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Diagnosing verification and validation problems in public civil engineering projects

How "building the right system right" can go wrong

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Voorwoord

Voor u ligt het laatste onderdeel van mijn opleiding Civil Engineering and Management aan de Universiteit Twente. Dit paper is het resultaat van het afstudeeronderzoek naar verificatie- en validatieproblemen dat ik uitgevoerd heb bij CROW. Tijdens deze stage heb ik veel kunnen leren over verificatie en validatie, en over de civiele techniek sector in het algemeen. Dankzij de interviews die ik bij opdrachtgevers en opdrachtnemers heb mogen afnemen, had ik de mogelijkheid bij veel verschillende bedrijven binnen te komen. Ik wil dan ook de geïnterviewden bedanken voor hun openheid en de tijd die ze voor mijn onderzoek vrij hebben gemaakt. De informatie uit de interviews was onmisbaar voor dit onderzoek. Ook gaat mijn dank uit naar mijn begeleiders die mij op verschillende momenten van gerichte feedback hebben voorzien. Hierdoor kon ik steeds weer een stap verder komen en toewerken naar een gestructureerd eindproduct. Tot slot wil ik ook mijn vriendin, vrienden en familie bedanken voor hun steun, tips en afleiding. Hierdoor heb ik een leuke afstudeertijd gehad.

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Abstract

In the civil engineering industry systems engineering is widely applied to structure the projects. Verification and validation, considered as crucial parts of system engineering, are quality checks. They are carried out to prove that the design and the realized system meet the user needs and satisfy the developed requirements. In the civil engineering industry both the client and contractor carry out verification and validation, but they both have difficulties with verifying and validating parts of projects. This study diagnoses the client's and contractor's problems related to the application of verification and validation. Case study research is used to detect and analyze these problems. This is assessed in five civil engineering projects, which represent the diversity of the civil engineering industry. The elements of verification and validation, requirements, design, and system, are used to classify the verification and validation problems. Three major causes of verification and validation problems are identified: (1) different client and contractor interpretation of hierarchy in requirements, (2) lack of verification of the client's reference design, and (3) verification is not integrated in contractor's daily design and realization work. First, the client and contractor interpreted the hierarchy in requirements as the other's responsibility. They both did not validate the requirements. As a result the client was not convinced that all requirements were satisfied in the design and realized system. Second, in the civil engineering industry the client makes a part of the design as a preparation of the tendering process. The client did not verify its reference design, while doing so could have prevented contradictions between the requirements and the reference design. Third, the contractor did not integrate verification sufficiently in his daily work. As a result, the quality of the contractor's work was not as high as promised. The verification and validation practice can be improved by carrying out verification and validation more efficiently and by differentiating derived requirements from decomposed requirements.

1. Introduction

Systems engineering is getting more and more attention in the civil engineering industry in the past decade as a response to the increased use of integrated contracts (Akeel & Bell, 2013; CROW, 2014; Farnham & Aslaksen, 2009; Locatelli, Mancini, & Romano, 2014). Systems engineering is defend by the International Council on Systems Engineering as "An interdisciplinary approach and means to enable the realization of successful systems. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs" (INCOSE, 2007). Before the introduction of systems engineering in the civil engineering industry, quality management was a widely used method for ensuring the product quality that meets the user needs.

Verification and validation are essential parts of the system engineering method (Emes, Smith, & Marjanovic-Halburd, 2012) and the quality management method (ISO9000:2015). In both methods verification and validation are parts that compare what should be made to what has been made (O'Leary, 1993). In general, verification is described as 'building the system right' and validation as 'building the right system' (Bahill & Henderson, 2005; INCOSE, 2007; Larsen & Buede, 2002; O'Keefe, Balci, & Smith, 1987; O'Leary, 1993; ProRail, 2015; ProRail et al., 2013). 'Building the system right' means that the system satisfies the requirements. 'Building the right system' means that the system meets the user needs.

The primary purpose of verification and validation is ensuring the quality of the system by detecting deficiencies (Bjarnason et al., 2014; Maropoulos & Ceglarek, 2010; O'Keefe & O'Leary, 1993;

O'Leary, 1993). Verification and validation are also regarded as parts of systems engineering that contribute to avoid unnecessary costs and avoid delay (Adrion, Branstad, & Cherniavsky, 1982; Bjarnason et al., 2014; Boehm, 1983; Bulajic, Stojic, & Sambasivam, 2014; Larsen & Buede, 2002; Maropoulos & Ceglarek, 2010; Nagano, 2008).

