three methods are used by contractors to plan and schedule construction works and operations.

- Gantt-charts are project planning diagrams often used by contractors. Dependency relations between activities exist. In addition, expected time to complete the activity is presented.
- Time-distance diagrams are occasionally used for long, linear construction sites. Time-distance diagrams can only show a single spatial dimension.
- Critical path networks (CPN) represent activities by a network of nodes and edges. Dependency relations and activity durations are used to compute and visualise the critical path.

The risks and inefficiencies resulting from the use of these three methods affect multiple stakeholders. Key stakeholders are the planning departments, the TVP-coordinator and the BCU. It is found if causes of risks and inefficiencies are detected during the planning phase by the TVP-coordinator, they can be avoided during the construction phase of a project. The identified causes of risks and inefficiencies are stated as following:

1. *Absence of clash detection*: some clashing activities and invalid state sequences are left unidentified in the planning phase, resulting in failure costs during the construction phase.
2. *High project complexity*: Gantt-charts become too complex to comprehend, resulting in experts making mistakes when creating planning schedules.
3. *Missing project overview*: no basic site overview is available, resulting in non-expert stakeholders making wrong decisions.
4. *The impossibility to perform a scenario analysis*: this results in failure costs as no control measures and fall back scenarios can be quantitatively analysed.
5. *The impossibility to show construction logistics real-time*: train paths and machinery locations are unknown, resulting in failure costs when making operational decisions.
6. *The impossibility to determine delay propagations real-time*: measures to settle delayed activities cannot be quantitatively analysed real-time, resulting in failure costs when making operational decisions.

Concluding, there is insufficient insight into planning and scheduling site operations. Risks and inefficiencies occur because of the very limited representation of the spatial component. Currently, this spatial information is unavailable in the planning methods. Key stakeholders state that connecting the time dimension with geometrical dimensions results in a risk reduction. A better planning visualization method must be developed.

User requirements and high-level design (sub question 3 and 4)

A set of user requirements and wishes span the solution space for the high-level design. The user requirements are obtained during a set of interviews and transformed into clear, complete, consistent and unambiguous requirements. A distinction between functional, non-functional, interface and institutional requirements is made. Furthermore, six categories of requirements are distinguished: Clashes, construction logistics, delays, spatial overview, user interface and miscellaneous. It was

concluded that the presented set of requirements is at least necessary for the stakeholders to fully satisfy them.

With a complete set of requirements, a literature study was done. Conclusions from literature state that the problems BAM Rail encounters are not unique. However, no solution has yet been found in literature for the unique TVP characteristics.

Before implementing a solution, a high-level model design and software design are presented. It was found that a connection exists between activities and the state of the system. In addition, five different types of clashes were identified. After investigation, it was concluded that all five types of clashes can be included in the visualization model. By back tracing the user requirements it was verified that the system specifications, the model architecture and software architecture present a complete high-level design.

Software implementation for BAM Rail (sub question 5 and 6)

No ready-to-use software package exists for the implementation of the high-level design. Until recently, both from the contractors' side as from the software developers' side no incentives existed to create a planning visualization model. Only recently the need to decrease failure costs became a reason for BAM to develop cost saving software innovations. Several software packages are currently available as possible solutions for the problem statement.

- Project planning software packages as *MS Project* and *Primavera P6* have limited geospatial plugins that allow the projection of spatial activities on a map. State-based output and moving activities cannot be expressed.
- BIM software package *Navisworks* can link a 3D design to a planning, creating a 4D BIM model. *Navisworks* facilitates the connection of physical objects with a planning schedule. States and activities cannot be represented with these 3D models.
- GIS software package *ArcGIS* connects spatial data to non-spatial data. A 2-dimensional layered model can represent activities by projecting polygons on a background map. In addition, 2D CAD drawings can be used as an underlay.

With the help of an MCDA it is concluded that *ArcGIS* is most suitable for the implementation of the high-level design. *ArcGIS* can project an aerial photo as underlay and present activities and states rather than physical objects. These characteristics match with the requirements stated by users for the 9 day TVP. *ArcGIS* is not yet ready for implementation of the high-level design. Five main functional aspects need further development: clash detection, moving activities, state representation, scenario analysis and software integration.

