Design Validation

"A gaming simulation on the effect of 3D visualisation"

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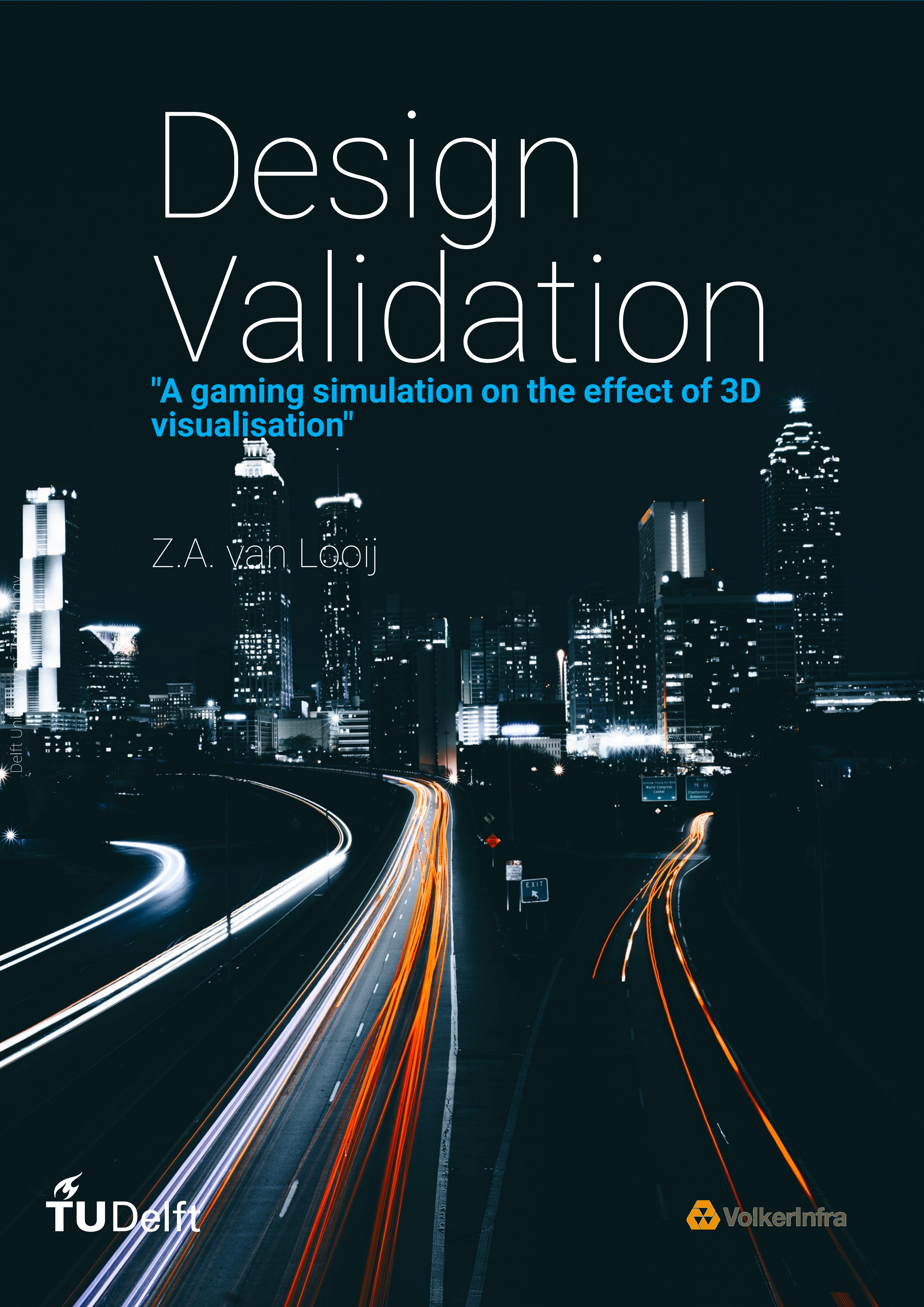

TU Delft

VolkerInfra

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"A gaming simulation on the effect of 3D visualisation"

by

Z.A. van Looij

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at the Delft University of Technology,
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This thesis is confidential and cannot made public until June 20, 2019.

Preface

This report presents the research I conducted to complete the master Construction Management and Engineering at the Delft University of Technology in the Netherlands. The research is executed at the contractor firm VolkerInfra, within the department project control, systems engineering. In the year between my bachelor and master program I worked as a systems engineer consultant. While working I wondered about the problems with verification and validation during integral infrastructure projects and in particular the consequences when it is not correctly executed. From small quality deficiencies till considerable time delays and significant failure costs in projects. This interest turned into this research in the effects of 3D visualisation on design validation. Undoubtedly, it was not possible to address the entire problem or the multiple problems within the verification and validation processes. However, my motivation was to improve the validation process partly by investigating the use of 3D visualisation.

Before presenting the results of this research I would like to thank a few people for supporting me during this research. First, I would like to thank all my colleagues at VolkerInfra because they shared all their knowledge, but also the nice working environment and fun lunches in Vianen. Besides that, I would like to thank all colleagues who participated very enthusiastic in the experiment and contributed to the results in this research.

Secondly, I would like to thank the members of my graduation committee for their comments, constructive feedback, and suggestions during the process. You made it possible to improve the report and academic level of the research.

A special thanks to my company supervisor Erwin Boersma, who supported me during the process. I would like to thank you for thinking along during the research, the brainstorm sessions, and the encouragements.

And last, but not least, I would like to thank my friends and family for their endless support, motivational speeches and reviews throughout my thesis.

I hope you will enjoy reading the report.

Z.A. van Looij
Amsterdam, December 2018

Summary

Over the last decades, the civil engineering industry has been influenced by the introduction of Systems Engineering (SE). Nowadays, this approach is more and more instructed by clients in the Netherlands. The switch to Systems Engineering was necessary because of the development of integrated contracts (UAV-GC; Uniform Administrative Conditions for Integrated Contracts) such as Design-Build-Finance-Maintain (DBFM) and Design & Construct (D&C). Before the introduction of integrated contracts, mainly RAW contracts (Rationalization and automation Soil, Water and Road Construction) were used in the Netherlands for public procurement in infrastructure projects. In RAW contracts, the to be built system is described in detail and the segregation of responsibilities between client and contractor is distinctly defined. In integrated contracts, this distinctly defined segregation of responsibilities is missing. As a result of the integrated contracts, the projects became more complex and multidisciplinary, which asked for a more structured approach (Emes et al., 2012). Another difficulty of integrated contracts is the communication between client and contractor because more information has to be transferred. An important element of SE are the verification and validation processes. This validation process is considered complicated in the civil engineering industry.

Four subproblems are determined by means of literature and practical knowledge. First, the interaction between client and contractor. Findings of a questionnaire performed by the CROW (2017) about the relationship between client and contractor are:

- 56.9% of the contractors' employees do not feel equally treated by the client;
- 43.6% of the clients' employees and 69.7% of the contractors' employees agree on the statement that the other party is mainly defensive instead of cooperative;
- Another issue during the interaction between client and contractor is trust. 23.3% of the clients' employees and 17.7% of the contractors' employees say that the other party cannot be trusted;
- 73.6% of the clients' employees and 73.5% of the contractors' employees disagree on the fact that the other party puts the common interests of the project above their own interests.

The second subproblem is the confusion between verification and validation. Verification is the process of determining if the system meets the specified requirements (Alsem et al., 2013). Nevertheless, the purpose of the validation process according to ISO (2015) is "to provide objective evidence that the system, when in use, fulfils its business or mission objectives and stakeholder requirements, achieving its intended use in its intended operational environment" (ISO, 2015, p. 74).

The third subproblem is executing sufficient validation. The difficulty is to represent the client and stakeholders needs in requirements. Therefore, the validation is often conducted last-minute in the construction phase of the project. The fourth subproblem is that the effects of the use of 3D visualisation during design validation on project performances are unknown.

These problems result in the following research objective and question. The aim of this research is to gain insight in the effects of 3D visualisation during the design validation on the project performances, namely time, costs and quality.

What are possible effects of 3D visualisation on design validation within the civil engineering sector in the Netherlands?

The methodology for this research consists of three phases: (1) context, which includes literature and project evaluations, (2) experiment, which contains baseline and follow-up measurements and (3) the results and conclusion. Phase two, experiment, is a gaming simulation called the ontwikkelstraat. In this research, the following definition is used for gaming simulation: "a special type of model that uses gaming techniques to model and simulate a system. A gaming simulation is an operating model of a real-life system in which actors in roles partially recreate the behaviour of the system (Meijer, 2009)".

The Ontwikkelstraat is a two-day case imitating a project from tender till exploitation and includes design, construction and maintenance of a hydrogen factory. During this gaming simulation, three types of measurements are conducted: questionnaires, recordings of the interaction between client and contractor, and observations.

Context
According to the literature, sufficient design validation has to fulfil several conditions. The aim is to acquire proof that the system in its ability to achieve its intended use (ISO, 2015). Rijkswaterstaat (2017) prescribes three conditions the design validation should meet, namely:

- Design validation is an integral element of the design process;
- Confirmation by client and stakeholders;
- Determine the validation process in cooperation with the client.

There are multiple ways of conducting design validation. Several design activities are of importance for design validation. During the system design phase, these activities are analysing contract documents, as well as document functionalities, requirements and systems. In the preliminary design phase, these activities are based on the variants and validation of the design products. It is concluded from the three cases studied that alignment of the design products with client and stakeholders is a key validation step in all cases.

Bryde et al. (2014), Sebastian and Van Berlo (2011), and Azhar (2012) described the capabilities of 3D visualisation. Three-dimensional visualisation can be static or dynamic. With a static image of the 3D model of the design, the communication and coordination between actors and disciplines are more detailed. By decomposition in subsystems and objects, the technical details of the design can be sufficiently discussed during the validation sessions with the client and stakeholders.

Another capability of the 3D visualisation is expectation management between contractor, client and stakeholders. 3D visualisation can also be used for dynamic images for moving systems, such as locks and movable bridges, which can be used for showing the functionalities of the design. Dynamic images can confirm that the design meets the intended functionalities and use of the system that is going to be built.

Currently, 3D visualisation is used within the civil engineering sector in the Netherlands is by means of BIM. Within the civil engineering sector in the Netherlands companies deviate in the BIM maturity level, as well as the multiple subsidiaries within the contractor firm VolkerWessels. According to the BIM wedge that is developed by Bew and Richards (2008), level 1 of the BIM maturity is implemented. Therefore, the use of 3D visualisation is implemented in all integral projects within the infrastructure branch of VolkerWessels. The 3D models are used for clash detection, reinforcement in concrete, immediate vicinity and quantities.

Conclusion
According the results of the gaming simulation, visualisation does not have an effect on the project performances time, costs and quality. A possible explanation that no effect of visualisation on the project performances has been found is that the physical model of the hydrogen factory in the ontwikkelstraat was only used during one of the follow-up measurements. During the other two follow-up measurement, the physical model was not used by the participants. The follow-up measurement where the physical model was used, it was used by one participant, who built the model. However, the participant did not communicate his findings from the physical model to the other project team members. Therefore, there are not enough results to conclude that there are no effects of visualised validation on the project performances.

From observations during the gaming simulation, it can be concluded that not the availability of the 3D model, but the standard practice of project teams is the issue.

Reflection
This research aimed to fill the theoretical gap on the effects of 3D visualisation on design validation. Although this aim is achieved, every research has to make compromises to stay within scope. The main limitations are presented in the itemisation below.

- Lack of proper literature regarding the conditions for sufficient design validation;
- Small sample size of the gaming simulation, which makes it harder to generalise the findings;
- Time constraints during the gaming simulation, the participants are under a lot of time pressure during particularly the design phases. Therefore it is possible they overlooked the physical scale model.

Further research
Soms suggestions for further research are:

- It is found that not the availability of the 3D visualisation is the problem, but the standard practice of project teams play a role. Therefore, research on the problems of implementation of 3D models during design validation and how to solve these problems would b relevant for the whole construction industry;
- During the project evaluations, it has been found that the way of handling changes in the contract after pro- curement is challenging. It turns out that validation of the design is often obstructed because the results of the validation process can result in uncertainties for all actors in a construction project. Research on the politics behind the changes in construction projects is relevant, because of the uncertainties these politics bring in the development of projects and the relationship between all actors that are involved;
- Lastly, further research on the interaction between client and contractor is needed. Research on the development of achievable strategies to manage the counterbalance between collaboration and competition between client and contractor would be significant.

Recommendations for practice
Based on the literature and project evaluations, a proposed approach, called visualised validation approach (VVA) is developed. The VVA is a combination of two different project management methodologies, which are the V-model and the scrum. During the System design phase, three activities are essential: determining V&V management plan, requirement validation, and interaction with the client about the intended use of the system. The preliminary design phase is an iterative process, with scrum design sprints and validation sessions with the client and stakeholders.

The biggest challenge in the construction industry is the implementation of the visualised validation approach. According to an internal investigation, the accessibility of the process and in particular the 3D models have impact on the implementation of the VVA. Several employees indicated that they are reserved to use new approaches because of the lack of skills or manpower.

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List of Abbreviations

Abbreviations	Explanation	Dutch
2D	Two-dimensional	
3D	Three-dimensional	
avg.	Average	
BDS	Building Description System	
BIM	Building Information Model	
BIR	Building Information Board	Bouw Informatie Raad
CAD	Computer Aided Design	
CROW	Center for Regulation and Research in Soil, Water and Road Construction and Traffic Engineering	Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw
D&C	Design & Construct	
DBFM	Design Build Finance Maintain	
DO	Final Design	Definitief Ontwerp
EBIT	Earnings Before Interests and Taks	
EXPL	Exploitation	
FBS	Functional Breakdown Structure	
GWW	Soil, Road and Water construction	Grond-, Water-, Wegenbouw
ISO	International Organization of Standardisation	
LoD	Level of Detail	
OCD	Operational Concept Description	
OG	Client	Opdrachtgever
ON	Contractor	Opdrachtnemer
ProMaSys	Project Management System	
RAW	Rationalisation and automation Soil, Water and Road Constuction	Rationalisatie en Automatisering Grond-, Water- en Wegenbouw
RBS	Requirement Breakdown Structure	
RWS	Rijkswaterstaat	
SBS	System Breakdown Structure	
SE	Systems Engineering	
SMART	Specific Measurable Attainable Realisable Time-bounded	
SO	System Design	Systeem Ontwerp
SRR	System Requirements Review	
TOM	Trade Off Matrix	
UAV-GC	Uniform Administrative Conditions for Integrated Contracts	Uniforme Administratieve Voorwaarden voor Geïntegreerde Contractvormen
UO	Execution Design	Uitvoerings Ontwerp
V&V	Verification and Validation	
VHB	Van Hattum en Blankevoort	
VI	VolkerInfra	
VISE	VolkerInfra Systems Engineering	
VO	Preliminary Design	Voor Ontwerp
VR	VolkerRail	
VVA	Visualised Validation Approach	

Part I
Introduction

Part I is divided in two chapters, (1) the introduction and (2) context. In paragraph 1.1, the problem statement is elaborated. Paragraph 1.2 contains the research objective, and paragraph 1.3 discusses the research and sub-questions. Afterwards, paragraph 1.4 explains the scope and methodology (paragraph 1.5) and finally, in paragraph 1.6, the reading guide of this report is given. The aim of this chapter is to introduce the subject and methodology of the research.