In practice though, many organizations in the civil engineering industry experience verification and validation problems. Verification and validation are regarded as time consuming and inefficient. However, research addressing the verification and validation problems is scarce, especially in the civil engineering industry. Only a few studies are carried out in this industry, e.g. Bahill and Henderson (2005) researched verification and validation failures in 24 randomly selected cases (Bahill & Henderson, 2005). One of these cases was a civil engineering project, The Tacoma Narrows Bridge, which was classified as unvalidated.

One of the important characteristics of the civil engineering industry is the contractual relation between the client and the contractor (Dubois & Gadde, 2002). This is considered one of the most difficult aspects of civil engineering projects (Farnham & Aslaksen, 2009). The introduction of the integrated contracts changed the contractual relationships between the client and contractor. In these contracts the client is responsible for developing the requirements and making a reference design as preparation of the tendering process. The contractor is not merely responsible for realization and execution, but also for further development of the requirements and for completing the design. Also maintenance could be included as the contractor's responsibility. The design for every project is unique and is part of the project itself (Chang & Ive, 2007). Public clients are obliged to procure the realization activity of civil projects in a tendering process according to European and national procurement laws. In the tendering process, the contractor is selected and contracted. Because of the increased responsibility of the contractor, the client has to rely more on verification and validation to gain trust in the quality of the contractors work.

This research aims to diagnose the problems regarding verification and validation in civil engineering projects for public works. The following research question will be answered: what are the verification and validation problems in public civil engineering projects and why do they occur? Answering this research question contributes to existing research in two ways: (1) verification and validation are studied in an industry where research on this topic is scarce, and (2) the cause of verification and validation problems is studied, which improves the understanding of verification and validation problems. The research question was answered by studying five civil engineering cases. These are classified with the Systems and Requirements Classification model (Bahill & Henderson, 2005).

The structure of this paper is as follows. Section 2 describes existing literature on verification and validation, providing an overview on the status quo on this topic. The framework for the case study analysis is presented as well. Section 3 describes the multiple case study method. The cases and research context are introduced, as well as the way the framework of analysis is used. Section 4 describes the results, which are analysed in section 5. Next, section 6 captures the discussion and section 7 the conclusion, followed by the limitations in section 8.

2. Verification and Validation

Verification and validation in the civil engineering industry consists of three important elements: (1) requirements, (2) design, and (3) the system (Adrion et al., 1982; Maropoulos & Ceglarek, 2010; Nagano, 2008). The relations between the elements are shown in Figure 1 and the elements are discussed below.

The first element is requirements. The requirements are a translation of all user needs and restrictions into a consistent, complete and accurate representation of what has to be built (Bijan, Yu, Stracener, & Woods, 2013; CROW, 2011; Smartt & Ferreira, 2015). The requirements are formulated on different levels of detail. During the development of requirements upper level, less detailed requirements are derived into more detailed requirements (Bahill & Dean, 2009; Brace & Cheutet, 2012). In civil engineering projects the client develops the upper level, less detailed requirements. The contractor usually finishes the requirements development by deriving and formulating the most detailed requirements.

Second, the client and contractor both make parts of the design. In integrated contracts the client usually makes an abstract, less detailed design (also referred to as the reference design) as preparation for the tendering process. The contractor uses the reference design to make a more detailed design. These designs have to be in accordance with the requirements and represent a solution for the user needs. In the civil engineering industry the contractor makes a verification and validation plan which describes how the design will be verified and validated. The contractor documents the results of the verification and validation in the verification and validation report (ProRail et al., 2013).

Third, the contractor realizes the system, based on the design. Where development of requirements and the design activity are carried out simultaneously, the realization of the system can first start after finishing the design. The client or contractor verifies and validates the elements to check whether they satisfy the requirements and the user needs (ProRail et al., 2013; U.S. Department of Defense, 2001; U.S. Department of Transportation, 2009). The contractor documents the verification and validation results in the verification and validation reports (ProRail et al., 2013).