Answer to the main research question

The main research question of this research was:

How can BAM Rail get insight into the state of the construction works at a line construction site at each time step?

A planning visualization model must be developed to give users insight into the state of a construction site at each time step. *ArcGIS* is the most suitable software program to make this planning visualization

model. ArcGIS has the possibility to project activities and states as polygons on a map. Furthermore, CAD drawings and aerial photos guarantee an overview on scale. Finally, intuitive navigation through ArcGIS results in satisfying the desires of all users – from planner to site manager – to get insight into the state of the construction site at each time step.

However, an ArcGIS planning visualization model is not yet fully functional. Five main functional aspects need to be implemented by Esri before all requirements can be fulfilled. These main functional aspects are: clash detection, moving activities, state representation, scenario analysis and software integration. Software company Esri estimates a financial investment of [CONFIDENTIAL] is necessary to design a fully functional TVP visualization model for BAM Rail. Esri expects this model can be completed [CONFIDENTIAL]. It is concluded this is on time for the model to be used in preparations of the 9 day TVP in August 2016.

16.2 Recommendations

The **main recommendation** for BAM Rail has been presented in Section 14.3: It is recommended to implement the presented visualization method in ArcGIS. Two types of additional recommendations are described. First, recommendations for BAM are discussed. Both for implementation of the visualization method as well as recommendations resulting from general observations during this research. Finally, recommendations for further research are given, both within and outside the scope of this research.

Recommendations for BAM

It was observed that the on-site communication between the coordinating construction site manager (BCU) and construction site managers (Uitvoerder) during construction works is done by phone calls, once every 2-4 hours. During these phone calls, the BCU and the site manager communicate if they are on schedule and if any difficulties occur. Occasionally extra information is exchanged. Each of these phone calls take about 10 minutes on average (Immers, Aerts, de Groot, 2015). The BCU manually draws a progress line on a large printed Gantt-chart on the wall to monitor the progress. He takes action when delays become a danger to the milestones.

It is recommended to research the possibility of an integrated mobile system (e.g. tablet application) for site managers to report the progress. Activities could be marked as ‘completed’ or a ‘percentage completed’ in a checklist, to be filled in by each construction site manager. If any extra information needs to be transferred, it can be either typed into the mobile application or a call-back request can be made. This recommendation should be researched by a committee, consisting of a site manager, software engineer and BCU.

According to several stakeholders, the currently executed TVP risk analysis is a simple ‘copy paste’ from previous TVPs and not thoroughly researched. Based on expertise and very rough qualitative estimations a risk analysis is presented (Integraal draaiboek OV SAAL 2-5-2). This risk analysis should be tested more extensively to detect TVP-specific risks. Two solutions are recommended:

- It is recommended to execute a probabilistic scenario analysis, instead of a deterministic scenario analysis. In the *recommendations for further research* below, a more elaborate explanation is done.

- It is recommended to register incidents in an incident database. Each occurred incident can be inserted in this database. When planning future TVPs the database can be consulted to better identify and assess risks and consequences.

Additionally, the situation beforehand must be completely inspected to reduce extra risks. Currently, it often occurs physical obstacles or deviating situations are only discovered during the construction phase. If no thorough investigation is conducted, removal of these objects is not taken into account. When these objects or deviations are discovered, delays can occur threatening the critical path. It is recommended for each TVP the responsible construction site manager checks beforehand if the actual state of the system matches that the planned state of the system.

The final recommendation for BAM refers to the implementation of the visualization method. During the research, the addition of a spatial component to a Gantt-chart was often mentioned as needless by general interviewees. The spatial component needs a better integration even in the first stages of planning and scheduling. Planners need to consider the location of activities when planning activities. It is recommended to make the *location* attribute field obligatory to fill in for planners when creating a planning schedule in MS Project.

Recommendations for further research

It is important to emphasise that this thesis presents a *visualization* algorithm rather than an *optimization* algorithm. Several recommendations are presented for the next step: implementing an optimization algorithm to not only *visualize* planners' decisions, but also *making* them.