In chapter two, an outline is given on the essential factors of the research. This is done by means of literature and project evaluations. The first paragraph consists of an elaboration on design validation. Paragraph 2.2 discusses 3D visualisation, what it is and how it is conducted currently in infrastructure projects. The chapter ends with an interim conclusion, which elements are considered during the gaming simulation.

1 Introduction

Over the last decades, the civil engineering industry has been influenced by the introduction of Systems Engineering (SE). Nowadays, this approach is more and more instructed by clients in the Netherlands. The switch to Systems Engineering was necessary because of the development of integrated contracts (UAV-GC; Uniform Administrative Conditions for Integrated Contracts) such as Design-Build-Finance-Maintain (DBFM) and Design & Construct (D&C). Before the introduction of integrated contracts, mainly RAW contracts (Rationalization and automation Soil, Water and Road Construction) were used in the Netherlands for public procurement in infrastructure projects. In RAW contracts, the to be built system is described in detail and the segregation of responsibilities between client and contractor is distinctly defined. In integrated contracts, this distinctly defined segregation of responsibilities is missing. As a result of the integrated contracts, the projects became more complex and multidisciplinary, which asked for a more structured approach (Emes et al., 2012). Another difficulty of integrated contracts is the communication between client and contractor because more information has to be transferred. An important element of SE is the verification and validation process. This validation process is considered complicated in the civil engineering industry.

Research regarding validation problems is scarce, notwithstanding, a few studies are done combining verification and validation (V&V) problems in the construction industry. For example a research by Bahill and Henderson (2005) concerning verification and validation well-known failures in which two dozen projects are discussed. In a comprehensive study of 260 construction projects in Australia, Love et al. (2009) conducted two conclusions about these modifications or rework, first, rework costs are meanly 11.07% of the contract value; and secondly, the errors and omissions in contract documentation were two of the most highly correlated causes of rework.

Lee et al. (2012) determined several causes for design errors, which are illogical design (22.28%), discrepancies between drawings (50.49%) and missing items (27.22%). When the validation process is improved by means of visualisation and executed sufficiently in the early design phase it would lead to cost and time reduction for the whole industry (Kennedy et al., 2014).

1.1. Problem description

As stated previously, the validation process is considered complicated in the civil engineering industry. Within this subject, several problems are identified. The subproblems are determined by means of literature and practical knowledge. In the following paragraphs, the subproblems are explained.

1.1.1. Subproblem 1 - Interaction client and contractor

In the past, RAW contracts were mainly used in the Netherlands for public procurement in infrastructure projects. In these contracts, the segregation of responsibilities between client and contractor is distinctly defined. The integrated UAV-GC 2005 contracts, led to other responsibilities for client and contractor. According to Welten (2017) these responsibilities are unambiguous:

- The client is responsible for the content of the tender specification and all other information that has been made available to the contractor;
- The contractor is responsible to warn the client if these documents contain mistakes or defects.

This warning duty asks the contractor to study the provided information in detail and to make design suggestions (Welten, 2017). When the specification of the client is more specified and detailed, the contractor has less responsibility regarding the warning duty, due to the limited design phase. Within the UAV-GC 2005, the content of a project can vary considerably, so in practice, the content of a project determines the responsibility of the contractor. Nevertheless, the client actually wants to decide 'what should be built', without having the responsibility for the information they provided (Welten, 2017). This contradiction decreases the collaboration between client and contractor (Dorée, 2001).

During the interaction between client and contractor, trust is a major issue (Laan and Sijpersma, 2006). A statement, which is often heard in the civil engineering industry is that contractors cannot be trusted because they enter the tender sharply and claim additional work if possible afterwards. Another statement is that clients do not take responsibility for all risks and they do begrudge the contractor any profit (van Ommen, 2017).

These statements were a reason for the Center for regulation and research in the soil, water and road construction and traffic engineering (CROW) to investigate how clients and contractors within the soil, water and road industry (GWW) think about each other. In 2017 a questionnaire was provided to 280 persons, from which 148 work at a client firm and 123 at a contractors firm. The remaining participants were not working in the industry. The survey consisted of 27 questions about the biggest grievances within the industry. In figure 1.1, the numbers of the most important results are shown. These four questions were particularly related to the interaction between client and contractor, namely unequal treatment, setting common interest above own interest, trust and acting defensive instead of cooperative.

The upper left histogram shows the percentage of reaction on the statement: 'The client / Contractors do not treat us as equal'. A difference can be seen in answers of the client, who answer disagree and contractors, for which 48.6% answer agree.

The upper right histogram shows the percentages of answers on the question: 'Clients/Contractors place the common interest above their own interests'. The results show that most participants on both sides disagree with this statement.

The lower left histogram shows the percentages of answers on the question: 'Clients/Contractors can be trusted'. Most participants answered neutral, however, 17.7% of the participants working at contractors and 23.2% of the participants working at clients answered disagree.

The lower right histogram shows the percentage of answers on the question: 'Clients/Contractors are mainly defensive rather than cooperative'. Most participants from both parties answered agree on this statement (CROW, 2017).

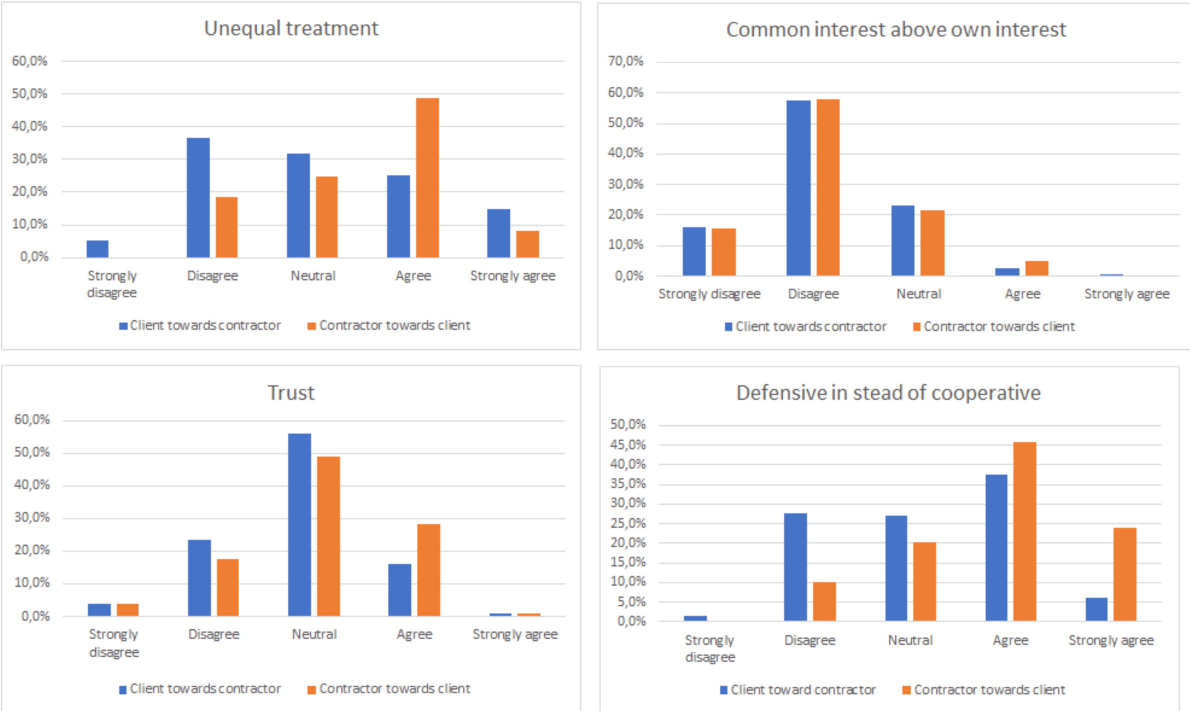

Figure 1.1: Results of the great grievances in the construction industry in the Netherlands (CROW, 2017)

Based on these results it can be concluded that collaboration between clients and contractors is challenging, for the reason that common interest and cooperativeness are not experienced high values in this collaboration. Improvement of this relationship is not within the scope of this research, however, the interaction between client and contractor plays a role during the design validation process. The conditions of the current interaction between client and contractor are considered during the visualised validation approach.

1.1.2. Subproblem 2 - Confusion between verification and validation

The second problem concerns essential elements of SE, namely the verification and validation (V&V) processes. These terms are frequently used in literature, although, they are often confused or combined as one process (Lucko and Rojas, 2010). Verification is the process of determining if the system meets the specified requirements (Alsem et al., 2013). Nevertheless, the purpose of the validation process according to ISO (2015) is "to provide objective evidence that the system, when in use, fulfils its business or mission objectives and stakeholder requirements, achieving its intended use in its intended operational environment" (ISO, 2015, p. 74).

1.1.3. Subproblem 3 - Validation

Over the past years, contractors experience problems regarding the validation process. In practice, the process is considered time-consuming and complicated. Currently, the validation process is often conducted last-minute in the construction phase of the project. However, the validation process has to be continuous and iterative during the different life-cycle phases of the project (Kennedy et al., 2014; Wasson, 2006). If the validation results in modifications at the end of the construction phase or no validation takes place, it could result in higher time delays, budget overruns or insufficient quality.

Project life-cycle within construction projects have a tendency to be sequential without considerable overlap between the phases. Therefore, it is problematic to build prototypes and evaluate them in order to improve the design. This limits the ability to let user groups actively evaluate the end product and get feedback concerning the quality of the end result in comparison to their expectations.

Additionally, representing the client needs in the specification is complicated. Client needs are defined as the needs and wishes of all stakeholders. Examples of clients in the Netherlands are Rijkswaterstaat (RWS) and ProRail. Other stakeholders are governmental institutions, local residents and users of the system, such as maintenance workers, operational workers or road users. This causes problems regarding the design process, in which validation is important from the start. If the validation is conducted at the end of the design process when the final design is presented, it might lead to high budget overrun, time delays, or most essential for validation, the system's intended use is not met.

1.1.4. Subproblem 4 - Unknown effects

Many studies on the advantages and project benefits of the usage of 3D models or Building Information Models (BIM) have been conducted, such as the study of Bryde et al. (2014) and Azhar et al. (2012). Bryde et al. (2014) determined the following advantages:

- Better expectation management, because of the early and accurate visualisation;
- Better communication and coordination;
- Quality increase and fewer failure costs;
- Shorter lead time of design and execution.

These advantages are quantified by Bryde et al. (2014) by means of analysing data of 35 completed construction projects that implemented BIM. The success criterion which was found most frequently was cost reduction, which was found in 21 of the 35 cases (60%). Thereafter, communication improvement (37.14%), time reduction, coordination improvement and quality increase (34.29%).

While in literature, these benefits are so explicit and well-studied, in practice, project teams do not accept the implementation of BIM or 3D visualisation. The people do not feel the urgency to use BIM due to the ignorance what BIM can add to projects. This added value of the use of 3D visualisation with the purpose design validation within an infrastructure project is unknown.

1.1.5. Conclusion problem description

The previous paragraphs describe the subproblems, which are the motivation for this research. These subproblems are determined by means of literature and practical knowledge. In figure 1.2, an overview of the problems is presented. The subproblems lead to an insufficient validation process during the early design phases. As a result of this insufficient process, mistakes and/or changes are made during the project. These are detected later than with sufficient design validation due to for example interpretation differences between client and contractor. These mistakes and/or changes lead to poor project performances.

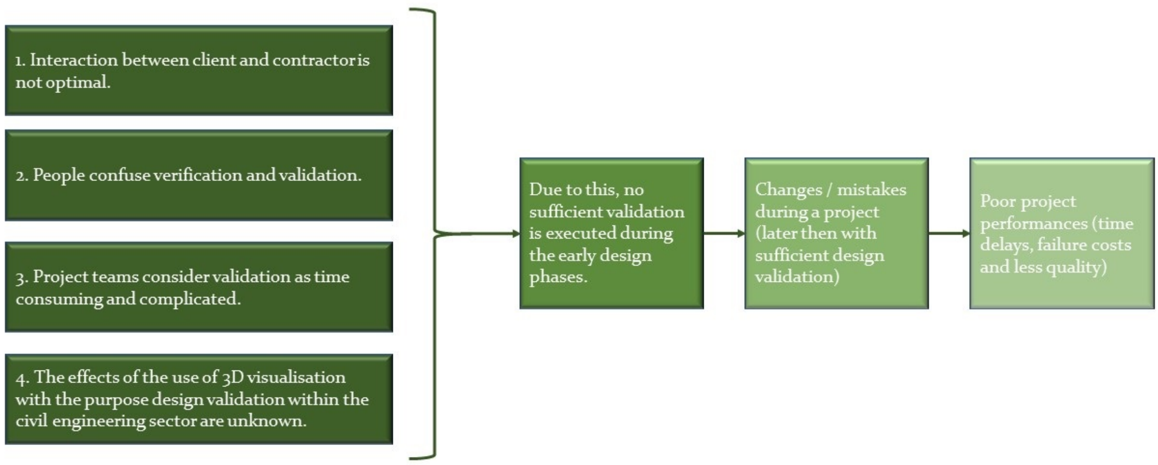

Figure 1.2: Visualisation problem (own image)

1.2. Research objective

In the problem definition, it is stated that the effect of visualisation on design validation is unknown. Therefore, the following research objective is determined:

The aim of this research is to gain insight in the effects of 3D visualisation during the design validation on the project performances, namely time, costs and quality.

1.3. Research question

The problem definition and research objective stated in §1.1 and 1.2, results in the following main research question:

What are possible effects of 3D visualisation on design validation within the civil engineering sector in the Netherlands?

To answer this main research question, two sub-questions are determined:

1. What is design validation and how does it contribute to the construction industry?
2. What are capabilities of 3D visualisation and how does it contribute to the construction industry?

Sub-question 1 and 2 are scrutinised in chapter 2 Context.

1.4. Scope

The scope of the research is determined in order to narrow down the subject. A visual presentation of the four elements of the research question is given in figure 1.3, presenting the scope.

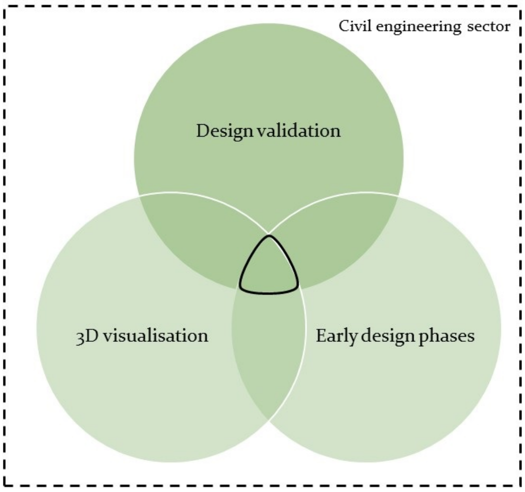

Figure 1.3: Visualisation scope (own image)

As shown in figure 1.3, the research is conducted within the civil engineering sector and particularly directed to infrastructure projects in the Netherlands. Even though the measurements take place within the Dutch contractor firm VolkerWessels, research to the effect of 3D visualisation on design validation is relevant for the entire industry. The scope is represented by three elements within the civil engineering sector, namely, visualisation, design validation and early design phases.