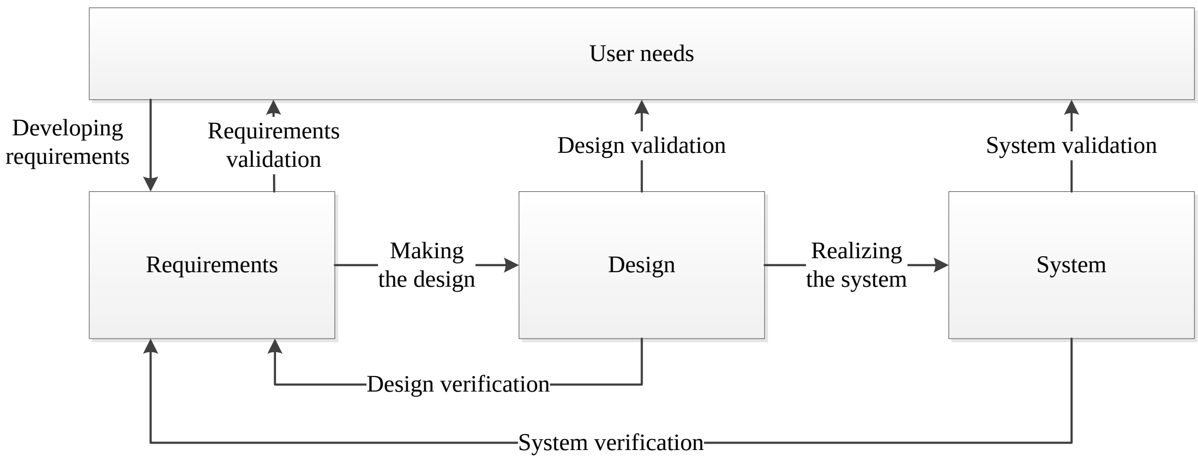

Figure 1: Flow chart of verification and validation elements

Figure 1 shows that verification and validation are not only performed as a control on the final, realized system, but also on the design and the requirements. Deficiencies should be detected as early as possible in the project life cycle, to eliminate them when they are relatively harmless. Therefore verification and validation are performed as early as possible (Bjarnason et al., 2014; Boehm, 1983; Bulajic et al., 2014; Larsen & Buede, 2002; O'Keefe et al., 1987).

In Figure 1 three validation types and two verification types are indicated. These types are requirement validation, design validation, system validation, design verification and system verification. These are defined below.

- Requirement validation: Ensuring that the set of requirements is complete, unambiguous, consistent, and represents a feasible and working system in the intended environment (Bahill & Henderson, 2005; Byun et al., 2013; Kotonya & Sommerville, 1998; Larsen & Buede, 2002; Marchant, 2010; Rijkswaterstaat, 2009; Sommerville, 2005; Zave & Jackson, 1997).
- Design verification: Ensuring that the design complies with the requirements (Bahill & Henderson, 2005; ProRail et al., 2013; U.S. Department of Defense, 2001)
- Design validation: Ensuring that the design matches the intended use of the system and fulfils the user needs (Larsen & Buede, 2002; Rijkswaterstaat, 2009).
- System verification: Ensuring that the realized system complies with the requirements and the design (Bahill & Henderson, 2005; O'Keefe & O'Leary, 1993; U.S. Department of Transportation, 2009).

- System validation: Ensuring that the realized system suits its intended use and fulfils the user needs (Bahill & Henderson, 2005)

These definitions reflect the different elements of verification and validation. The System and Requirements Classification Model (SRCM) contains these elements and has been used by Bahill and Henderson to study verification and validation problems in projects (Bahill & Henderson, 2005). The SRCM is adjusted to enable studying different verification and validation problems within a project. This study also addresses the responsible organizations, which were included in the adjusted SRCM. The adjusted SRCM is used in this research as a framework to study the different types of verification and validation. The adjusted SRCM is presented in Table 1.

