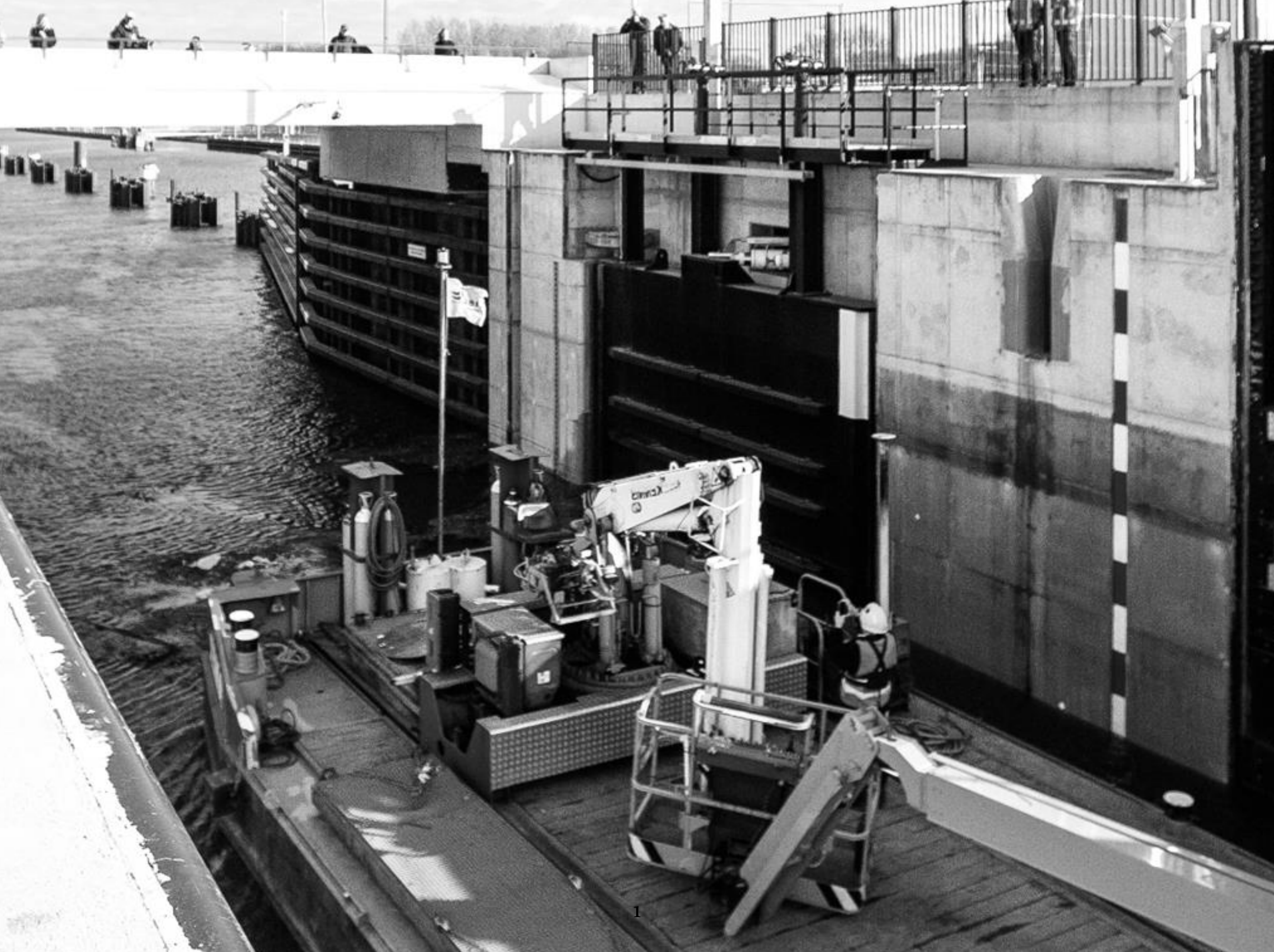
THE VERIFICATION PROCESS OF SUBCONTRACTED WORK IN THE CIVIL ENGINEERING INDUSTRY

B.W.J. Lubbers

JUNE 2020

mobilis | TBI

UNIVERSITY OF TWENTE.