- Visualisation – Several definitions of visualisation are given in literature. In the past, the definition of visualisation was constructing a visual image in the mind. These days, however, the term visualisation is broader, according to Ware (2012) it means a graphical representation of data or concepts. Another definition of visualisation is any kind of physical representation designed to make an abstract concept visible. However, this representation is not restricted to physical items but also 2D graphs, diagrams, charts and 3D models (Uttal and O'Doherty, 2008). In this research, visualisation is defined as a representation of an object, system or a set of data such as requirements by means of a physical scale model or a digital model. According to Johnson (1998) representations improve performance by effectively allowing certain ideas to be evaluated more conveniently. This means that visualisation can be used for the validation process. In this research, the effect of 3D visualisation is analysed in the context of design validation.

- Design validation – The definition of design validation in this research is to provide evidence that the preliminary design is able to achieve the intended use and user needs based on the functionalities of the system. If there is no sufficient validation of the design, the system might or might not meet the intended use in terms of functionality, which causes public and economic costs. Though, sufficient validation is not similar to a sufficient design. The process only provides evidence if the design is able to achieve the intended use. For the scope, it is crucial to notice that exclusively the design validation process is taken into account. Other types, such as requirement validation and system validation are out of scope. Besides that, the verification process and the results of the validation process are out of scope.

- Early design phase – The early design phases refer to the system design phase (Dutch: systeem ontwerp fase or SO-fase) and the preliminary design phase (Dutch: voorontwerp-fase or VO-fase). First, after winning a tender, the system design phase will be completed. This encompasses the processes: analysing the contract documents, capturing functionalities of the system, capturing requirements and requirement validation, capturing (sub)systems, and capturing strategic solution directions. Therefore, deliverables of the system design phase are System Requirements Review (SRR), System Breakdown Structure (SBS) until conceptual level, interface register, verification report, functional breakdown structure (FBS), requirement breakdown structure (RBS), risk dossier and several test plans. Next, the preliminary design phase will be executed. In this phase, the following processes are carried out: determining variants, elaborating unique draft design, and design validation. For project performances, the design phases and particularly the early design phases are of importance, since the decisions made have a severe impact on the subsequent phases of the project (Bertoni et al., 2012). Many studies have shown that at the start of a project the costs of changes are low and increases over time, and the influence on cost and quality decrease over time, this is shown in figure 1.4 (Spekkink, 2012).

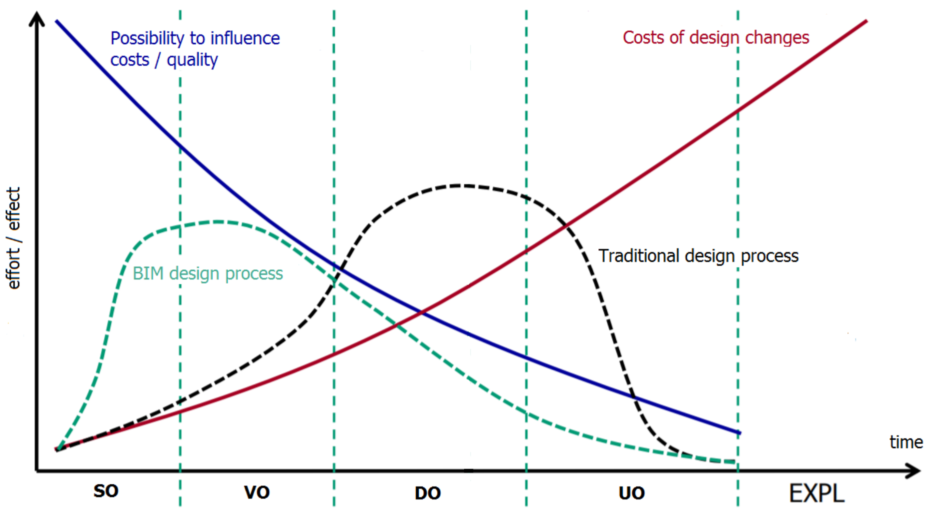

Figure 1.4: Influence on costs/quality vs. costs of design changes (translated from Spekkink (2012)

1.5. Methodology

This paragraph describes the methodology of this research. This research consists of a quantitative and qualitative part and is practice-based. According to Verschuren and Doorewaard (2013) practice-based mean that the research provides knowledge and information that can contribute to a successful intervention in order to change an existing situation. The research is conducted in three phases; (1) literature research and project evaluations (2) the experiment divided into baseline measurements and follow-up measurements and (3) results and conclusion. These steps lead to recommendations for in practice. An overview of the research phases is represented in figure 1.5.

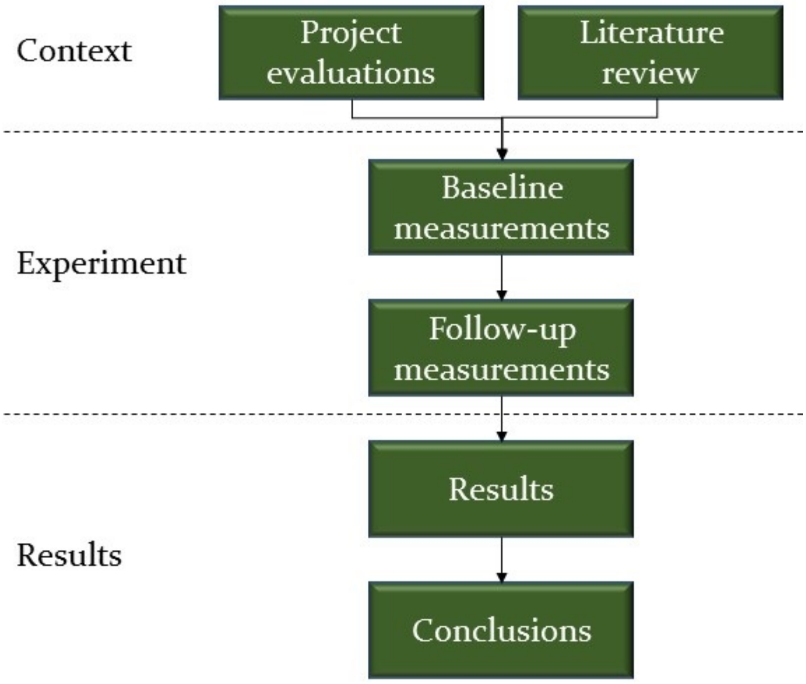

Figure 1.5: Research design (own image)

1.5.1. Context

In this paragraph, the methodology of the literature review and project evaluations are described.

Literature review

During the literature research, the databases Scopus and Google Scholar were used. First, a broad search was done on the context of this research, for the context the following search terms are used: 'systems engineering', 'ISO15288', 'quality control', 'construction costs'. The aim of the literature study was to focus on the theory and definitions of systems engineering, validation, and available visualisation technologies and summarises the existing knowledge on these topics. The search terms that were used are e.g.: 'validation construction industry' (84.900 hits), 'BIM advantages' (17.100 hits), 'BIM validation process' (18.100 hits) and 'trust client contractor' (17.700 hits).

During the literature search, three tools were used. First, multiple sources were scanned for literature, to identify which sources should be included in the literature study. Secondly, the literature that was found was skimmed for relevant information and their specific contribution to the research. Thirdly, the relevant literature was mapped and managed in bibliography documentation (Machi and McEvoy, 2012). The next step was to survey the literature. This provided insights into the key elements of the validation process, 3D visualisation and the interaction between client and contractor. Mainly, the sources are selected by the following criteria: they should scientific articles or method descriptions by Rijkswaterstaat (RWS) or ISO. For the literature in which it is important that they are recently written, the publishing date is from 2008.

Project evaluations

During the project evaluations documentation on executed projects or projects in the design phase or construction phase (VITAL, N18, Renovatie Waalbrug) and internal documents from VolkerInfra were analysed. For the selection of the projects, critical case sampling was used, as stated by Glaser (1978), researchers will go to the cases they believe will maximise the possibilities of obtaining data and that will lead to more data on their question. Several projects conducted by the infrastructure branch of VolkerWessels, such as VITAL, N18, and Waalbrug, were used for the project evaluation. These projects are analysed on the current strategy for design validation. After speaking to the integration manager or system engineer of these projects, documentation such as the contract specification, the VISE database (Relatics), V&V management plans was gathered. Subsequently, the information was analysed on currently used validation and visualisation methods.

1.5.2. Experiment

In this research, gaming simulation is used for testing the hypotheses quantitatively using the data gathered from the multiple session. Therefore, it is essential to first introduce what gaming simulation is and why gaming simulation is suitable in this case. In literature, there are multiple definitions for gaming simulation, besides that several terms are used simultaneously, such as serious gaming, simulation and gaming. In this research the following definition is used for gaming simulation:

"a special type of model that uses gaming techniques to model and simulate a system. A gaming simulation is an operating model of a real-life system in which actors in roles partially recreate the behaviour of the system (Meijer, 2009)".

There are several functions that gaming simulations can serve. The main function is transferring knowledge. Other functions are scientific research, team building, strategy development, or improving skills (Meijer, 2009). For scientific research the choice has to be made between studying a situation within its context in depth, so including all related issues and conditions or secondly, researching the situation in general sense, which has the risk to miss important contextual issues. According to Meijer (2009) gaming simulation provides an in-between step because of a session in a reality context and the possibility of repeatability in a controlled manner. For research purposes, there are three main functions; hypotheses generation, hypothesis testing and multi-agent modelling.

In this research, the gaming simulation is used for testing the hypothesis. This is done by means of baseline and follow-up measurements. These are further elaborated in chapter three.

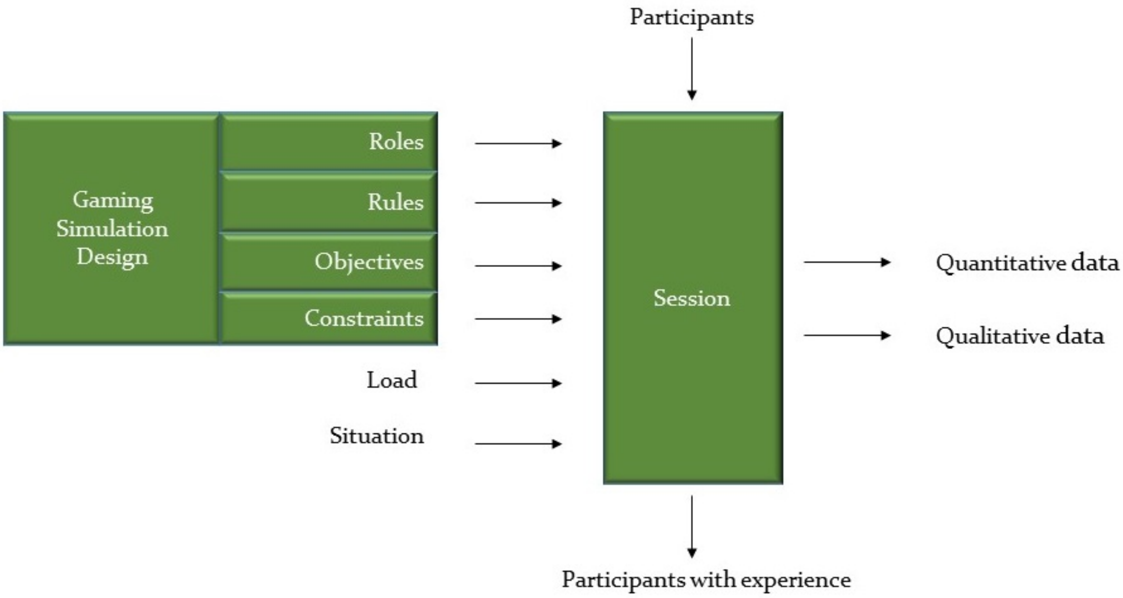

Figure 1.6: Input and output gaming simulation (Gibbs, 1974)

According to Gibbs (1974), and shown in figure 1.6, the roles, rules, objectives, and constraints are input variables. Besides that, there is the load, and situation, which are not part of the design of the gaming simulation. Next, the input variables are elaborated:

- The roles for participants and game leaders are separated in gaming simulation. This distinguishment is necessary because the game leaders fulfil a role, however, the behaviour of these roles are pre-scripted. In this case, all roles symbolise a real-world role within a project environment in the civil engineering sector in the Netherlands.
- All roles within the gaming simulation session have specific rules. These rules can be instructions that influence the behaviour of the participants.
- In gaming simulations, the objective can be different for the different roles within a session, furthermore, it is possible that there is one objective for the entire group of participants. The purpose of objectives is to guide the session in the desired direction of the gaming simulation.
- Next to rules, there are constraints within gaming simulation, these differ because constraints limit the possible actions in sessions by means of punishments, and the amount of money allowed in a session.
- The definition of the load are the values of the variables in the design. This means, for example, the number of participants in a specific role or the number of points at the beginning of the session.
- Lastly, the situation implies all the surrounding variables of a session, such as the location of the gaming simulation, the selection of the participants and how the participants are prepared (Gibbs, 1974).

1.6. Research quality

In the following sections describe several strategies to ensure the reliability, internal and external validity of this research. The validity of the gaming simulation, which is explained in 3.2.1, is divided into several elements, namely psychological reality, structural validity, process validity and predictive validity.

1.6.1. Reliability

The reliability of this research is ensured by means of several methods. According to Baarda et al. (1995) reliability can be defined as the extent to which research results are independent. This means that the results of this research, when repeated the research with similar methodologies, is the same. Besides that, the methodologies used, and the application of these methodologies have to be reliable. In this research two strategies for increasing the reliability are used. Firstly, the documentation of the results is explicit to such a degree that all assumptions and conclusions are traceable. Secondly, triangulation is used, which is the use of at least two methods to address the same research problem (Morse, 1991). In this case, this is done by means of literature study and field research.

1.6.2. Internal validity

In this research, ensuring internal validity implies that cross-checking information prevents differences between the data and reality (Baarda et al., 1995). Another strategy for conformity is discussing the results of the research in focus groups. The experiment is done in a regulated environment, for the control group as well the experiment group the fourth measurement is done to validate the experiment itself.

1.6.3. External validity

The objective of external validity is to generalise the research results to other settings or projects Baarda et al. (1995). The process is generalised in such a way that it is applicable to all civil engineering projects, which project management is based on Systems Engineering. However, the measurements only take place at contractor firm VolkerWessels in the Netherlands.

1.7. Reading guide

First, in part I introduction, the problem description of this research is given. Followed by the research objective, research question, scope and methodology. Chapter 2 contains the context, definition and methods of design validation and visualisation are discussed. Besides that, the current use of 3D visualisation and validation are explained. The context ends with the hypothesis determined based on the literature and project evaluations.

In part II, consists of the research design. In chapter 3, the gaming simulation, called the ontwikkelstraat, is elaborated and the set-up of the experiment is presented. The experiment consists of baseline and follow-up measurements. The aim of the experiment is to measure the effects of the use of 3D visualisation during design validation on the project performances.

Part III contains the results of the gaming simulation. The results are presented by means of three project performances, namely time, costs and quality. In chapter 4, these results are also interpreted.

Lastly, part IV consists of chapters five and six. In these chapters, the conclusion, reflection and recommendations of this research are presented. An overview is shown in figure 1.7.