Table 1: The framework of analysis based on the SRCM of Bahill and Henderson (2005)

	Requirements		Design		System
	Client	**Contractor**	**Client**	**Contractor**	**Contractor**
Validated and verified	A1a	A1b	B1a	B1b	C1
Unvalidated and verified	A2a	A2b	B2a	B2b	C2
Validated and unverified	n/a	n/a	B3a	B3b	C3
Unvalidated and unverified	n/a	n/a	B4a	B4b	C4

This framework has been used to analyse the cases. In the research method section it is described how this was done. The adjusted SRCM differs on the following aspects from the SRCM:

- Verification and validation are differentiated from the elements of verification and validation: requirements, design and system. These elements are in line with the defined verification and validation types. The differentiation in objects is important for the civil engineering industry to diagnose when problems arise.
- For the elements ‘requirements’ and ‘design’, a differentiation is made in the responsible organization. There is a column for the client and one for the contractor. For the elements ‘system’ this differentiation is not made, since only the contractor realizes the system.
- The types of requirement quality as used in the SRCM are captured under the column ‘requirements’. The set of requirements are considered as a whole, this study does not focus on the quality of a particular requirement. Therefore ‘requirement verification’ is not included.
- The category of ‘unvalidated or unverified systems’ is split up into ‘unvalidated and verified’ and ‘validated and unverified’ to differentiate in the kind of observed problems.

Although these points are adjusted, this framework of analysis and the SRCM both classify how well verification and validation are carried out. The adjustments were made to focus the research on verification and validation within civil engineering projects.

The SRCM has been developed for (1) categorizing entire projects in terms of design conformity and requirements satisfaction and (2) providing a way to study requirements not yet satisfied by any system (Bahill & Henderson, 2005). The former purpose states whether the realized system is made according to the design and whether the requirements are fulfilled. The latter purpose states the SRCM is appropriate for unfinished projects, the requirements do not necessarily have to be satisfied yet. Therefore, the SRCM is appropriate for this study as well, since unfinished cases are studied. In the next section is explained how the adjusted SRCM is used.

3. Research method

This research was conducted as a multiple case study, which is described by Eisenhardt (1989) and Yin (2009). For this multiple case study, cases were selected according to the case selection criteria. After the selection, data were collected from the cases to detect problems and analysed afterwards to diagnose these problems. The elements of verification and validation (requirements, design, and system) are studied to diagnose where the problems arise. Analysis of the problems appoints whether the client or the contractor is responsible for these problems. First each case is studied individually to gain in-depth understanding of the problems and their causes and consequences. Then the cases are compared in the adjusted SRCM to detect the problems that occur repeatedly. In the next paragraph the case selection method is described, followed by the characteristics of the focus area are described, and special attention is paid to the use of systems engineering.

Case selection and research context

Theoretical sampling is used to select five suitable cases. It is an appropriate sampling method for the diagnostic goal of this research, since interesting cases can be studied (Eisenhardt & Graebner, 2007). The theoretical sampling is used to select cases in such way that they reflect the variety in the Dutch civil engineering industry and its characteristics.

The civil engineering industry in the Netherlands is used as the focus area. In this country verification and validation are considered as difficult parts of a project. The specific contractual conditions for integrated contracts (UAC-ic 2005) differentiate the Dutch civil engineering industry from others. A typical aspect is the contractual separation of design activities between the client and contractor. The client usually starts making the design, and the contractor finishes it. Also the fact that systems engineering is being applied for over a decade now, makes it remarkable that still verification and validation are considered as difficult aspects. This makes it an interesting area to study.

Systems engineering is used as a response to integrated contracts. It was introduced in the Dutch civil engineering industry by Rijkswaterstaat and ProRail ten years ago (ProRail, 2015; ProRail et al., 2013; Rijkswaterstaat, 2009). Rijkswaterstaat and ProRail are national clients for civil engineering projects. Also other clients increasingly start to use systems engineering in their projects. It helps to keep control now larger parts of a project are outsourced. It structures a project using top-down and bottom-up approaches with verification and validation moments at every level of detail and for every requirement (Blanchard & Fabrycky, 1981; U.S. Department of Defense, 2001; U.S. Department of Transportation, 2009). The next section describes how the data were collected to do research on verification and validation in these activities.

Data collection method

The data are collected via semi-structured interviews and document inspections. These methods were chosen to get insight in the project specific situation regarding verification and validation. Semi-structured interviews were used to find out what problems the client and contractor faced, why these problems occurred, and what elements of verification and validation are related to the problems. The document inspections were used to get more insight in the formal communication about verification and validation. Using two data collection methods, as methodological triangulation, increases the construct validity of this research.

The interviewees were chosen because of their inside knowledge about verification and validation. In every case, interviews were conducted with employees from the client and the contractor, to get better insight in the way both parties deal with verification and validation.