THE VERIFICATION PROCESS OF SUBCONTRACTED WORK IN THE CIVIL ENGINEERING INDUSTRY

MSc Thesis Project – Scientific Paper

The paper is submitted to acquire the degree of Master of Science for the programme of Construction Management & Engineering at the University of Twente.

Document: Scientific Paper
Version: Final
Place, date: Almelo, 10 June 2020

Research conducted by:
ing. B.W.J. (Bas) Lubbers
S1881418
b.w.j.lubbers@student.utwente.nl

Commissioned by:
ing. R. (Remco) Lensen
Head of Design and Work Preparation
Mobilis

ing. H.A. (André) Schröder
Design manager
Mobilis

Supervised by:
dr.ir. R.S. (Robin) de Graaf
Construction Management & Engineering
University of Twente

dr. J.T. (Hans) Voordijk
Construction Management & Engineering
University of Twente

The verification process of subcontracted work in the civil engineering industry

B.W.J. Lubbers

Construction Management and Engineering, University of Twente

ABSTRACT: The civil engineering industry has experienced a shift in the responsibilities from the client to the contractor with contractors no longer focussing solely on construction tasks but also on designing and executing the project. Within these projects, the contractor is responsible for the verification process. However, verification problems are often experienced when parts of the project are performed by subcontractors. This research aims to identify these problems and find potential solutions for contractors. A theoretical framework has been created to analyse the verification process, consisting of three main activities: prepare for verification, perform verification and manage results for verification. A case study has been conducted to identify verification problems. This research found that if verification activities are not performed according to theory, problems are likely to occur. One example of this was demonstrated in the case study, where a number of problems were related to a lack of coordination of the verification activities. Problems were also experienced that were not directly related to the framework but arose from the collaboration with the subcontractor. This document proposes a number of solutions for these problems, including the need for clear assignment of accountability and responsibility of the verification process at all stages of the project.

Keywords: Verification, Subcontracting, Civil Engineering

1 INTRODUCTION

Over the last couple of years, design tasks have shifted from the client to the contractor. Projects are getting more complex and new ways have been created to tender a project. As a result, D&B-contracts (or design and build) arose where both the design and construction of the product is combined into one integral contract. Rather than focusing solely on construction tasks, contractors now need to expand their knowledge to include design. Clients draft specifications of the project which the contractor must further evaluate and create a detailed plan to eventually fulfil. This process requires a methodology to document and deliver these projects. The System Engineering methodology is often proposed or, in some cases, even considered as a precondition. System Engineering means that the responsibilities of contractors transform from merely carrying out a predefined, structured assignment into solving an ill-defined, ill-structured and complex problem in an early stage of the project (de Graaf et al., 2016). It is the contractor's task to verify and validate the fulfilment of the client's requirements. These developments are acknowledged by large civil contractors in the Netherlands who have increased their design departments and gained the necessary experience to create civil designs in-house. This is exactly where the challenge lies for contractors. During the design process, it is essential to verify and validate the design solutions with the client. Verification of a product shows proof of compliance with requirements and validation of a product shows that the product accomplishes the intended purpose in the intended environment (Hirshorn, 2016).

Main contractors often outsource parts of their project to subcontractors, including design tasks. Since contractors sometimes subcontract up to 90 per cent of the total project turnover, suppliers have a large impact on project performance (Bemelmans et al., 2012; Makkinga et al., 2018). They do have, after all, the knowledge of their own product they are selling (Shafaat et al., 2014). Usually, the main contractor sets additional requirements for the subcontractor to make sure it fits their own design. Some subcontractors might incorporate a significant influence on the final product, increasing the role subcontractors play in the verification process. The main contractor is responsible for the verification process of the final product, so they must make sure the subcontractor performs their work complying with the overall requirements. It may be expected that the subcontractor verifies their work, however many problems are experienced with allocating these verification responsibilities to subcontractors and with the verification of subcontracted work (Makkinga et al., 2018). It remains unknown how the main contractor should organise the verification process and to what extent subcontractors could take part in this process.