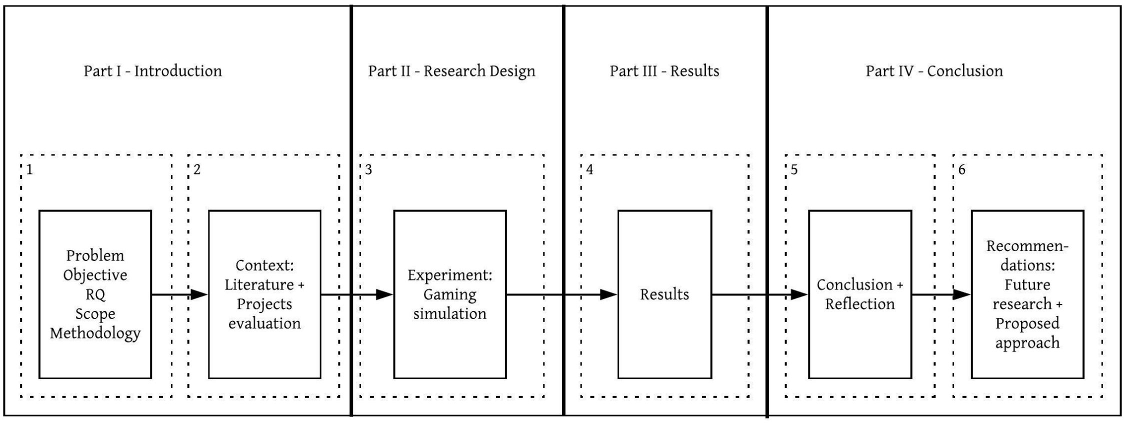

Figure 1.7: Report overview (own image)

2 Context

In chapter 2, an outline is given on the essential subjects of the research. This is done by means of literature and project evaluations. Paragraph 2.1 consists of an elaboration on design validation. Paragraph 2.2 discusses 3D visualisation, what it is and how it is conducted currently in infrastructure projects. The chapter ends with an interim conclusion, in which the hypothesis is determined and which elements are considered during the gaming simulation.

2.1. Design validation process

In this paragraph, the validation process is explained, and in particular the design validation process. Besides the definition, the current methods of design validation are explained by means of three project evaluations. The validation process is an element of the systems engineering (SE) method for project management. Elaboration on SE is given in appendix A. In this paragraph the first sub-question 'what is design validation and how does it contribute to the construction industry?' is discussed.

2.1.1. Definition and methods

The objective of the validation process is "to acquire confidence in its ability to achieve its intended mission, or use, under specific operational conditions. Validation is ratified by stakeholders. This process provides the necessary information so that identified anomalies can be resolved by the appropriate technical process where the anomaly was created" (ISO, 2015, p. 74). Validation of an entire project involves multiple tests and methods of all components in the whole life-cycle. These methods are explained in table 2.1 and discussed below.

Table 2.1: Validation methods

Method	**Explanation**
Review	Check if the design fulfils its intended use by means of cross-checking the output of the design process in accordance with the intended use of the system.
Modelling	Imitation of the design in a physical or digital model
Simulation	Demonstrating the performances of the design or system
Analysis	Use of analytical data to proof if the design fulfils its intended use, for example, fault tree analysis or reliability analysis
Reference	Reference to previous relevant projects and their intended use

According Larsen and Buede (2002) these methods has to exercise those functions of the system to determine whether the product behaves as intended use. Larsen and Buede (2002) introduce four components of validation: conceptual validity, requirements validity, design validity, and policy validity. Conceptual validity is the correlation between the operational concept and the stakeholders' needs. Next, the requirements validation is the relation between the requirements and operational concept. Followed by the design validation, this type of validation means the agreement between the originated requirements and acquired requirements. Lastly, policy validity considers solutions to organisational policies (Larsen and Buede, 2002).

Other literature defines three elements of V&V, which are (1) requirements, (2) design, and (3) the system (Adrion et al., 1982; Maropoulos and Ceglarek, 2010). These elements are presented in figure 2.1.

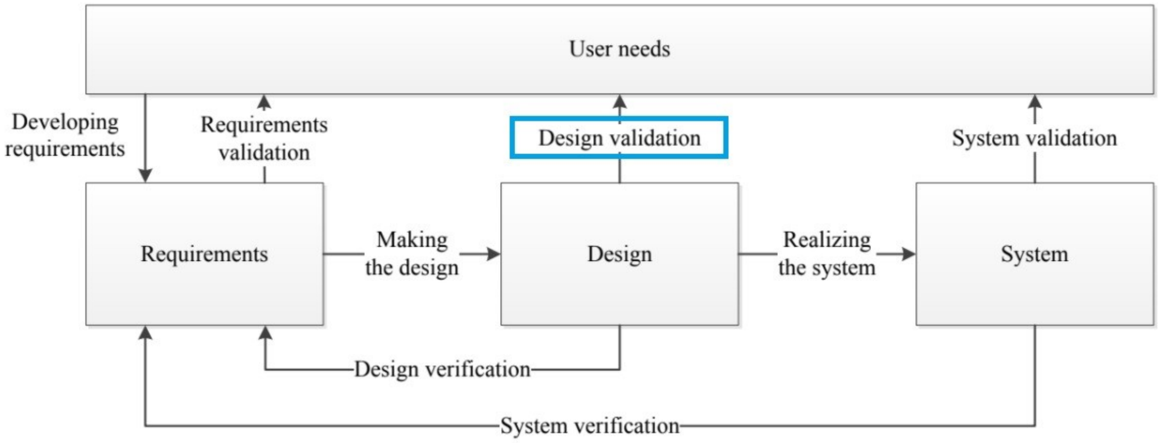

Figure 2.1: Verification and validation elements (Schipper, 2016)

First, requirements and in particular requirement validation. According to Bijan et al. (2013) requirements are a transformation of the needs of stakeholders into a specification, which can be of assistance for the development of a system. Requirement validation is to ensure the set of requirements is consistent, complete and the specification represents a working system in the intended environment (Byun et al., 2014). After the requirements are validated by the contractor, the design can be made. This takes place in several phases on the contractor's side. During the tender phase, a tender design is made, this will be reviewed entirely when the contractor won the project in the system design phase. After that, a preliminary design (VO), a final design (DO) and finally an execution design (UO) are made. In all phases, the designs have to be validated for the intended use and user needs (design validation) (Wasson, 2006). During this process, the quantity of interaction with the client is important. The number of validation sessions between client and contractor can improve the project performances. Lastly, the realised system has to be validated. Some aspects and performances can be made provable after exploitation. After completion functionalities can be tested on intended use by means of in advance established use cases.

Validation is possible if it satisfies three minimum requirements (Rijkswaterstaat, 2016), these are:

- Method of proof: the aim of validation is to proof objectively whether the intended use of the system is fulfilled. Provability is for this requirement crucial and is defined by (Rijkswaterstaat, 2016, p. 3) as: "provide evidence that the processes have been followed correctly (complete and accurate)";
- Criterium: the proof has to be compared to at least one value or variable;
- Assessor: Someone has to be competent enough and has permission contractually to confirm if the design meets its intended use.

Furthermore, some additional conditions are required for the manageability of the projects, i.e. time when validation has to take place, start condition, validity of the method, and the risks if the criterium is not fulfilled. Critical aspects in the system have to be clear for client and contractor (Rijkswaterstaat, 2016).

In this research, requirement and system validation are out of scope. If the design validation is sufficient can only be confirmed after completion of the project, when it is clear if the system fulfils its intended use. However, Rijkswaterstaat (2016) conducted the following requirements for an adequate design validation process:

- If validation is an integral element of the design process, then it is part of the quality assurance;
- Proof by means of working explicit, so confirmation by client and stakeholders;
- Define the validation process in cooperation with the client.

2.1.2. In practice

In this paragraph, the current validation approaches, that are used in practice by contractors in the Netherlands, are explained. The information in this paragraph is based on management plans from several projects. A general description of these projects is given in appendix B.

The first project is a renovation project of the light rail connection. The validation approach adopted by this project has the following principles:

- Validation is done continuously by aligning expectations with the client and stakeholders by means of kick-off, technical consultations, presentations, document assessments, etcetera;
- Validation is focused on the intended use of the final product;
- Validation takes place during the design phases about the design solutions, and during realisation about the realised product;
- The accent in terms of validation is during the design phase: the design meets the intended use;
- Validation has to be executed in cooperation with the client and relevant stakeholders.

Currently, December 2018, the project is just in the execution phase. During the early design phases, several validation sessions are conducted. During the system and preliminary design, several design presentations are presented to client and stakeholders. During the system design phase, without 3D visualisation, however, during the preliminary design phase, these presentations included 3D images. In dialogue with the client, the critical objects were determined which were discussed during these design validation sessions.

The second is a renewed highway project of 23 kilometres from Groenlo till Enschede. The aim of the verification and validation in this project is to find the most suitable solution in the least amount of iterations. The following validation steps are conducted, which are all registered in a validation register:

1. Interests validation;
2. Ratification of the requirement specifications;
3. Validation of all design phases and work preparation;
4. Completion conform execution organisation.

This project was completed in May 2018. During the design phases, every three weeks a validation session was organised with the client and main stakeholders. The design phase was conducted with an agile method similar to scrum. Scrum is a project management method which is an iterative and incremental process. An important element of this way of development is that stakeholders are frequently involved during the early design phases (Cho, 2009). The project team used in the preliminary design some 3D visualisations of critical objects.

The third project is the renovation of the Waalbrug. The renovation is necessary because the bridge construction degraded over time and it is an important link for local and regional transport. The goal of the validation process of this project is to prove objectively that the requirements of intended use and intended application of the system, that needs to be built, are met.

The following validation steps are conducted during the renovation Waalbrug project. These steps are captured by the system engineer in a validation register and coupled to the work package. This capturing is done to deduct all information discussed during the validation sessions.

1. Aligning verification and validation strategy with the client;
2. Requirement validation with the client;
3. Aligning design solutions with the client and relevant stakeholders.

Currently, December 2018, the project is in the execution design phase. During the system design phase, validation sessions concerning the requirements are conducted. These were divided into requirement sessions on process and sessions on technical requirements. In these sessions, the interpretation and requirement texts were adjusted. During the preliminary and final design phase, there were design validation sessions. These were made explicit in Relatics (VISE). The client has also access to this information system. For the critical objects, 3D visualisation is used during the validation sessions.

2.2. Three-dimensional visualisation

In this paragraph, the use of 3D visualisation within the civil engineering sector is discussed. Besides that, the definition and method are explained.

2.2.1. Definition and methods

A brief introduction on visualisation is given in the problem description (§1.1). Concerning digital modelling, Multiple Computer Aided Design (CAD) programs are used for three-dimensional visualisation. This development started in the fifties of last century, which meant that pencils and straight-edges were the past. In 1982 two companies for this software development were established, i.e. Autodesk in the United States and ArchiCAD in Hungary. This was the first basis for the development of Building Information Model (BIM). The first working prototype of BIM was called Building Description System published by Eastman (1974). In the Building Description System (BDS) multiple documentation, such as profiles, perspectives and drawing, are interactive so that changes can be implemented once and all documentation updates. In the beginning of the nineties, CAD was introduced in which non-graphical information is coupled to the drawings. Stated by Day (1996) most commercial developments were focussed on two particular functions, firstly, increasing the productivity in drawing production and secondly, conducting 3D models to visualise the systems final appearance. In 2007, the BIR (Building Information Board, or Dutch: Bouw informatie Raad) is established. The BIR is a cooperation between several branches within the Dutch building and infrastructure sector with the aim to strengthen the quality, continuity and competitiveness focussing on BIM (Bouw Informatie Raad, 2017).

Nowadays, BIM has several functions, for example it is becoming more important as a method for communication between architects, engineers, suppliers and contractors on improving the project performances (Sebastian and Van Berlo, 2011). Due to complex communication processes between numerous project participants, which involves much information exchange and leads to errors and omissions during design and construction (Eastman et al., 2012). Besides that the functions of BIM are (2D/3D/4D/5D) modelling of the system, engineering i.e. volume and strength calculations, decomposition into objects, visualisation i.e. animation or stills, coordination between disciplines and planning. Two examples of BIM output are shown in figure 2.2.

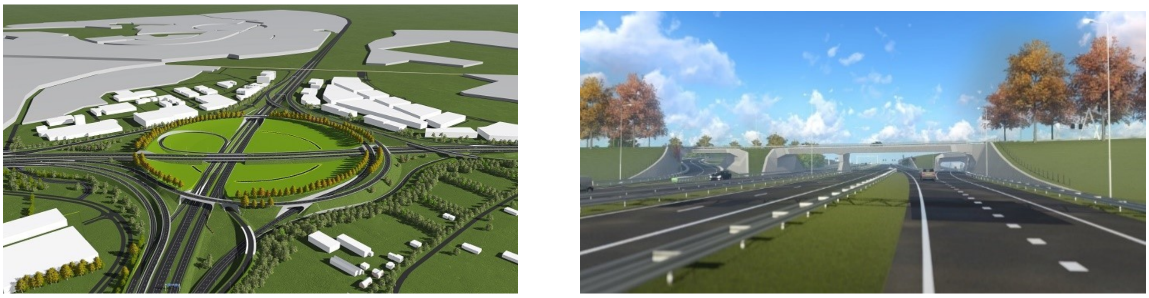

Figure 2.2: BIM output examples (Knooppunt Hoevelaken)

The implementation of BIM brought new risks as well, these are divided into two categories: technology-related risks and process-related risks (Azhar et al., 2012). For multidisciplinary projects, multiuser access is necessary for the BIM model, the absence of standards for model integration is a risk. It could lead to deviations in the model, because every company choose their own standards, therefore, frequent model checks are needed to avoid any issues. Secondly, there are problems regarding interoperability. This means that the ability to exchange data between applications is not working the way it should (Azhar et al., 2012).

Next, process-related risks, which consists of legal, contractual and organisational risks. Regarding organisational, the biggest risk is the control and responsibility of the accuracy of the data. Besides that, the ownership of the data is questionable (Azhar et al., 2012).

Liu et al. (2017) researched the critical effects of BIM on collaborative design. They found eight concepts which influence the development of BIM collaboration, which are (1) IT capacity, (2) technology management, (3) attitude and behaviour, (4) role-taking, (5) trust, (6) communication, (7) leadership, and (8) learning and experience. For communication, BIM is used by contractors to conduct clash detection during the construction phase and to submit a BIM execution program according Liu et al. (2017). They gained from interviews that BIM is not used to improve communication between actors, which implies they disbelieve BIM for deep communication. However, the capabilities are there to improve the quality of the interaction between client and contractor. By using BIM the way of information exchange will adjust in the way that much more details are integrated (Liu et al., 2017).

2.2.2. Current use of 3D visualisation within VolkerInfra

As stated in paragraph 2.2, the visualisation of 3D models is done through a BIM, which is used by the design team. The actual use of BIM is explained by means of the maturity levels for BIM. The aim of BIM-maturity models is to assess which strategies are suitable for the BIM industry. In other words, when industries adopt inappropriate BIM strategies would waste resources and time. To identify these differences, information regarding the current state of BIM is necessary (Bew and Richards, 2008).

Several models on BIM maturity can be found in literature, for example, the BIM wedge by Bew and Richards (2008) and the BIM maturity levels by Universiteit Twente (2015). The 'BIM-maturity level diagram by Bew and Richards (2008), also known as the BIM Wedge, is shown in figure 2.3. Elaboration on the levels zero till three are given in appendix C.