Table 2 shows more details about the interviews. The interviews were set up semi-structured, which give the interviewer the freedom to anticipate on interesting answers by asking related, in-depth questions.

Table 2: Overview of the interviews per case

Case	Interviewees Client	Roles	Interviewees Contractor	Roles
1	4	Technical manager Chief of design Systems Engineer Verification and Validation manager	1	Systems Engineer
2	2	Technical manager Contract manager	1	Technical and Contract manager
3	3	Construction manager Quality manager Systems Engineer	1	Project manager
4	2	Quality manager Auditor	2	Process coordinator Verification & Validation coordinator
5	1	Auditor	1	Process coordinator

Five cases are used for collecting the data: (1) Highway interchange, (2) Dike reinforcement, (3) Road underpass, (4) Rail zone project, and (5) Road expansion. These cases represent the current state of the art of the application of verification and validation in public works. They have in common that they are Dutch public infrastructural works based on an integrated contract, on which the Uniformal Administrative Conditions for integrated contracts 2005 (UAC-ic 2005) are applied. The cases differ in types of civil engineering projects, in size, and in types of client.

Case 1 is a project for planning, designing and constructing a highway interchange. The national client contracted a combination of two contractors. The planning phase and part of the design were carried out during the study by the contractor, which enabled detailed study of verification and validation early in a project. On the other hand the realization of the system could not be studied. The contract is awarded in June 2015 for €800 million. The project is planned to be completed in 2024.

Case 2 is a project that enhances the design and construction of the dike reinforcement two Dutch rivers. A water board is the client and contracted a construction company for this project, which is part of the Hoogwaterbeschermingsprogramma (high water protection program). The contract is awarded in February 2014 for €14 million and is planned to be completed in 2016. During the study the realization of the system was almost finished. The development of requirements, the design activity and the realization of the system were studied.

Case 3 is a design and construct rail tunnelling project. The former railway crossing is being replaced by two tunnels, one for pedestrians and one for motor vehicles. The latter one is focused on in this study. The national client awarded this contract to a contractor for €7 million in 2014. During the study the tunnel was already in use, the project was about to be finished. The development of requirements, the design activity and the realization of the system were studied.

Case 4 is a design and construct railway tunnelling project. The railway and the railway station are being brought underground. This project is awarded in 2008 by a national client to a combination of construction companies. The contract is awarded for €335 million. During the study parts of the system were realized. The development of requirements, the design activity and the realization of the system were studied.

Case 5 is a road expansion project with a design, construct and maintain contract. The client is a regional organization, and a combination of construction companies is the contractor. The design activity of the constructor was almost finished and the realization of the system was started during the case study. The contract was awarded for €70 million and is planned to be finished in March 2017. The development of requirements and the design activity were studied.

These cases, as a representation of the current state of the art of verification and validation in civil engineering projects, were used to collect the data. The next section describes how these data was analysed.

Data analysis methods

After collecting the data, those were cross-case analysed, which means the findings of each case were compared with the other cases' findings. To structure this analysis, the cases were allocated in the framework of analysis. The information gathered in the interview and document analyses did appoint whether problems did arise, in which element those occurred, and who was responsible. When problems were detected, the according classification was assigned. When for instance requirements were not defined unambiguous by the client, the case was classified as 'unvalidated client's requirements'.

When no verification problems were detected, the case was classified as 'verified'. The term 'unverified' is used in two ways: (1) the verification has not been carried out at all and (2) the verification was carried out but resulted in problems, e.g. not all requirements were satisfied. The same two meanings are applicable on the term 'unvalidated'.

After classifying all cases, patterns were identified and analysed. When cases were classified the same, the reasons for this identical classification were examined. When similarities were detected in these reasons, extra attention was paid to these major problems to find out why they occurred. This was done by analysing and comparing the arguments given in the interviews.

4. Results

This section describes the results of the gathered data in the case studies. Table 3 shows how the cases are classified in the framework of analysis, as introduced in section 2. The reasons for assigning the cases to these classifications are described in Appendices I, II, III, IV, and V. The cases were analysed for the elements requirements, design, and system. Per element every case was classified as having or having not verification and validation problems. It is also indicated whether the client or the contractor was responsible for that activity. The problems that were observed in most cases are described here. Also the problems with the highest impact on the project quality are described here. These problems are further described in the analysis section. These problems, that occur often or have severe impact on the project quality, emphasize best that measurements for improvement need to be undertaken.