In this study, the research question is: How should main contractors perform the verification process of work, subcontracted by the main contractor to subcontractor, during the design phase of civil engineering projects?

Chapter 2 presents the theoretical background, which includes theory on involving subcontractors in civil engineering projects and on the verification process. In the end, a theoretical framework is developed. Chapter 3 describes the methodology of this research, including a description of the case study. Chapter 4 shows the results of this research, which are analysed in Chapter 5. Additional problems and solutions are presented in Chapter 6. The paper ends with a discussion in Chapter 7, limitations in Chapter 8 and conclusions in Chapter 9.

2 THEORETICAL BACKGROUND

Involving subcontractors in the design

The civil engineering industry in the Netherlands has introduced more integrated contract forms over the last couple of years. These are contracts where multiple phases are performed by the contractor, including the design and executing phase. The responsibility of contractors increases and gives them more freedom in terms of the design (Bemelmans et al., 2012). However, main contractors do not have the complete knowledge to complete these projects. Therefore, main contractors must involve subcontractors to fill in this remaining knowledge gap. As a result, the main contractor has to rely on subcontractors and it is essential that they share their knowledge in a construction project (Shafaat et al., 2014; Voordijk & Vossebeld, 2013). Instead of only delivering a product or providing services in the executing phase, subcontractors often design and execute a particular part of the entire system (ProRail et al., 2013). Therefore, main contractors should accept at an organisational level that subcontractors can bring added value to the project (Dainty et al., 2001).

There are several enablers to outsourcing activities. Some traditional motives are to cut costs and to increase capacity (Hätönen & Eriksson, 2009). Shafaat et al. (2014) note that involving subcontractors could add value to the project, as subcontractors could bring wealth of process and product design knowledge. Therefore, the involvement of subcontractors makes it possible for experienced design and construction people to share and leverage their knowledge (Gil et al., 2001). A strategical motive is presented by Insinga and Weije (2000), where subcontractors could have the potential to yield competitive advantage, which is more likely to happen for activities that are not widely available on the market. It is the degree of dependence on subcontractor's knowledge that contractors should consider. There are barriers to outsourcing too, including opportunistic behaviour. Subcontractors could take advantage of more responsibilities and steer the project towards a more favourable solution that benefits the subcontractor. Hofman et al. (2009) note another barrier that subcontractors are often reluctant to adapt to design rules of the main contractor.

Verification solutions proposed in literature

At the start of the project, the client and stakeholders define their needs and establish requirements. Makkinga et al. (2018) recognised that the contracted requirement set influences the verification process. These requirements must be analysed and verified with the client to prevent any wrongfully interpreted requirements. This process must be performed by the parties who translate the requirements into a system or preliminary design. For specific parts of a project, a contractor could be dependent on the knowledge of a subcontractor. Thus, the contractor should not only possess expertise and knowledge to create designs but also understand

and analyse the requirements. Afterwards, verification activities are performed to demonstrate proof of compliance with the requirements. This requires the parties to plan, perform and manage the verifications. A detailed explanation of the verification process is presented in the next paragraph.

As explained in the introduction, many problems are experienced when outsourcing verification activities to subcontractors. Makkinga et al. (2018) propose two pre-contract and two post-contract solutions which can be applied by contractors to overcome these verification problems. The pre-contract solutions include carefully considering the level of detail of the subcontracted work in relation to the specific subcontractor and explicitly stating the subcontractor's scope, responsibilities and expectations. The post-contract solutions are continuously coordinating and monitoring the verification performance of the subcontractor and, worst-case scenario, completely taking over the verification activities.