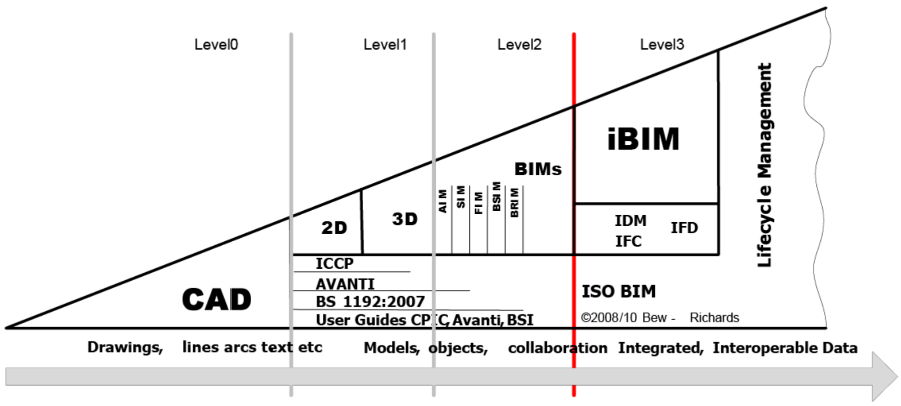

Figure 2.3: BIM maturity model Bew and Richards (2008)

Another tool for BIM maturity is developed by Siebelink et al. (2018). This tool uses six criteria to measure the maturity of BIM, which are the strategy, organisational structure, people and culture, process and procedure, information and communication technology (ICT), and data structure. An elaboration on these criteria can be found in appendix C.

Siebelink et al. (2018) researched BIM maturity within the construction industry in the Netherlands and made a division in sub-sectors within the industry. VolkerInfra belongs to the subsector 'construction company soil, road and water (Dutch: Grond Weg Waterbouw)'. In figure 2.4, the results for this subsector are shown. This subsector distinct itself in five areas, three lower compared to average: people and culture, organisational structure and strategy, and two above average, namely data structure and management support Siebelink et al. (2018).

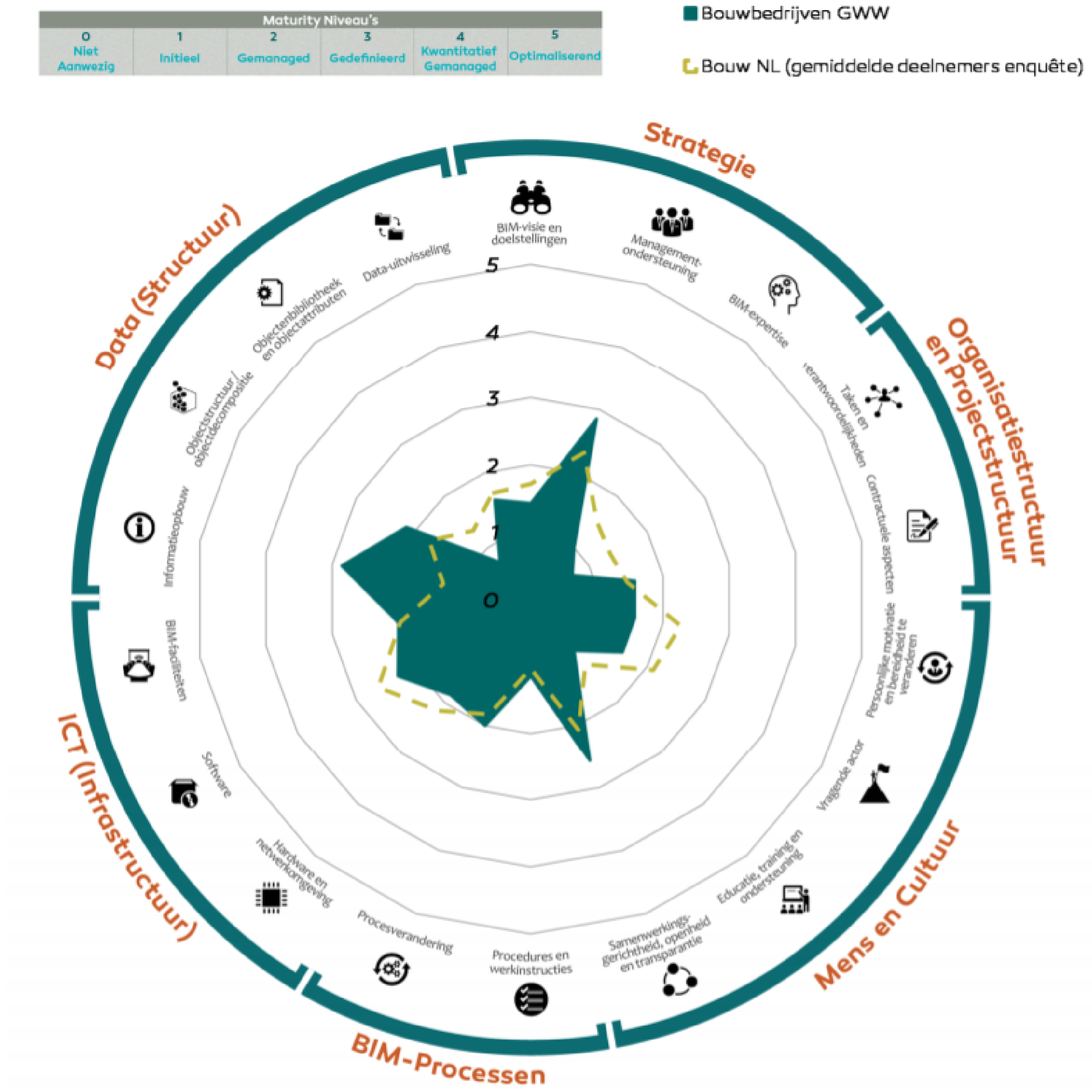

Figure 2.4: BIM-maturity radar diagram construction companies Soil Road Water (Sieberink, Voordijk & Adriaanse, 2014).

Within the infrastructure branch of VolkerWessels, the BIM maturity is measured by means of experiences that the different operating companies have during projects, even though these companies interact during multidisciplinary and integral projects, the maturity of the use of BIM distinct.

Based on practice, VolkerInfra is in a relative far stadium concerning the use of BIM. On all projects of VolkerInfra, that include design, BIM is implemented until execution design (UO). From internal evaluation sessions about the usage of BIM, it was concluded that there were more failure costs when the use of BIM was stopped too early. To notify the client which applications VolkerInfra possesses, the information management department of VolkerInfra made a BIM menu. Based on the BIM menu, the client can decide which applications shall be used during a specific project. Overall, the standard applications are 3D designs to visualise the system during the design phase. Other applications that are regularly used by the infrastructure branch of VolkerWessels are ProMaSys and VISE, which is a document control system.

During the past years, VolkerInfra has set a clear vision for applying BIM during their projects. In 2017, BIM maturity level 1 of Bew & Richards (2008) was completely implemented by VolkerInfra. During 2018, VolkerInfra aims to perform at BIM maturity level 2, and for 2020 BIM maturity level 3 should be achieved. Nevertheless, not all implementations of BIM applications are currently successful. In practice, the level 1 applications are fully implemented on the integral projects within the infrastructure branch of VolkerWessels. However, the vision of VolkerInfra to perform at maturity level 2 at the end of 2018, is ambitious based on the current situation. To achieve this vision it is necessary to implement 3D, 4D and 5D, which is complicated for in particular 4D and 5D.

During a few pilots about the usage of BIM that were executed by VolkerInfra, it is confirmed that there are no technical difficulties with the software. Nonetheless, the implementation of BIM is not accepted by the project teams. The project teams do not accept the implementation because, according to an internal investigation, the people do not feel the urgency to use BIM due to the ignorance what BIM can add to a project. Besides that, there is a lack of training, skills and manpower. For the integral multidisciplinary projects, a collaboration between the subsidiaries is essential because of the interfaces within projects, therefore, it is crucial that all subsidiaries implement BIM. Among the subsidiaries there is a contrast in BIM maturity.

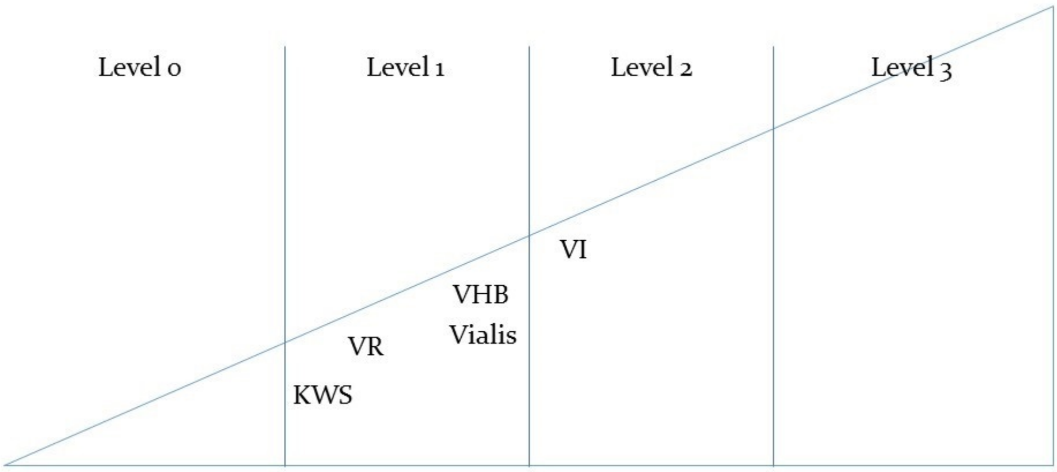

Figure 2.5: Positions subsidiaries adjusted from Bew & Richards (2008)

Figure 2.5 shows the differences of the subsidiaries within the infrastructure branch of VolkerWessels. The subsidiary KWS is least far regarding the implementation of BIM, according an information manager at KWS, bigger projects are using 3D models more and more, however, the smaller projects are not ready for this implementation and are still using 2D drawings. An information manager at the subsidiary VolkerRail (VR) stated that VR is dropping a few stitches in the process, particularly on the ‘soft’ side and collaboration, another issue is the implementation of the applications. Next, the subsidiaries Van Hattum en Blankevoort (VHB) and Vialis are approximately on the same BIM level. It is common in all projects to make 3D models, however, regularly old methods are used during projects. A Vialis BIM manager stated that it is hard for all employees to accept the new methods because there is no unambiguous vision on the use of BIM. The procedures and applications used by the subsidiary VolkerInfra (VI) are already discussed above.

2.3. Interim conclusion

Literature research was used in order to formulate a hypothesis. Bertoni et al. (2012) state that for improving project performances, the early design phases are of importance, since the decisions made during these phases have a severe impact on the subsequent phases of the project. Additionally, Wasson (2006) declares that the design of a system has to be validated for the intended use and user needs iteratively in all design phases. Moreover, Bryde et al. (2014) determined several advantages of BIM 3D visualisation, namely better expectation management, better communication, quality increase, fewer failure costs and a shorter lead time. Liu et al. (2017) say that the way of information exchange adjusts by use of BIM in the way that much more details are integrated. These four statements are combined in the hypothesis:

"The use of 3D visualisation in the design validation process during the early design phases has effect on the project performances within the civil engineering sector."

In this research, this hypothesis is tested by means of a gaming simulation. The project performances time, costs and quality are considered during this experiment. The gaming simulation and the measurements on the effects of the use of 3D visualisation in the design validation process are explained in the next chapter.

Part II
Research Design

Part II contains of the experiment set-up. In the research a gaming simulation is used to acquire results on the effects of the use of 3D visualisation on the design validation process during the early design phases. The aim of this chapter is to elaborate on the ontwikkelstraat and research population. Besides that, the validity of the gaming simulation is shown.

3

Research Design

In this chapter, the gaming simulation and experiment set up is discussed. The aim is to explain the types of measurements conducted during the experiment and show the validity of the gaming simulation.

The gaming simulation consisted of baseline measurements without visualisation (N=3), and follow-up measurements with visualisation (N=3). The baseline measurements are important for comparison of the data conducted from the experiment, in such a way the effect of visualisation can be quantified. Quantification and applicability of the dependent variables were essential for valid research results. Next, the visualisation was implemented, which is a physical model of the hydrogen factory. This physical model is shown in figure 3.1. Lastly, the same measurements were done as during the baseline measurements, whereby the data results were compared.

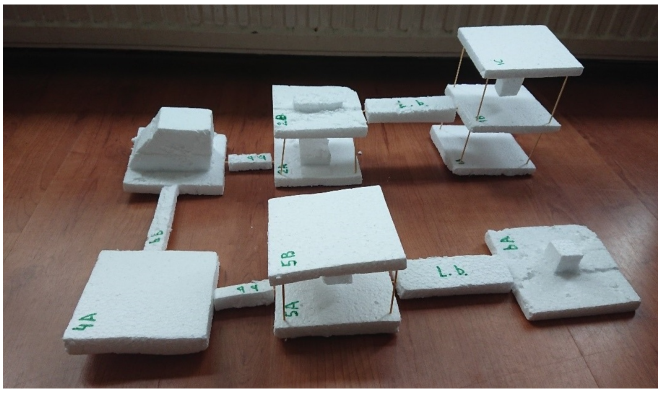

Figure 3.1: Physical model (own image)

3.1. The Ontwikkelstraat

The gaming simulation in which the experiment is implemented is called The Ontwikkelstraat (Dutch for development street), which is a two-day case about a hydrogen factory construction. The case takes place in Van der Valk hotel in Harderwijk, in which two areas are reserved for the experiment, one represented the project site and the other was used as an office for the design processes. In this case, the whole life-cycle from tender until completion of the hydrogen factory was imitated. The first morning strategical and financial control are lectured. In the afternoon, the design phases are executed. The second day the execution phase is imitated.

The purpose of this so-called serious game is to learn employees of the infrastructural sector of VolkerWessels to work with 'Top in projecten' and to improve integral infrastructure projects. Top in projecten is the strategy used within the infrastructure branch of VolkerWessels for integral projects. The three main goals of Top in projecten are safety, sustainability and integrity.

During the afternoon of the first day of the case, the participants started with the design phases of the project case. For the baseline measurements or control group, a predefined moment during the early design phases was implemented for validation. To measure the effect of visualisation on the validation process it is essential that the implementation of visualisation is the single variable that changes between the control group and the experiment group. In this way, the effect could be measured by means of several dependent variables, which are explained in the sections 3.1.1-3.1.3. Therefore, during the experiment measurements, the baseline measurement and the predefined validation moment are at the same moment in the case. The baseline measurements were done three times in a regulated environment, as well as the follow-up measurements. In appendix D, the gaming simulation is further elaborated. This elaboration explains the roles, rules and situation of the ontwikkelstraat.

The participants of the ontwikkelstraat are employees of the infrastructural branch of the firm VolkerWessels, which are randomly assigned to do the case. All employees are working in the infrastructure sector, in different phases of a project and they have different functions, for example modellers, contract managers or designers. All participants answered a short questionnaire concerning their study background, current function and work experience. Generally, every Ontwikkelstraat had fifteen participants, the experiment for this research is performed six times. Therefore, the research population is 90 (6 experiments with each 15 participants).