Table 3: Results of the case classifications in the framework of analysis

	Requirements		Design		System
	Client	**Contractor**	**Client**	**Contractor**	**Contractor**
Validated and verified			Case 4	Case 2 Case 4	
Unvalidated and verified	Case 1 Case 2 Case 3 Case 4 Case 5	Case 1 Case 2 Case 3 Case 4 Case 5			
Validated and unverified	n/a	n/a	Case 1 Case 2 Case 3 Case 5	Case 1 Case 3	Case 3 Case 4
Unvalidated and unverified	n/a	n/a		Case 5	Case 2
Not studied					Case 1 Case 5

As shown by Table 3 all cases have unvalidated requirements. This validation problem occurred both in the client's requirements as in the contractor's. Four cases (case 1, 2, 3 and 5) had unverified client's designs. Only the design in case 4 was validated and verified for both the client and the contractor. Case 5 also had a contractor's design validation problem. All cases that were studied during the realization of the system (case 2, 3 and 4) had unverified systems. Case 2 also had an unvalidated system. Case 1 and 5 were not studied during the realization of the system.

The classifications regarding the requirements element of case 1 are described here exemplary. A complete description of this case is added in appendix I. The classifications of other cases and regarding the other elements are dealt with in the same way.

Case 1 is classified as 'unvalidated requirements' both in the client's part as in the contractor's. In this case the problem was a different interpretation of the responsibility for the hierarchy in requirements. It was classified as a client's problem because the contractor thought the client had not performed the requirements validation well. On the other hand the client argued the contractor had not performed the requirements validation well, hence the classification as a contractor's problem.

5. Analysis

Based on the results three major causes of verification and validation problems were identified: (1) different client and contractor interpretation of hierarchy in requirements, (2) lack of verification of the client´s reference design, and (3) verification is not integrated in contractor's daily design and realization work. These causes were observed the most (causes 1 and 2) or had severe impact on project quality (cause 3). The major causes of verification and validation problems are described below in relation to the case observations.

Different client and contractor interpretation of hierarchy in requirements

The first major problem is found in the client's and contractor's requirements. All cases had unvalidated requirements. Requirements validation ensures that the set of requirements is complete, unambiguous, consistent, and represents a feasible and working system in the intended environment. In all cases the cause of the unvalidated requirements was the different interpretation the client and contractor gave to the responsibility for the hierarchy in requirements (Appendices I, II, III, IV, and V).

In all cases the client's interpretation of the hierarchy in requirements is that the contractor has to prove the completeness and consistency of the derived, detailed requirements. These derived, detailed requirements might not completely and consistently represent the upper level, less detailed requirement. According to the client's interpretation the contractor had to analyse whether the derived, detailed requirements were a complete and consistent representation of the the upper level, less detailed requirements. If not, the client interpreted that the contractor had to identify what aspects were needed to completely satisfy the upper level, less detailed requirements.

In all cases the contractor's interpretation was that the derived requirements were undoubtedly a complete and accurate representation of the upper level, less detailed requirement from which they were derived. The client was responsible for this hierarchy, and when some aspects were missing, the client had to bring them in. This could cost the client more money, since the contract needed to be changed and the contractor could ask more money for doing more work.

This resulted in a second different interpretation: the client and contractor interpreted differently which requirements the contractor had to verify. In all cases the client desired that the contractor verified all requirements: the upper level, less detailed requirements and the derived, detailed ones. The client interpreted the verification of the upper level, less detailed requirements as evidence for completeness and consistency in the requirements hierarchy (requirements validation).

The contractor on the other hand, interpreted that he only had to verify the derived, detailed requirements. Since the hierarchy in requirements was not his responsibility, he did not have to prove that the derived, detailed requirements completely and consistently cover the upper level, less abstract requirements. Therefore verification of the derived, detailed requirements should convince the client that all requirements were met.

In all of the cases, the way the client and contractor solved these problems was that the contractor agreed in analysing whether the abstract requirements were satisfied, after verifying all derived requirements. The contractor thus took the responsibility for the hierarchy in requirements. This convinced the client that all requirements would be satisfied.