Several factors require careful consideration when deciding how to subcontract design and verification processes could depend on a number of factors. Literature reveals three main factors should be considered: subsystem complexity, level of experience and interface complexity.

Shafaat et al. (2014) state that when the subcontracted work has vital unclear aspects and when the uncertainty is high, a switch from routine-mode to group problem-solving mode is made. Subcontractor involvement is necessary in complex projects as the subcontractor can come up with creative design solutions (Gil et al., 2001).

Contractors should also carefully balance the complexity of the work to be subcontracted to the knowledge, skills and experience of the subcontractor (Makkinga et al., 2018; Shafaat et al., 2014). It is important to be sure the subcontractor has the technical capability that matches the responsibilities transferred (Liker et al., 1998).

Makkinga et al. (2018) note the number and complexity of interfaces between the subsystem and the rest of the system should be considered. These solutions offer a first insight on how to deal with the verification process of subcontracted work.

Towards a theoretical framework

In this paragraph, the verification process is further elaborated into three main activities. These three activities form the basis for the theoretical framework. Within the civil engineering industry, no specific handbook or standard is designated to be used, which includes a detailed step-by-step explanation of the verification process. Therefore, literature of other industries is used as the baseline for the theoretical framework. The verification activities are divided into three main activities: (1) Prepare for verification, (2) Perform verification, and (3) Manage results for verification.

Table 1 shows the framework where all activities are presented and described, including a list of the sources used. Note that this framework is adjusted as explained in the next paragraph, where some activities are tailored to civil engineering. Appendix I shows an extended table which includes the quotes used to establish a single description of the activity. For more trackability, the table in the appendix includes the original activities.

Prepare for verification

The purpose of the verification process is to provide objective evidence that a system or system element fulfils its specified requirements and characteristics ('ISO/IEC 15288', 2015). In order to do so, the project team must perform certain activities to prepare for verification.

The project team should develop a verification strategy, which includes a list of items for verification and the corresponding actions, verification constraints that could impact the implementation of the verification actions, and the verification scope. Verification procedures should also be developed. These procedures identify the purpose of the verification actions, the technique to be applied and the environmental conditions. Furthermore, the verification schedule is developed, which states the moment of verification of each item to be verified. Verification constraints arising from the verification strategy are identified. These are constraints relating to system requirements, architecture or design elements. Lastly, the project team should ensure all necessary enabling systems, products, or services for the verification actions are available when needed.

Perform verification

After the preparation of the verification is performed, the actual verification actions can be executed according to the verification strategy and the verification procedures. Afterwards, the verification results must be analysed to determine conformance to the requirements.

Manage results for verification

The last activity of the verification process is to manage the results of the verification. The verification results should be identified and recorded in a Requirement Verification and Traceability Matrix and any anomalies encountered during the verification process should be recorded. Traceability of the verified system elements should be maintained. Key information items should be provided that have been selected for baselines. The verification schedule and strategy should be updated according to the progress of the project and the verification activities should be coordinated with the project manager, designers and configuration manager.

Tailoring to the civil engineering

The current theoretical framework is mainly based on System Engineering handbooks that are applicable in multiple industries. However, the Dutch civil engineering employs certain concepts that do not directly occur in other industries. For example, design phases are often indicated by preliminary, final and executing design (VO, DO and UO in Dutch). Furthermore, conformance to certain system requirements is demonstrated by specifying them on drawings. Certain verification activities are also performed differently within this industry. These activities are explained below.

Develop a verification strategy

The first verification activity in the theoretical framework is the development of a verification strategy. This includes the items to be verified and the verification methods to be used. In civil engineering, it is common practice to draw up a verification and validation management plan (ProRail, 2015; ProRail et al., 2013; Rijkswaterstaat & Bouwend Nederland, 2015), in which the verification strategy is laid down. This verification and validation management plan (which from now on will be stated as a verification management plan), includes the strategy of the verification process, the organisation of the verification activities, agreements on starting principles, the verification methods to be used per project phase, phasing and agreements on the verification status and verification reporting.