3.1.1. Questionnaires

During the gaming simulation, two surveys were taken by all participants of The Ontwikkelstraat. The aim of these questionnaires was to gather information on the background and knowledge level of the participants on design validation. The questionnaires were handed out hardcopy during The Ontwikkelstraat and the participants completed the questionnaires themselves. The first survey was taken the first day of the case after the lunch break and start of the design phases of the simulation game. The second survey was taken at the end of the second day of the case after completion of the hydrogen factory. The survey questions were about the amount of work experience of the participants, the knowledge they have on design validation and about if they think if design validation influence the project performances. The two surveys, apart from the question on the activities regarding design validation in their current position, were similar. In this way, the effect of the gaming simulation on the participants could be measured. Another purpose of the questionnaires was to clarify the qualitative data extracted from the simulation game. The questions of the two surveys can be found in appendix E. During the six measurements between 14 and 16 participants filled in the questionnaire, therefore, the number of participants questionnaire is 93.

In both surveys, three questions on design validation were asked by means of a Likert-scale from one to five. The data was analysed by means of averaging these scores of the baseline measurements and follow-up measurements. By comparing these scores, the effect of the visualisation implemented in the gaming simulation was measured.

3.1.2. Interaction client - contractor

During the simulation game, the conversations between client and contractor were recorded. Subjects discussed during these conversations were the functions of the to be built system and technical details of the hydrogen factory. These recordings were used for qualitative and quantitative research. First, the quantitative data were the time recorded and when the conversations took place in the design process. Besides that, the number of questions that were asked by the contractor was included as quantitative data.

In the ontwikkelstraat, the client was imitated by one or two persons. Averagely, four participants participated in the conversations. Mostly, the project manager and the control and finance manager conducted the conversations, that were assisted by the two project leaders of the water and air department on the contractor side. However, all participants had influence on the interaction between client and contractor. Nevertheless, the research population for the interaction between client and contractor is 36 number of participant conversations (6 experiments with 4 participants from the contractor side and 2 participants from the client side)

All conversations between client and contractor were transcripted, these transcriptions can be found in appendix F. The qualitative data gathered from the recordings was analysed by means of the trust scale stated by Dietz and Hartog (2006) which is shown in figure 3.2. Additionally, the questions asked were analysed on whether they contribute to a better design validation and in which part of the process they were asked. As shown in figure 3.2, there are five levels of trust according the trust scale developed by Dietz and Hartog

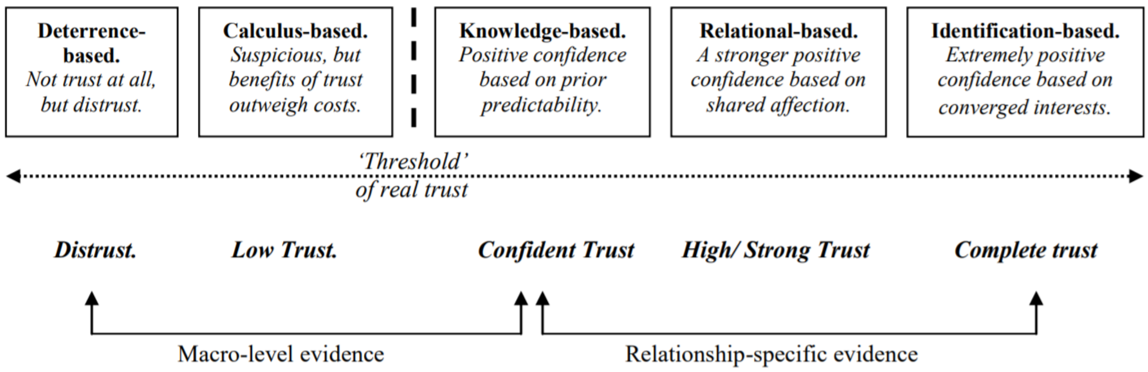

Figure 3.2: Trust scale (Dietz and Hartog, 2006)

(2006). With deterrence-based trust, there is no positive expectation of goodwill and only through external incentives compliance can be pledged. Calculus-based trust can also not be seen as trust because it is just based on a cost-benefit analysis. Between calculus-based and knowledge-based trust, there is a threshold of real trust. With knowledge-based trust, the trust is based on motives, abilities and reliability (Dietz and Hartog, 2006). Relational-based trust a strong trust is based on more subjectivity and emotion. Eventually, identification-based trust is based on the two parties having a common identity, in such a way that they can personify the other's interests (Dietz and Hartog, 2006).

3.1.3. Observations

Besides the questionnaires and conversations between clients and contractors, the participants of the ontwikkelstraat were observed. These observations consisted of general participative observation on group dynamics and of observations about the estimation and final costs of the project. These costs estimations were made by the participants after the first day of the ontwikkelstraat when they have to hand in their orders on materials for the construction phase the next day. Sources for this estimation were the material pricing lists, the factory specifications and the operational concept description (OCD), which were provided to the participants. The final costs of the hydrogen factory project were calculated through an excel sheet in which during the construction phase all technical changes were documented by the researcher. The observations were done for every gaming simulation; therefore, the research population is six.

The data gathering was done by participative observation. The researcher took part in the gaming simulation and communicated with the participants. The researcher being in the same room as the participants meant that the group dynamics could be monitored during the gaming simulation. During these observations, the interaction between participants was observed. Afterwards, these observations were noted and analysed by means of cross-checking the different measurements.

3.2. Validity experiment

In this paragraph, the validity of the experiment is discussed. In the first section, the comparison between the gaming simulation and the real-world is presented. The second section contains the validity of the research population. It shows that the baseline and follow-up groups can be compared with each other.

3.2.1. Validity gaming simulation

A gaming simulation is imitating the real world, however, the roles, rules, objectives and constraints are inevitably different from reality. Therefore, it is important to confirm if the model represents the real world or the definition stated by Raser (1969): "a model can be said to be valid to the extent that investigation of that model provides the same outcomes as would investigation in the reference system". An important note for the design of gaming simulation is the translation of reality into the design elements, which is shown in figure 3.3.

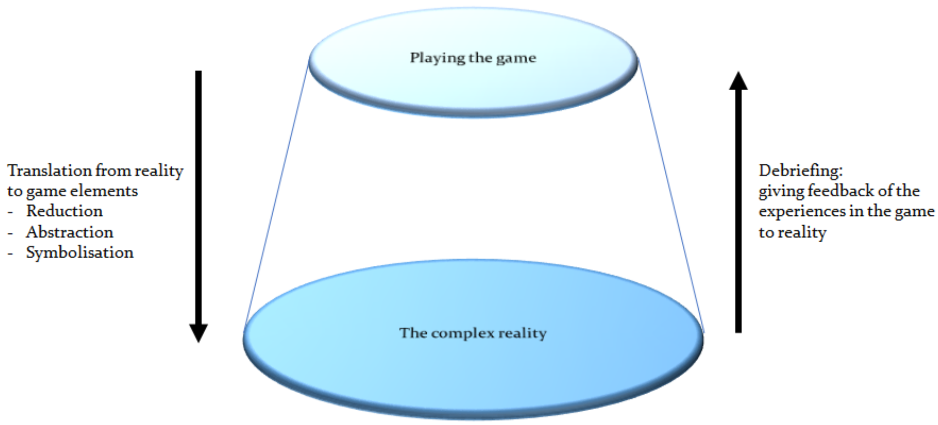

Figure 3.3: Gaming development (Peters and Van de Wesetelaken, 2011)

The validity of the gaming simulation is measured in several elements, namely psychological reality, structural validity, process validity and predictive validity.

- Psychological reality: Providing evidence if the gaming simulation has a realistic environment towards the participants.
- Structural validity: Providing evidence if the structure of the gaming simulation is similar to the reference system.
- Process validity: Providing evidence if the processes researched in the gaming simulation is similar to the real-world system.
- Predictive validity: Providing evidence if the gaming simulation can generate output of the real-world system (Meijer, 2009).

The input variables are analysed regarding the several elements of gaming simulation validity, this is shown in table 3.1. In this table, an overview is given on the validity of the gaming simulation. The ontwikkelstraat is compared to the real world, in this way it can be concluded that it is a sufficient imitation of the reality.

Table 3.1: Validity of the gaming simulation 'the ontwikkelstraat'

	Psychological reality	**Structural validity**	**Process validity**	**Predictive validity**
Roles	In the game there are fewer roles than in the real world, however, the roles in the game are similar to real world projects. Participants know what the roles contain in a real infrastructure project.	Roles are consistent with the real world.	Functions for the roles are adjusted to the game, nevertheless, corresponding to the real-world.	Real world project performances are used in the sessions too, to which participants act.
Rules	The rules are simplified compared to the real world.	The phases or structure of the game is similar to the real world.	Processes conducted during the game are comparable to the real world	N/A
Objectives	In the game the participants have the same KPIs as in the real world, namely conducting the project within time, money and quality.	The structure of the game is identical to the real world projects.	To get to the objective of the game, the same processes are followed during the game as in the real world.	It is the goal of real world projects to execute these projects within time, costs and with high quality. This is the same objective as the game.
Constraints	N/A	Time-constraints are the main difference between the real world and game structure.	During the game, not all processes are executed, due to time-constraints and simplification.	N/A
Load	The number of participants per game is always around 15 people, however, in a real world project, the number of project team members deviate.	Not all roles are with the same amount of people than in the real world.	Participants are not always in a role they also execute in the real world.	Risks are corresponding to real-world risks in a project, this leads to the same risk avoidance strategies.
Situation	The game is executed inside, while the execution phase in real world projects would be generally outside.	Participants played their role by how they would act in real world projects.	Participants did not know each other beforehand, however, working in the same company, there are common interests.	All actions by the participants are self-generated.

3.2.2. Validation research population

The research population is validated by means of the questionnaire. The goal of the questionnaire was to gather information on the background and knowledge level of the participants on design validation. In figure 3.4, the results relevant to the validation of the research population are presented. The elaborated results of the questionnaire can be found in appendix C.

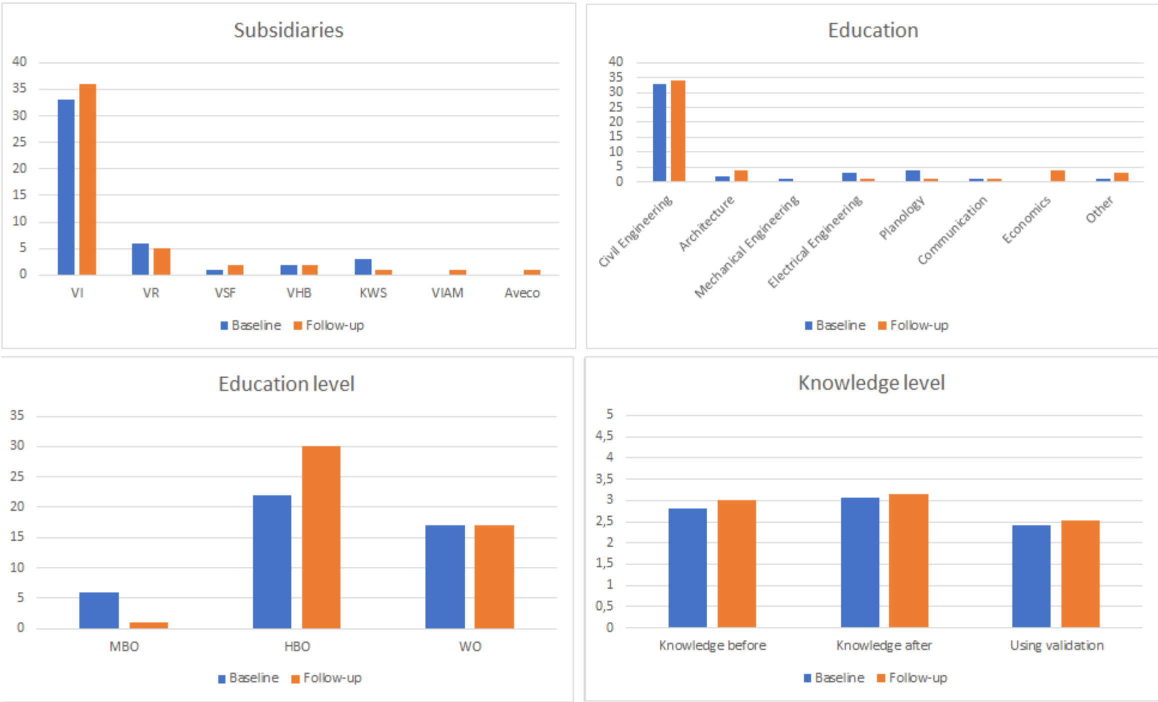

Figure 3.4: Results questionnaire (own image)

In figure 3.4, the comparison between the participants of the baseline measurements and the follow-up measurements on four characteristics is shown. These four characteristics have been compared in order to demonstrate that the participant groups can be compared to each other. In these graphs, the blue columns represent the results of the participants engaged in the baseline measurements, the oranges columns represent the results of the participants engaged in the follow-up measurements.

The upper left histogram shows the subsidiaries the participants work. The most participants of both measurements work at VolkerInfra, namely 33 persons that participated during the baseline measurement and 36 persons that participated during the follow-up measurement. The other participants work at the other subsidiaries within the infrastructure branch of VolkerWessels.

The upper right histogram shows the field of educational background of the participants. Most participants studied civil engineering, namely 33 people that participated during the baseline measurements and 34 persons that participated during the follow-up measurements. Other participants studied architecture, mechanical or electrical engineering, planning, communication, economics or other fields of education.

In the lower left histogram presents the results of the education level of the participants. Education level is divided in secondary vocational education (MBO), higher professional education (HBO), university education (WO).

The lower right histogram shows the knowledge level of the participants. The answers were given in a Liker-scale, so from one to five, in which one is low and five is high. The first column represents the knowledge level indicated by the participants on the first day of the gaming simulation. For persons that participated during the baseline measurements the average score is 2.82 and for persons that participated during the follow-up measurements, the average score is 3. The second column shows the knowledge level indicated by the participants at the end of the second day of the gaming simulation. For persons that participated during the baseline measurements, the average score is 3.07 and for persons that participated during the follow-up measurements the average score is 3.15. The third column presents the answers given by the participants on the usage of design validation in their current function at the infrastructure branch of VolkerWessels. For persons that participated during the baseline measurements, the average score is 2.42 and for persons that participated during the follow-up measurements the average score is 2.54.

As shown in the figure 3.4 and explained above, there is not much of difference between these two groups. Therefore, the comparison for the effects of visualised validation on project performances can be made.

Part III Results

Part III contains the results gained in the gaming simulation ontwikkelstraat. The effects are divided on the project performances, time (4.1), costs (4.2) and quality (4.3). Furthermore, in paragraph 4.4, the results are interpreted and an interim conclusion is presented. The aim of this part is to present the results from the experiment.

4
Results

In this chapter, the results of the gaming simulations are presented. In paragraph 4.1, the effects on time are presented. The second paragraph discusses the effects on costs. Paragraph 4.3 explains results on quality. Finally, the results are interpreted.

4.1. Effects of visualised validation on time

In table 4.1, the effects of the visualised validation on time is measured by means of the gaming simulation. During the gaming simulation, the effects of visualisation on design validation were measured in order to answer sub-question 8. During the baseline measurements (N=3), the interaction between client and the project team (contractor) lasted an average of 17 minutes with a standard deviation of 38 seconds in the system design phase. On the contrary, during the follow-up measurements (N=3), the interaction between the client and the project team (contractor) lasted an average of 16 minutes with a standard deviation of 6 minutes. During the preliminary design phase, an average of 12 minutes with a standard deviation of 23 seconds interaction between client and contractor is conducted, and during the follow-up measurements, the interaction between client and the project team (contractor) lasted an average of 13 minutes with a standard deviation of 4 minutes.