A major assumption made in this research is that the activity duration is considered deterministic rather than probabilistic. In addition, each activity requires a predefined starting time instead of a variable starting time depending on previously completed activities. It is recommended to research the possibility of the following aspects:

1. Add a probabilistic activity duration by estimating the probability density functions for each activity duration.
2. Express the starting time of each activity in completion time of prior activities. For example:

$$t_{start}(activity\ C) = \max(t_{completion}(activity\ A), t_{completion}(activity\ B))$$

Combining these two aspects results in several advantages for the complete planning process:

- No 'useless' waiting time exists, as early completion of previous activities allows a new activity to start instantly, instead of waiting for the predefined starting time.
- Conditional planning schedules can be created, allowing user-defined thresholds to decide which scenario to execute. For example: *Only if $t_{completion}(activity\ C) < 15.00h$, activity D can start. Else, $t_{start}(activity\ D) = 16.00h$.*
- A Monte Carlo analysis can be done to test a planning schedule for robustness. Random sampling activity durations facilitates that clashes and the critical path can be investigated numerically.

For the implementation of an optimization algorithm, all constraints and restrictions must be carefully reviewed. Currently temporal and infrastructure restrictions are only considered qualitatively and are not expressed in Gantt-charts. It is recommended that all constraints are carefully researched, as errors would either detect non-existing clashes or leave actual clashes undetected. Both situations result in failure costs. It is advised that the TVP coordinator coordinates this process.

An important side note is necessary when performing further research in optimizing a Gantt-chart. Already before the start of a TVP, working schedules are made. Working crew, material deliveries and machinery is all planned in advance. Thus, sudden changes in a schedule cannot always be executed, as resources are not always available.

Therefore before an optimization algorithm is implemented, it is recommended to implement resources as an extra dimension in the model. If we consider a dimension as an independent variable with a set of constraints, many more resources can be added similarly as is done in the research. For example, consider the availability of a certain type of working crew (resource) as a dimension. There are constraints for this dimension as well. If for each activity the number of necessary working crew would be inserted, an optimization algorithm can be created.

A final recommendation is presented. It is not related to an optimization algorithm, but presents a final, albeit unrelated, recommendation for further research.

For the solution presented in this research, the highest cost savings can be achieved during the planning and preparations phase. However, real-time monitoring of the construction site and eventually comparing the state with the planned schedule is an interesting follow-up step. If a BCU could compare the actual state of the system with the planned state of the system, a new model run can be done to detect clashes for the new situation. For instance, BAM can place GPS trackers on machinery for implementation in the visualization method for this step.

16.3 Personal reflection

The past six months were a fun and challenging period with a steep learning curve. I applied at an internship at BAM as I expected BAM to be practical, pragmatic and in need of 'something new'. All proved to be true, and I had a great time every day at Duivendrecht at the construction site of OV SAAL.

Two parts I enjoyed most during this research. First, the stakeholder interviews to really understand the risks and inefficiencies resulting from the current way of planning. I was unaware of many processes before starting this research. An example of a surprising fact I did not know was the working of the tamping machine (stopmachine). Not because of its relevance for this research, but out of curiosity. In addition, stakeholders occasionally took me for site visits to explain techniques, notify risks, inefficiencies or just because it was sunny outside.

Second, I enjoyed the creation of the ArcGIS visualization model. I expected already during the problem analysis ArcGIS probably would be useful in solving the problem. Thus, when I finished the problem analysis I was able to 'dive' into ArcGIS and experiment with the software package. In addition, I was slightly disappointed when I noticed ArcGIS's features were not as extensive as I expected.

The most challenging research part was conducting a complete and consistent set of requirements. During the complete research new requirements popped up and needed to be added to the requirements analysis. Validating a requirements analysis of a feasibility study proved to be difficult, as no clear completion moment can be defined. The only method to check for missing requirements is by model test runs and by searching for missing or illogical parts.

The most challenging writing aspect was writing the discussion, as primarily qualitative results were presented during the research. Especially the interpretation and critical review of the results was experienced as difficult. Often, interpretation of results is already done in corresponding chapters. For example: interpreting the set of requirements results in system specifications. Interpreting these lead to an implementation. Only a critical review could be done in the discussion chapter.

I personally would recommend any master student to perform their MSc thesis at a company rather than at the TU Delft with a purely TU Delft assignment. The practical application of scientific knowledge is challenging, but with a sharp eye and good supervision is very well feasible. Stakeholders often challenge you with real-world examples you will face after graduation as well.

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