Lack of verification of the client’s reference design

The second major problem cause is the unverified client’s reference design. Design verification is the check that the design complies with the requirements. Four of the five cases (Case 1, 2, 3, and 5) had an unverified reference design. The client made a reference design as preparation on the tendering process. In cases 2, 3, and 5 the contract stated the contractor has to comply with both the reference design as well as the requirements. In case 1, the reference design was exemplary. In the other cases the contractor had to work out the client’s design more into detail.

The client did not verify his reference design for a variety of reasons: there was not enough time (case 3), the client did not recognize the verification information of the reference design would be useful for the contractor (case 5), or he thought it was the contractor’s job to verify the reference design (case 2). In case 1 the client did verify the reference design, but not as early as possible. The client did not share it with the contractor for strategic contractual considerations. For more details about the reasons, see Appendices I, II, III and V.

The consequences were the same; the contractor noticed contradictions between the client’s design and the requirements, which hindered him in further design works. In case 5 it even resulted in delay of parts of the project. In cases 2, 3 and 5 the client stated the reference design was leading over the requirements. This means that in case of contradictions between the reference design and the requirements, the contractor had to stick to the reference design. In case 1 the requirements were leading, since the reference design was exemplary.

Verification is not integrated in contractor’s daily design and realization work

The final major problem is the lack of integration of verification in the contractor’s design and realization activities. In case 5 the contractor verified that certain requirements were satisfied in the design. At least, that is what the contractor stated in the verification report. The client detected that the verification evidence in the verification report did not match with the contractor’s design. This was caused by the contractor who changed parts in the design, but did not change it in the verification report as well.

In case 2 the same happened in the system verification. A sewer pipe had to go through a water barrier with a waterproof connection. The contractor indicated in the verification report that the system satisfied all requirements. During on-site inspections the client noticed that the connection was no way near waterproof. The client obliged the contractor to make the connection waterproof, which the contractor did.

Both examples show that the client could not rely completely on the verification report. The information did not always stroke with the actual design or system. The contractor did not integrate the verification in his daily design and realization activities sufficiently. Therefore deficiencies between the verification report and the design or realized system could occur.

In case 4 the client had his concerns about the integration of verification in the contractor’s system realization activities. He asked for more system verifications and for higher detailed verification evidence. The verification report that the constructor handed over to the client, did not convince the client that all requirements were satisfied.

Thus, because the contractor did not integrate verification in his daily design and realization work, the verification report was not very accurate. Also the verification evidence was not always highly detailed. Therefore the client did not rely much on the verification report. This resulted in more work for the contractor and the client. The contractor had to make more detailed versions of the verification report. The client carried out more on-site inspections. The client and contractor experienced verification as time consuming while it did not contribute much to the project quality.

6. Discussion

The results showed that the client and contractor interpreted the hierarchy of the requirements in a different way. The client interpreted the hierarchy of requirements as the contractor's responsibility. This means the contractor had to prove completeness and accuracy of the derived, detailed requirements and prove satisfaction of the derived, detailed requirements and the upper level, less detailed ones. The contractor interpreted the hierarchy of requirements as the client's responsibility. This means the contractor did not have to prove completeness and accuracy of the derived, detailed requirements and verifying only these derived, detailed requirements is sufficient. These different interpretations result in a problem: neither the client nor the contractor takes the responsibility for the hierarchy in requirements. Therefore, the set of requirements may be incomplete.

The different interpretation of the hierarchy in requirements can be found in literature as well. Two types of more detailed requirements are described. Besides the derived detailed requirements, also decomposed requirements are known (Bahill & Dean, 2009, pp. 232-234). Verification of derived requirements alone is not enough to satisfy the upper level, less detailed requirements. Verification of decomposed requirements however, is enough to prove satisfaction of the upper level, less abstract requirement. This difference enhances a difference in required verification efforts as well. Derived requirements also require design and system verification of the upper level, less detailed requirement. Clients seem to explain the hierarchy in requirements as derived requirements, which asks more effort of the contractor. Contractors are likely to explain this hierarchy as decomposition of requirements, which asks less effort.

Second, the lack of verification of the client's design is, according to the literature, a verification failure. As preparation of the tendering process the client makes a reference design. The client did not verify it. There was no approval that the reference design was in accordance with the client's requirements, which were also made as a tendering process preparation.