Table 4.1: Results of duration interaction between client and contractor

Measurements	**no**	**System design phase (mm:ss)**	**Preliminary design phase (mm:ss)**
Baseline measurements	1	17:15	19:14
	2	16:22	19:35
	3	17:37	08:56
	avg.	17:05	16:05
Follow-up measurements	4	12:22	13:50
	5	11:35	08:23
	6	11:53	16:01
	avg.	11:57	12:45

Additionally, the end time of the execution phase was measured during the gaming simulation. The normal time of completion of construction of the hydrogen factory is set at 2:15 p.m. In table 4.2, the elaborated results of the six measurements during gaming simulation are presented.

Table 4.2: Results time of completion of construction of the hydrogen factory

Measurements	**no**	**Time of completion**	**Duration execution phase**
Baseline measurements	1	1:40 p.m.	280 min
	2	2:15 p.m.	315 min
	3	2:15 p.m.	315 min
	avg.	2:03 p.m.	303 min
Follow-up measurements	4	1:15 p.m.	255 min
	5	2:15 p.m.	315 min
	6	2.15 p.m.	315 min
	avg.	1:55 p.m.	295 min

In table 4.2, the duration of the execution phase is presented. For the baseline measurements, the second and third measurements were ready exactly at the deadline of 2:15 pm. For the follow-up measurements, the fifth and sixth measurements were ready exactly at the deadline of 2:15 pm. The other two measurements, one of the baseline measurements (1:40 pm) and one of the follow-up measurements (1:15 pm), were finished before the official end time. The baseline measurements have an average of 303 minutes with a standard deviation of 20 minutes. The follow-up measurements have an average of 295 minutes with a standard deviation of 35 minutes.

4.2. Effects of visualised validation on costs

During the gaming simulation, the effects of visualised validation on the costs of the project are measured in order to determine the effects of the 3D visualisation on the project performance costs. At the end of the first day of the ontwikkelstraat, the participants were asked to order the materials that are needed for the construction of the hydrogen factory. The before costs are composed of the material costs and the labour costs. The labour costs are calculated through the following equation: no of participants ×€2500, – per minute. In table 4.3 results of the before costs are shown.
The after costs are the final costs of the hydrogen factory project, after construction of the project at the end of the second day of the ontwikkelstraat.

The difference between the before costs and after costs are the failure costs made during the second day of the ontwikkelstraat. The project is awarded a budget of 135 million. Therefore, EBIT (Earnings Before Interest and Tax) is calculated by means of the following equation:

$$EBIT = \frac{Awarded\,budget - After\,costs}{After\,costs}$$

Table 4.3: Results before, after and failure costs and EBIT

Measurements	**no**	**Before costs**	**After costs**	**FailurecCosts**	**EBIT**
Baseline measurements	1	€126.896.000,00	€128.289.750,00	€1.393.750,00	5.0%
	2	€128.208.500,00	€129.221.250,00	€1.012.750,00	4.3%
	3	€128.756.000,00	€130.663.500,00	€1.907.500,00	3.2%
	avg.	€127.953.500,00	€129.391.500,00	€1.438.000,00	4.2%
Follow-up measurements	4	€126.596.000,00	€126.278.250,00	-€317.750,00	6.5%
	5	€129.783.500,00	€140.935.000,00	€11.151.500,00	-4.4%
	6	€128.208.500,00	€136.219.000,00	€8.010.500,00	-0.9%
	avg.	€128.196.000,00	€134.477.416,67	€6.281.416,67	0.4%

Subsequently, the results (see table 4.3) are not as expected based on the literature. The average EBIT of the baseline measurements is 4.2%, during the follow-up measurements have an average EBIT of 0.4% . The last two follow-up measurements have a negative EBIT because the project teams exceeded the 135 million budget, therefore, they operated at a loss.

4.3. Effects of visualised validation on quality

During the gaming simulation, the effects of visualised validation on quality are measured in order to determine the effects of visualisation on the project performance quality. In this research, quality is defined as the quality of a project. Furthermore, quality is defined as the quality of the relationship between client and contractor. In table 4.4, the number of all questions asked by the contractor to the client during the system and preliminary design phase of the gaming simulation are presented.

Table 4.4: Amount of questions by the contractor during gaming simulation

Measurements	no	System Design Phase	Preliminary Design Phase
Baseline measurements	1	20	8
	2	17	12
	3	12	3
Follow-up measurements	4	15	7
	5	18	9
	6	14	13

In table 4.4 the results of the number of questions asked by the contractor are presented. During the system design phase, more questions are asked. This can be explained by the amount of time spoken to the client in this phase (see table 4.1). The subjects discussed during these conversations can be found in table 4.5.

Table 4.5: Number of questions asked about a certain subject

	System Design phase		Preliminary design phase	
	Baseline	Follow-up	Baseline	Follow-up
Budget	1	3	1	5
Collaboration	1	3	1	2
Construction site	3	5	2	2
Design	5	2	7	9
Documents	4	5	1	2
Drawings	2	0	0	0
Functions	8	7	3	1
KPIs	1	1	0	1
Location	1	0	0	0
Maintenance	5	3	2	1
Material	1	0	0	1
Physical interfaces	1	1	0	0
Planning	0	1	0	2
Process	8	5	2	1
Quality	1	1	2	0
Risks	4	1	1	0
Safety	3	2	0	1
Scope	2	1	0	1
Stakeholders	2	2	1	1
Supplies	1	0	0	0
Testing	1	2	1	0

Shown in table 4.5, are the subjects discussed during the interaction between client and contractor in the ontwikkelstraat. During the system design phase, the functions of the system are essential to discuss because it is the basis of the design validation of the project.

Trust between the client and contractor is measured by means of the trust scale, explained in paragraph 3.1.2. During the conversations between client and contractor, the change of tone is recognizable, when there is trust or distrust between the two parties. In multiple occasions, for example, the contractor starts to criticise the client about stricter requirements and immediately tries to get more budget for these changes. According to the five levels of Dietz and Hartog (2006), client and contractors are balancing around the threshold of real trust, so between calculus-based and knowledge-based trust.

4.4. Interpretation results

In this chapter, the results of the gaming simulation are presented. These results are both qualitative as quantitative of nature and gained by means of questionnaires, recordings of the interaction between client and contractor, and participative observations. The results from this research are discussed by means of the hypothesis.

"The use of 3D visualisation in the design validation process during the early design phases has effect on the project performances within the civil engineering sector."

Derived from the gaming simulation results, it appeared that the use of 3D visualisation in design validation does not have any effects for the project performances time, costs and quality. The findings of time and costs show even a negative effect, which is the opposite than expected. The findings on quality did not show any effects at all.

A possible explanation that no effect of visualisation on the project performances has been found is that the physical model of the hydrogen factory in the ontwikkelstraat was only used during one of the follow-up measurements. During the other two follow-up measurement, the physical model was not used by the participants. The follow-up measurement where the physical model was used, it was used by one participant, who build the model. However, the participant did not communicate his findings from the physical model to the other project team members.

Similar to the real world, during the gaming simulation the participants are submerged in information about the hydrogen factory. Part of this information was the physical model, therefore, it can be assumed that the participants did not know what to do with the 3D model. Notwithstanding, it confirms the internal research within VolkerInfra, where project teams do not accept the implementation because the people do not feel the urgency to use BIM due to the ignorance what value 3D models can add to the project.

Part IV
Conclusion

Part IV is divided into two chapters, namely conclusion and reflection, and recommendations. In chapter five, the conclusion of this research is given through answering the research question: 'What are possible effects of 3D visualisation on design validation within the civil engineering sector in the Netherlands?'. Besides that, a reflection is given on all elements of the research and the research validity is presented.

In chapter six, the recommendations are presented. In paragraph 6.1, the recommendations for further research is discussed. Paragraph 6.2 contains the recommendations for practice, which includes the proposed approach for visualised validation and advice.

5 Conclusion and reflection

In this chapter, the research is concluded. Besides that, the reflection regarding all elements of this research is presented. This includes research validity, gaming simulation and results.

5.1. Conclusion

During this research, the effects of 3D visualisation on design validation during the early design phases of a project within the civil engineering sector in the Netherlands were elaborated. The aim of this research was to gain insight in the effects of 3D visualisation on the design validation process and to develop and evaluate a structured approach for the visualised validation process, during the early design phases of a project.

What are possible effects of 3D visualisation on design validation within the civil engineering sector in the Netherlands?

To answer this main research question, two sub-questions are determined:

1. What is design validation and how does it contribute to the construction industry?
2. What are capabilities of 3D visualisation and how does it contribute to the construction industry?

SQ1: What is design validation and how does it contribute to the construction industry?
According to the literature in chapter 2, sufficient design validation has to fulfil several conditions. The aim is to acquire proof that the system in its ability to achieve its intended use (ISO, 2015). Rijkswaterstaat (2017) prescribes three conditions the design validation should meet, namely:

- Design validation is an integral element of the design process;
- Confirmation by client and stakeholders;
- Determine the validation process in cooperation with the client.

There are multiple ways of conducting design validation. Several design activities are of importance for design validation. During the system design phase, these activities are analysing contract documents, as well as document functionalities, requirements and systems. In the preliminary design phase, these activities are a decision on the variants and validation of the design products. It is concluded from the three cases studied that alignment of the design products with client and stakeholders is a key validation step in all cases.

SQ2: What are capabilities of 3D visualisation and how does it contribute to the construction industry?
Bryde et al. (2014), Sebastian and Van Berlo (2011), and Azhar (2012) described the capabilities of 3D visualisation. Three-dimensional visualisation can be static or dynamic. With a static image of the 3D model of the design, the communication and coordination between actors and disciplines are more detailed. By decomposition in subsystems and objects, the technical details of the design can be sufficiently discussed during the validation sessions with the client and stakeholders.

Another capability of the 3D visualisation is expectation management between contractor, client and stakeholders. 3D visualisation can also be used for dynamic images for moving systems, such as locks and movable bridges, which can be used for showing the functionalities of the design. Dynamic images can confirm that the design meets the intended functionalities and use of the system that is going to be built.

Currently, 3D visualisation is used within the civil engineering sector in the Netherlands is by means of BIM. Within the civil engineering sector in the Netherlands, companies deviate in the BIM maturity level, as well as the multiple subsidiaries within the contractor firm VolkerWessels. According to the BIM wedge that is developed by Bew and Richards (2008), level 1 of the BIM maturity is implemented. Therefore, the use of 3D visualisation is implemented in all integral projects within the infrastructure branch of VolkerWessels. The 3D models are used for clash detection, reinforcement in concrete, immediate vicinity and quantities.

The answers on the subquestions lead to the answer on the main research question.

RQ: What are possible effects of 3D visualisation on design validation within the civil engineering sector in the Netherlands?
According to the results described in chapter 4, visualisation does not have an effect on the project performances time, costs and quality. A possible explanation that no effect of visualisation on the project performances have been found is that the physical model of the hydrogen factory in the ontwikkelstraat was only used during one of the follow-up measurements. During the other two follow-up measurement, the physical model was not used by the participants. The follow-up measurement where the physical model was used, it was used by one participant, who built the model. However, the participant did not communicate his findings from the physical model to the other project team members. Therefore, there are not enough results to conclude that there are no effects of visualised validation on the project performances.

From observations during the gaming simulation, it can be concluded that not the availability of the 3D model is an issue, but the standard practice and habits of project teams play a role.

5.2. Reflection

This thesis aimed to fill the theoretical gap on the effects of 3D visualisation on design validation during the early design phases in construction projects. Although this aim is achieved, every research has to make compromises to stay within scope. In this paragraph, the multiple elements of this research are reflected. In paragraph 5.2.1, the literature review is considered. In the second paragraph, the project evaluations are reviewed. Finally, the gaming simulation is contemplated.

5.2.1. Literature review

The lack of literature is considered one of the main limitations of the research. The literature review lays the foundation of the research. The fact that the number of usable sources was considered limited, made it more difficult to build a proper, well-argued and workable theoretical foundation for this thesis. Searching on Google Scholar or Scopus a lot of literature can be found on BIM or 3D models and its advantages and disadvantages. However, searching for validation, most articles are related to the validation of a specific method or area within the construction industry. Concerning the relation between 3D visualisation and design validation, one article was found regarding the return of investment of BIM in South-Korea. On the subject design validation just practical guidelines, templates and action plans are found.

The lack of literature has implications for the thesis and the results presented in it. The conditions for sufficient design validation could not be found in proper literature. Therefore, it is hard to compose requirements for an improved process concerning design validation.

These implications must be taken into account considering the validity of the presented research. The lack of literature has crippled the researcher and it is believed that a stronger research could have been presented if the research was backed by more proper literature.

5.2.2. Project evaluations

For the project evaluations, internal documents and process flowcharts from VolkerInfra were analysed. The issue with these documents and therefore company processes is that theory and practice mostly deviate. In reality, projects are hardly ever executed precisely as planned. Therefore, these documents do not represent the actual procedures accurately. This implicates the research when researching the current situation of design validation and 3D visualisation by analysing these plans and flowcharts.

The deviation between theory and practice has no implications for the outcome of this research. However, these documents cannot be used to strenghten the results of the research.

5.2.3. Gaming simulation

Generally, the ontwikkelstraat is executed approximately two times a month, however, during the holidays the ontwikkelstraat did not take place for 9 weeks. The unavailability of the ontwikkelstraat during the summer led to the small sample size of gaming simulation. The gaming simulation is therefore conducted six times for this research. The gained quantitative data concerning time and costs of the hydrogen factory project and the qualitative data on the interaction between client and contractor both have a sample size of six. This sample size means less data, which make it harder to generalise the findings for the whole industry.

Another compromise in this research is that it is accomplished by one researcher. It was beyond the scope of this study to examine the implementation of a proposed approach. To get the approval of VolkerWessels to use the ontwikkelstraat for this research, it was necessary to adjust the experiment. Due to this practical constraints, it was not possible to implement a new approach in the gaming simulation. Consequently, only the effects of visualisation were chosen to investigate in the ontwikkelstraat. For a complete evaluation of a new approach, it should be sufficient to implement the approach in real-world projects.

A constraint of the ontwikkelstraat is time. As shown in table 5.1, every design phase is just two hours during the afternoon of day one. Compared to real-world projects, a lot of information has to be consumed in this short time. During the follow-up measurements, the physical scale model was available, however, it was not obligatory to use. Because of this time pressure, participants might have overlooked the possibility to use the physical scale model for design validation. In retrospect, compelling the participants to use the physical scale model may lead to more accurate results on the research question whether the use of 3D visualisation during design validation has effect on project performances.