This activity has been revised from *develop a verification strategy* to **develop a verification management plan**.

Develop verification procedures

The second activity is the development of verification procedures. As explained, the verification management plan describes on a generic level how conformance to the requirements is demonstrated, how often and in which phases of the project (Rijkswaterstaat & Bouwend Nederland, 2015). In contrast, the verification procedure describes a complete step-by-step plan of all activities; who will do what and when (ProRail, 2015). This procedure specifies for each requirement which verification method will be used, the required standard, when the verification will take place, by whom the verification will be carried out and which tools will be used for the verification. This list of verification activities for each requirement is also known as a verification plan (ProRail et al., 2013). Therefore, this activity has been revised from *develop verification procedures* to **develop a verification plan**.

Analyse verification results

This activity takes place after the verification actions are performed according to the verification plan. These verification results are then analysed to determine conformance to the requirements. Within civil engineering, these results are recorded in verification and validation reports (ProRail, 2015; ProRail et al., 2013). These reports are drawn up to substantiate that the system meets all requirements (Rijkswaterstaat & Bouwend Nederland, 2015). Eventually, these verification reports are linked to the requirements in an information management system (IMS). This activity is revised from *analyse verification results* to **develop verification reports**.

Identify and record verification results

In the civil engineering industry, verification results are often recorded in a verification matrix (de Graaf, 2014; Rijkswaterstaat & Bouwend

Table 1*: Theoretical framework tailored to civil engineering methodology*

Main activity	Activity	Theoretical pattern	Sources used
Prepare for verification	Develop verification management plan	The verification management plan is developed, which defines the strategy of the verification process, the organisation of the verification activities, agreements on starting principles, the verification methods to be used (per project phase), phasing and agreements on the verification status and verification reporting.	(ProRail, 2015) (ProRail et al., 2013) (Rijkswaterstaat & Bouwend Nederland, 2015)
	Develop verification plan	The verification plan identifies for each requirement the verification technique to be applied, the verification schedule, criteria and the responsible party or person for verification.	(INCOSE et al., 2015) ('ISO/IEC 15288', 2015) (Department of Transportation, 2009) (de Graaf, 2014)
	Identify verification constraints	Verification constraints are identified that arise from the verification strategy, that relate to system requirements, architecture or design elements.	(INCOSE et al., 2015) ('ISO/IEC 15288', 2015)
	Identify necessary enabling systems	The necessary enabling systems, product, or services are identified and available for the verification actions.	(INCOSE et al., 2015) ('ISO/IEC 15288', 2015) (de Graaf, 2014)
Perform verification	Perform verification actions	The verification actions are executed according to the verification plan.	(INCOSE et al., 2015) ('ISO/IEC 15288', 2015) (de Graaf, 2014) (Department of Transportation, 2009)
	Develop verification reports	The verification reports are developed to provide evidence of the conformance to the requirements.	(ProRail, 2015) (ProRail et al., 2013) (Rijkswaterstaat & Bouwend Nederland, 2015)
Manage results for verification	Record verification results in the verification matrix	The verification results are recorded in the Verification Matrix.	(INCOSE et al., 2015) (de Graaf, 2014) (Department of Transportation, 2009)
	Record anomalies observed	Anomalies encountered during the verification process are recorded. These include anomalies due to the verification strategy, enabling systems, verification execution or system definition.	(INCOSE et al., 2015) ('ISO/IEC 15288', 2015)
	Maintain traceability of verified system elements	Traceability is established and maintained of the verified system elements with the verification strategy, system architecture, design and system requirements.	(INCOSE et al., 2015) ('ISO/IEC 15288', 2015)
	Provide baseline information	Key information items are provided that have been selected for baselines.	(INCOSE et al., 2015) ('ISO/IEC 15288', 2015)
	Update verification strategy and schedule	The verification strategy and schedule are updated according to the progress of the project, including redefining or rescheduling planned verification actions.	(INCOSE et al., 2015) ('ISO/IEC 15288', 2015) (ProRail et al., 2013)
	Coordinate verification activities	The verification activities are coordinated with the project manager, designers and the configuration manager.	(INCOSE et al., 2015)