The contractor stated in every case that the reference design and the requirements were not completely in compliance. Reference design verification could have solved this before the tendering process. The client did not verify the reference design for a variety of reasons, amongst others because in the client's opinion it was the contractor's task to verify the reference design. Literature however, states that the one who builds or designs a (part of a) system could perform the verification and validation on that (part of the) system the best (ProRail, 2015; ProRail et al., 2013; U.S. Department of Defense, 2001; U.S. Department of Transportation, 2009).

Third, the verification is not integrated in contractor's daily design and realization work. This resulted in inaccuracy in the verification report. Requirements were documented as satisfied, while the actual design or system did not satisfy these requirements. The lack of integration could be the result of the change to integrated contract types in the civil engineering industry. The integrated contracts ask for more effort on verification and validation and require an explicit way of working. Organizations are still not used to these new contracts and new allocation of responsibilities. The client still wants to see on-site what is being built, and the contractor hence does not recognize the need for verifying and validating strictly. However, practice is improving, where three years ago research appointed no verification plans were being made in the researched projects (De Graaf, Voordijk, & Van den Heuvel, 2016), nowadays these plans are made in the projects.

7. Conclusion

This paper diagnosed verification and validation problems in the civil engineering industry. Five cases that reflect the diversity of this industry were studied during this multiple case study. This study focuses in detail on verification and validation of different elements: requirements, design, and the system. Insights are provided into the main verification and validation problems that arise during these activities. This study also focuses on the organizations that are responsible for these problems.

The results of this study show that verification and validation problems were present in every case studied. Verification and validation problems were detected in relation to the requirements, the design, and the system. Three major problems are found. First, the client and had a different interpretation of hierarchy in requirements. The client thought the contractor was responsible for proving the consistency and accuracy of derived, detailed requirements and the contractor had to verify all requirements, but the contractor interpreted it as the client's responsibility. Hence the contractor only verified the derived, detailed requirements. The client was not convinced that all requirements were satisfied.

Since the different interpretation of hierarchy in requirements was observed in all cases, it is considered as a problem that occurs in the entire Dutch civil engineering industry. Industry-wide agreements could be made to set guidelines for coping with hierarchy in requirements. An independent organization as CROW could initiate this. These guidelines could indicate when differentiate decomposing requirements from deriving requirements. Then it would be clear that the completeness and accuracy of derived requirements need to be validated, while verification of decomposed requirements is enough for proving satisfaction of the upper level, less detailed requirement.

The second problem is the lack of verification of the client's reference design. The design and the requirements were partly conflicting, while the contractor had to comply with both. The client did not want to verify his reference design. Therefore he could not have detected the deficiencies between them.

Public clients can contribute in improving the verification and validation practice by giving the right example. When they show their contractors how they verified their reference design, the contractor could verify his design in the same way. Large, national public clients could initiate this. The verification could be performed risk-driven for increasing the efficiency.

The third problem was that the contractor did not integrate verification in his daily design and realization work. This resulted in inaccurate verification reports. Requirements were marked as satisfied, while the actual design or realized system was not in compliance with these requirements.

For the third problem contractors could improve practice, by integrating verification more directly into their daily works. It will help when this can be done efficiently, e.g. with the focus on high-risk aspects. When contractors understand the importance of verifying certain requirements strictly, they might be more likely to incorporate it in their daily working processes. Clients can include verification reports as a condition for every payment.

Since this study shows many verification and validation problems are present in the civil engineering industry, further research is required to determine what measurements have to be taken to improve the identified verification and validation problems. Research on their impacts on the project goals as time and costs can point out how much improvements can be made.

8. Limitations

This research has three main limitations. These are pointed out here. The research only focused on diagnosing verification and validation problems. The analysis started when a verification or validation problem had been observed during the interviews and document inspections. This limits the research to obvious problems; latent problems were not observed nor analysed. Also no research was done on the parts of verification and validation that went well.

Next, this study does not include the consequences of the observed problems in relation to the project goals. Nothing can be concluded about the influence on time and money of the observed problems, based on this research. It will be interesting for future research to examine the influence of verification and validation on the project goals.

Finally, the limited available data of system verification and validation weakens the conclusions about these types. For requirements validation en design verification and validation five cases could have been studied, while for the system verification and validation only three cases could have been studied.

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