Table 5.1: Program day 1 and 2 of the ontwikkelstraat

Day 1		**Day 2**	
08:00 - 08:10	Opening	08:00 - 09:00	Start up
08:10 - 09:30	Strategy integral infrastructure	09:00 - 10:00	Execution day 1 projects
09:30 - 10:30	Project control	10:00 - 10:20	Team meeting
10:30 - 10:45	Break	10:20 - 11:20	Execution day 2
10:45 - 11:45	Introduction V model downwards	11:20 - 11:40	Team meeting
11:45 - 12:15	Introduction Simulation game	11:40 - 12:40	Execution day 3
12:15 - 13:00	Lunch	12:40 - 13:00	Team meeting
13:00 - 15:00	System design phase (SO)	13:00 - 14:00	Execution day 4
15:00 - 17:00	Preliminary design phase (VO)	14:00 - 14:15	Testing
17:00 - 19:00	Final design phase (DO)	14:15 - 16:00	Feedback
19:30	Dinner		

The previously mentioned limitations have influence on the results of this research. As a result of these constraints drawing conclusions on the effects of 3D visualisation on the project performances time, costs and quality based on the gaming simulation is problematic.

5.2.4. Questionnaire

Another limitation of the research is the self-reported data. The questionnaire has 93 respondents that had to fill in seven questions regarding knowledge, background, work experience and their opinion on design validation. Three questions, namely, what is your function, how much work experience do you have and in which field did you study, were concrete questions. However, the other four questions had a five-level Likert scale. Participants may have deviated regarding their interpretation or understanding of these questions. Notwithstanding, the short explanation prior to the questionnaire, the knowledge levels were different of the participants. Rating scales, such as the five-level Likert scale, are filled in differently by everyone. This naturally generates a deviation in scores between respondents that may reflect on the results in this research. Besides that, the second questionnaire during the follow-up measurements could have been complemented with a question why the participants did or did not use the physical scale model. These answers are interesting for further research on the implementation of 3D visualisation during design validation.

5.3. Research validity

As discussed in paragraph 1.6, the validity of the entire research is divided into reliability, internal and external validity.

The reliability of the research is increased by means of two strategies, namely explicit documentation of the results and triangulation. All responses on the questionnaire and transcripts of the interaction between client and contractors are documented in appendices C and D. The triangulation is done by means of a literature review, desk and field research. The reliability of the findings of the results is dependent on the quality of the data. The quality of literature data is ensured by the general scientific quality of the articles and applicability towards this research. Data gathered during the desk research is discussed with multiple employees within the infrastructure branch of VolkerWessels.

Subsequently, the internal validity is assured by cross-checking real-world projects and the gaming simulation. The cross-checking is done through the validity elements explained in subparagraph 2.4.4 and elaborated in table 6.1 by means of the input variables of the gaming simulation.

Lastly, the external validity is warranted by investigating several civil engineering projects. The projects, VITAL, N18 and renovation Waalbrug, are mainly conducted by the contractor firm VolkerWessels, however, the results are applicable to the entire civil engineering industry in the Netherlands.

6 Recommendations

In this chapter, recommendations are given regarding future research (6.1) and practice (6.2).

6.1. Suggestions for future research

This research has elaborated on the effects of 3D visualisation on design validation during the early design phases within the civil engineering sector in the Netherlands. This paragraph describes suggestions for further research.

The scope of this research did not include the implementation of the use of 3D visualisation during design validation. During the project evaluations, multiple problems, such as the lack of skill and manpower for the implementation of BIM, were mentioned as part of an internal research within the infrastructure branch of VolkerWessels. Besides that, it is found that not the availability of the 3D visualisation is the problem, but the standard parctice and habits of project teams play a role. Research on the problems of implementation of approaches and how to solve these problems would be relevant for the whole construction industry.

During the project evaluations, it has been found that the way of handling changes in the contract after procurement is challenging. It turns out that validation of the design is often obstructed because the results of the validation process can result in uncertainties for all actors in a construction project. If the validation process leads to a negative result, for example, big design changes, there is always the question who is going to pay for these changes. Research on the politics behind the changes in construction projects is relevant, because of the uncertainties these politics bring in the development of projects and the relationship between all actors that are involved.

Finally, it is suggested to further investigate the interaction between client and contractor. During this research, it has been found that many elements play a role, such as trust, culture in the construction industry and communication. During the gaming simulation, the recordings of the conversations between client and contractor can be used to examine patterns of trust. Which questions trigger the relationship between client and contractor and which soft skills are decisive, are interesting research questions. Research on the development of achievable strategies to manage the counterbalance between collaboration and competition between client and contractor would be significant.

6.2. Recommendations for practice

Considering the conclusion and reflection, a proposed approach is designed. This approach is based on the literature and project evaluations and presented in paragraph 6.2.1. In paragraph 6.2.2 recommendations are proposed to improve the project performances by means of visualised validation during the early design phase in future infrastructure projects.

6.2.1. Proposed approach

Based on the results of the literature and project evaluations a new approach for visualised validation is designed. The current process of design, validation and visualisation were taken into account in the new approach. Furthermore, gained from the literature research, the possibilities of the individual elements (methods of design validation and 3D visualisation) are considered in the proposed approach.

The proposed approach consists of an iterative process, which is based on openness between client and contractor, 3D visualisation technologies and abstract thinking. The proposed approach is called the visualised validation approach (VVA). The VVA has to meet some requirements which are presented in table 6.1. Next, the VVA is presented by means of a flowchart in figure 6.1.

Table 6.1: Requirements for the visualised validation approach (VVA)

Requirement	**Source**
The VVA needs to be an integral element of the design process	Rijkswaterstaat (2016)
The VVA needs to prove objectively that the designed system meets its intended use.	ISO (2015)
The VVA needs to be iterative during the early design phases of a project.	Kennedy et al. (2014); Wasson (2006)
The desired output of the VVA is explicit proof that the design meets the intended use confirmed by client and stakeholders.	ISO (2015)
The VVA needs to stimulate positive interaction between client and contractor, based on trust, cooperativeness, equal treatment and common interests.	CROW (2017)
The VVA has to be accepted by the client	Rijkswaterstaat (2016)

The VVA is evaluated by experts. A system engineer, integration manager, design leader have reviewed it. Besides that, these expert judges checked on the applicability in practice. During this evaluation, it turned out that some adjustments had to be implemented in the VVA. These adjustments were within the context of completeness of the approach, such as the different kinds of 3D visualisation is used.

Creation of a structured approach for the design validation process in the early design phases is based on the data conducted from the literature research and the desk research about the currently used methods, regarding design validation and visualisation, and variables that have influence on the interaction between client and contractor. Combining these factors resulted in the Visualised Validation Approach (VVA) for the design validation process. Designing the VVA is done by means of process mapping, which consists of, according Biazzo (2002), a model construction that represents the connection between activities, actors, documents and objects that are taking part in a particular process.

The VVA is a combination of two different project management methodologies, namely the V-model and the scrum. The primary methodology is the V-model, which is elaborated in appendix A - Systems Engineering. Generally, the V-model is used within civil engineering projects in the Netherlands. Within the VVA, the agile project management methodology scrum is implemented during the preliminary phase of the V-model. It is chosen to implement this methodology because it is an iterative mechanism and the advantages on client satisfaction. As seen in the project evaluations, the iterative process caused frequent involvement of client and stakeholders during the early design phases. This project management methodology is further elaborated in appendix H.

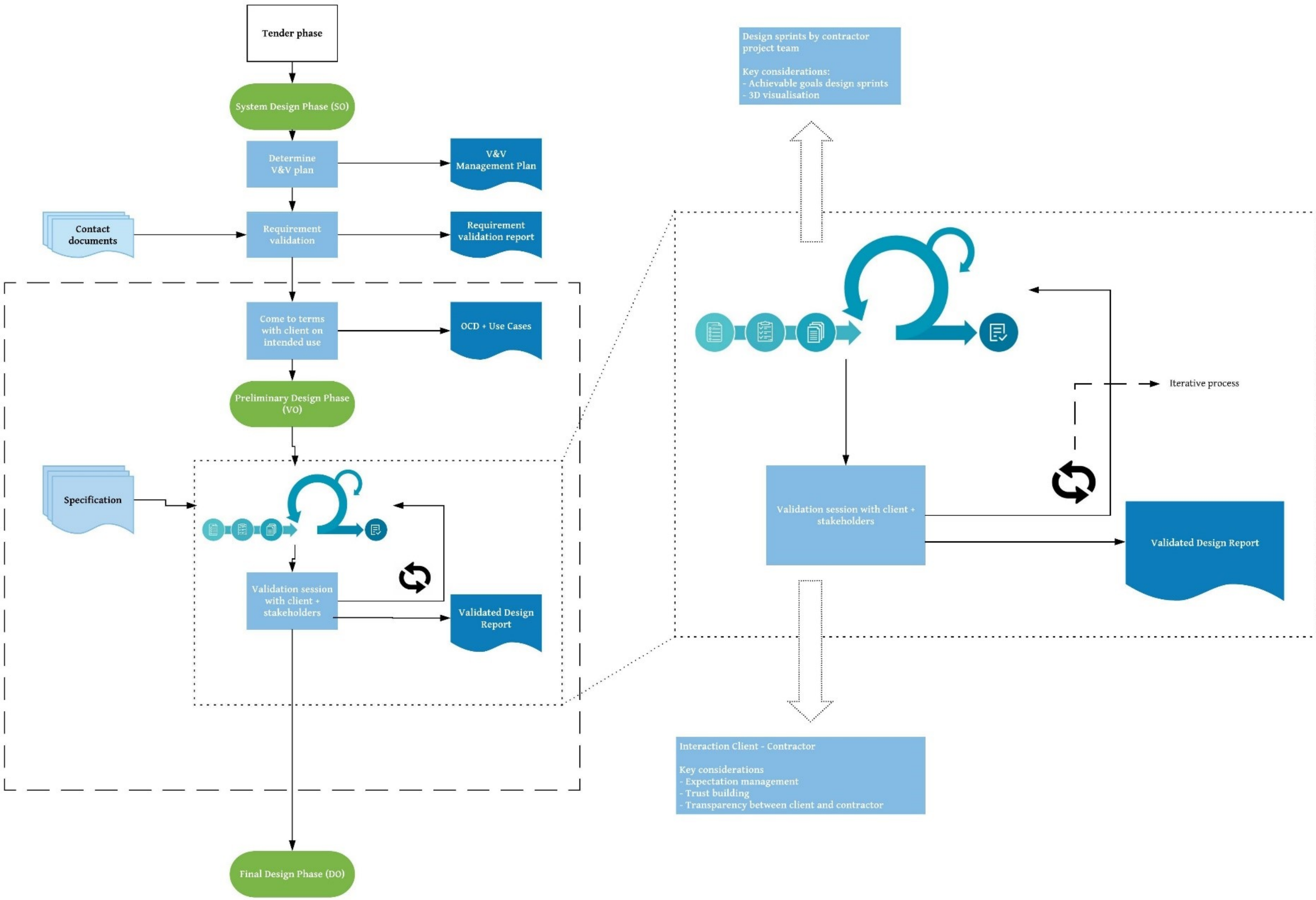

Figure 6.1: Visualised Validation Approach (VVA) (own image)

In figure 6.1, the visualised validation approach (VVA) is shown by means of a flowchart of the process during the system and preliminary design phases. The flowchart is developed based on the current ProMaSys process charts and input of the literature and desk research. In this section, all processes in the flowchart are elaborated. This design focusses on design validation during the early design phases. First, the dashed rectangle around a part of the process is illustrating the scope of this research.

Tender phase
Above this dashed rectangle, the tender phase is shown. The aim of the tender phase is to analyse the conditions and themes that are of interest for the project and to determine the objectives and ambitions for the project. During the majority of the tenders, a reference design is made. However, for the VVA, it is assumed that this reference design is not there or not representative. This assumption is made because it is important that all contract documents are reviewed critically.

System design phase
During the system design phase, three activities are essential for visualised validation, namely determining the verification and validation (V&V) management plan, the requirement validation, and interact with the client about the intended use of the system that will be built. The aim of the system design phase is to understand the project concerning critical activities, interfaces and risks. Besides that, it contains analyses on requirements, functionalities and the system.
'**Determining the V&V plan**' is a contractor responsibility. The V&V plan consists of several components, namely the relationship to other management plans and processes, the strategy on V&V, testing and quality, organisation, the system analysis, the verification process and the validation process. When the V&V plan is completed, it is important to align it with the client and their expectations. Afterwards, the feedback of the client can be implemented in the V&V plan and it can be accepted by the client and contractor.

The next activity is the '**validation of the requirements**'. During this activity, the critical requirements should be discussed with the client. Critical requirements are requirements that are not SMART formulated, critical within the system, or from which it is unknown how to interpret them. The aim of this activity is to identify interpretation differences between contractor and client/stakeholders and align them.

Parallel to the validation of requirements is the activity '**to come to terms with the client about the intended use' and application of the system**. The functionalities of the system are of importance for this alignment because the intended use of the system is based on the functionalities of the system that is going to be built. Besides that, combining the RBS and FBS is incorporated into this activity. The aim of this combination is to connect the specifications, the written requirements, and the practical functionalities of the system. The contents of the specification and functionalities should not contradict each other. The output for this activity is the operational concept description (OCD) including use cases. Use cases are a description of the behaviour of the system, how it responds on input from external, in other words, 'who' can do 'what' with the relevant system.

Preliminary design phase
The preliminary phase results in a project plan concerning design, execution and maintenance aligned with client and stakeholders for the project. In the preliminary design phase, the design process is an iterative process. By means of the scrum methodology, the preliminary design is conducted through several design sprints. Every two to four weeks, a design sprint is finished. The design sprints are in a top-down way, as the V-model, to break down the system in sub-systems and achievable tasks for the design sprints. An important output of the design sprints is the 3D visualisation model.

The output of the design sprints is used in the validation sessions planned after every scrum session with the client and stakeholders. During these meetings, the design version of the last design sprint is discussed, explained and aligned with the expectations of the client and stakeholders. The first meeting, at the end of the system design phase, is necessary to manage the expectations of the stakeholders. Additionally, trust building and transparency are key considerations during the interaction between the client, stakeholders and contractor.

The interaction between the design sprints and the sessions is an iterative process. After each validation session, the results of the alignment are documented in a validation report. This report has to be used during the next design sprint. At the end of the preliminary design phase, a validated design report is produced and accepted by the client. During the validation sessions, the needs and wishes of a stakeholder can change, which can result in changes in the design. How to handle these changes is not in the scope of this research.

Final design phase
In the final design phase, the different subsystems and objects are further elaborated to a level where the interfaces and risks are controlled, in such a way that monodisciplinary refinement is possible. This phase is not included in the scope of this research.

6.2.2. Advice

First of all, it is recommended to use the VVA during future integral projects. The use of the scrum methodology will be new for employees, therefore, it is important to get scrum experts on projects to fill in the role of scrum master or consult on how to execute the process.

The biggest challenge in the construction industry is the implementation of the visualised validation approach. According to an internal investigation, the accessibility of the process and in particular the 3D models impact on the implementation of the VVA. Several employees indicated that they are reserved to use new approaches because of the lack of skills or manpower.

Derived from the gaming simulation, it is recommended that solitary individuals have to be more appreciated in the organisations. Frequently, these individuals already detect weak signals but do not dare to communicate it to their colleagues. According to the individual that used the physical model during the ontwikkelstraat, it happens often that the weak signals were discounted by their colleagues.

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Appendix

Due to confidentiality, the appendices are not publicly available. The appendices are available upon request.

Appendix A – Systems engineering
Appendix B – Projects
Appendix C – BIM
Appendix D – The ontwikkelstraat
Appendix E – Questionnaire
Appendix F – Interaction between client and contractor
Appendix G – Project management system
Appendix H – Scrum methodology