Nederland, 2015). The verification reports of the previous activity are included and linked to this verification register (ProRail et al., 2013). The matrix will then contain information on the requirements, the verification plan and finally the verification report. This activity is revised from *identify and record verification results* to **record verifications results in the verification matrix.**

3 METHODOLOGY

In this section, the methodology of this research is described. An in-depth case study was performed where qualitative data has been acquired from a civil engineering project which included multiple subcontractors involved in the verification process. In this research, the core concepts are clearly defined and care has been taken to ensure the findings did not deviate from the intended scope. Therefore, the first step was to develop a theoretical framework to provide strong guidance for the research project. This required a literature study to identify the verification activities a civil engineering contractor should perform. As there is no specific step-by-step plan to perform these verification activities for contractors in the civil engineering industry, the literature on the verification process of other industries was used. The theoretical framework has been tailored to the Dutch civil engineering industry to make sure that the concepts used in this industry match the theoretical framework. Furthermore, the literature study included theory on subcontractor involvement in the design phase of a project. It is expected that aspects of that subject could influence the verification process.

The next step was to perform the case study. According to Yin (2003), there are four basic types of designs for case studies. This case study fits the embedded single-case design, where the case is one holistic project of the main contractor and the units of analysis are the verification relationships between main contractor and subcontractor. The project is part of the context of the verification process, so care must be taken that the characteristics of the project are not excluded. Therefore, several preconditions were set for the project to be researched. The project must be commissioned in an integrated form, so that the contractor performs the design and execution of the project, making the contractor responsible for the verification process. Furthermore, a diverse set of subcontractors should be involved in the verification process.

Data collection

Empirical data has been collected by means of two main sources: interviews and documents. An essential source in a case study is performing interviews as it is possible to gain insightful information including underlying reasons. Additionally, documents are used as a source of evidence. It is often very helpful to study documents together with interviews, as documents can be used to corroborate and augment the findings. In addition to documents relating to the project, such as drawings, plans and reports, the researcher had access to the IMS of the project. The interviews were mostly performed by using a structured format, but to gain more information on the context, additional questions were required. Therefore, the format has been restructured to better fit the research and gain more information. Interviews were conducted at both main contractors but also at the subcontractors. The employees that were interviewed have been selected based on their role in the project, such as project managers and design managers. In addition, employees that performed verification activities or managed the verification process were interviewed. Questions focussed on the organisation of the verification process, the different verification activities and the role of the subcontractors during the project.

Data analysis

The next step was to analyse the qualitative data collected during the case studies. This was done by making use of the pattern matching technique, which involves the comparison of predicted patterns with the ones found in empirically collected data (Yin, 2003). A rich theoretical framework supports the use of this technique as it is essential to identify any variances or gaps. For each activity, theoretical and empirical patterns are formulated. A pattern is defined as a description of the activity. It is important to note that the theoretical patterns were drafted in advance of the data collection and analysis phase.

The theoretical pattern describes how the verification activity should be performed according to theory, as presented in Table 1, whereas the empirical pattern describes how the activity is performed in practice. Care must be taken that the formulation of the empirical patterns is performed from the perspective of the subject of this research, which is the main contractor who is responsible for the organisation of the verification process and for the delivering a complete system, complying to all requirements. The results of the pattern match are later analysed and linked with the subcontractors to find the effects of involving subcontractors in the verification process.

The two patterns are checked to find if the comparison indeed matches, partly matches or is a mismatch. Matches are scored with a +, indicating that the theoretical and empirical pattern coincides; partly matches a o, indicating the pattern show some similarities, but do not completely match; and mismatches a -, indicating that the patterns do not match. To prevent multiple partly matched activities, a match or mismatch still counts as one if only one exception is found.

Verification problems

The results of the pattern match on their own do not answer any of the research questions. Therefore, an additional step is required, where it is evaluated if verification problems occurred in practice. The combination of the two gives more insight into the significance of each verification step. A hypothesis is used during the analysis, where problems are expected if the pattern partly matches or mismatches and no problems are expected for patterns that do match. The activities that did not match theory are related to the subcontractors. Additional attention is given to problems that are not in keeping with the hypotheses, in order words, where experienced problems do not directly relate to activities that partly matched or mismatched. These are the ones that suggest that, with the introduction of subcontractors, the theory is not sufficient.

Afterwards, the significance of the findings is discussed with the existing theory on the verification process and the limitations of this research are made clear.

Case study outline

The project concerns the expansion of a lock in the Netherlands, where a second lock chamber was planned to increase its capacity and to reduce the waiting times. The contractor, where this research is primarily conducted, entered a partnership with a sister company in the tender process and was eventually awarded with the DBFM-contract. Although the research was primarily conducted at the main contractor who performed the civil engineering part of the project, also empirical data has been gathered from the other main contractor. Both contractors organised all processes together, including the verification process.

Underneath, a general overview is shown of the individual subcontractors involved in the project, regarding the verification process and the problems experienced.

Subcontractor A

This subcontractor was responsible for a relatively large part of the project. The subcontract includes developing verification plans and verification reports. Requirement analysis was performed together with this subcontractor to make sure the right requirements were shifted towards this subcontractor. They had to work with both main contractors, as there were many interfaces with both parties, but communication was lacking regarding the verification process. Verification activities were not coordinated, which had a big impact on the verification process of this subcontractor. They did perform their verification responsibilities, but problems occurred with requirements that concerned multiple parties. This was exacerbated by the subcontractor not using the same IMS.

Subcontractor B

Similar to subcontractor A, this subcontractor had to design and verify their subsystem of the project. However, no major problems were experienced. Also, this subcontractor did not use the IMS of the main contractor. Instead, an employee of one of the main contractors felt responsible for the verification process of this subcontractor. He effectively had to invest time to make sure the subcontractor performed the verification actions. Although this particular employee saw this way of working as a problem, no verification issues were experienced. This solution was possible as the subcontractor only had interfaces with one of the main contractors.

Subcontractor C

The verification process of this subcontract was quite different. They were involved in the project as the client prescribed a verification method for a number of requirements belonging to this subcontractor. When it became apparent that the prescribed verification method could not be used, the client ordered this subcontractor to make this possible. Problems occurred when the client, without the contractor's knowledge, included more requirements. Furthermore, the subcontractor only had to show compliance with the requirements but was not responsible for the design. Therefore, they only had to develop the verification reports. The other activities remained with the main contractor.

Subcontractor D

A major problem was experienced for this subcontractor, which was mainly related to the contract. The main contractor chose to involve this subcontractor at a late stage of the project because they lacked experience to translate functional requirements to a design. Instead, a traditional contract was signed based on a design the subcontractor delivered. As a consequence, all risks remained at the main contractor, leaving the subcontractor with a lot of freedom. In the end, a subsystem was delivered which did not show compliance with the requirements. This contract-related problem resulted in a subsystem not performing any of the verification activities.

Subcontractor E

This subcontractor was not directly part of this study as originally, they are subcontracted by subcontractor A. However, when a big design decision changed the demarcation of both subcontractor A and E, many requirements were copied towards this subcontractor. The lack of coordination of the verification activities impacted the verification of this subsystem as well. They did not have the knowledge to perform the verification activities of this new part at the desired level, which only became apparent at the end of the design phase. The necessary knowledge of this part, however, could have been provided by one of the main contractors.

4 RESULTS

With the help of the theoretical framework, consisting of a total of 12 activities divided over 3 main categories, the theory and practice were examined. Pattern matching was used to confront theory and current practices. As noted in the methodology, the current practices are presented from the perspective of the main contractor. Every activity has been scored and is indicated by a three-point scale: matches (+), partly matches (0) and mismatches (-). Table 2 shows the results of the pattern match. An extensive overview of the evidence gathered is shown in Appendix II. Overall, the pattern match shows 6 matches, 4 partly matches and 2 mismatches.

Matches

First, a brief overview is given of the activities that match:

- develop verification management plan;
- develop verification plan;
- develop verification reports;
- record verification results in verification matrix;
- record anomalies observed;
- update verification strategy and schedule.

The verification management plan was developed at the start of the project by the main contractors, which includes the verification strategy. All aspects suggested by theory, except for the agreements on the verification status, were present in practice. The next activity, develop verification plan, is primarily performed in the IMS, asking for the same input theory suggests for planning the verifications. The third and fourth activity matching theory regard the development of the verification reports and the recording of these results in the verification matrix. Although practice showed it took hard work to eventually complete the reports and to record them in the matrix, it was rather due to the delay in performing the verification actions, which is further explained in the next section. The fifth match regards the recording of the anomalies, which was performed by recording them as a deviation. These deviations are then handled with the client. The last match regards updating the verification strategy and schedule. The verification strategy was described in the verification management plan, which was updated three times to match the actual process.

Partly matches

This section addresses the activities that partly match:

- identify verification constraints;
- identify necessary enabling systems;
- perform verification actions;
- maintain traceability of verified system elements.

Theory suggests the verification constraints should be identified arising from the verification strategy. In practice, verification constraints are identified by identifying risks arising from other processes. These risks were linked to the IMS. The IMS, however, showed several constraints that should have been resolved. Therefore, the supporting verification system did not match the intended process throughout the project. This directly links with the next activity that partly matched theory, which is to ensure necessary enabling systems are identified and available for the verification actions. As the IMS had several constraints, the tool did not support the project team. Furthermore, the design of the system was not sufficiently thought through and the employees lacked expertise to work with the system. Although the IMS was available, it was not fully utilized. To solve this, the main contractor chose to chase the people responsible for verification to perform the activities. However, by doing so at a late stage of the design process, the IMS appeared as if it was only being used to demonstrate compliance to the requirements, while the system could have supported the team during the design process. Other necessary facilities and tools are identified by performing a Test Readiness Review. The next activity is performing the verification actions according to the verification plan. The practice showed that these were performed in accordance with the verification plan, but people had to be persuaded to actually perform these verification actions. It seemed that people weren't engaged in the verification process and just wanted to continue with the project itself. It is possible to take on some of the work of the persons performing the verification actions, but the accountability remains with them. Eventually, the verification of the requirements was performed.

The final activity partly matching theory is maintaining traceability of verified system elements. Practice showed that this activity was performed by combining the design and verification processes, linking the requirements with system elements and the design. However,

Table 2*: Pattern matching results*

Main activity	Activity	Theoretical pattern	Empirical pattern	Match
Prepare for verification	Develop verification management plan	The verification management plan is developed, which defines the strategy of the verification process, the organisation of the verification activities, agreements on starting principles, the verification methods to be used (per project phase), phasing and agreements on the verification status and verification reporting.	The verification management plan is developed, which defines the strategy of the verification process of both system and management requirements, the organisation of the verification activities, starting principles, verification methods to be applied and verification reporting.	+
	Develop verification plan	The verification plan is developed, which identifies for each requirement the verification technique to be applied, the verification schedule, criteria and the responsible party or person for verification.	The verification plan is developed, which identifies for each requirement the technique to be applied, the verification schedule, criteria and the responsible party or person for verification.	+
	Identify verification constraints	Verification constraints are identified that arise from the verification strategy, that relate to system requirements, architecture or design elements.	Verification constraints are identified by identifying risks arising from other processes.	o
	Identify necessary enabling systems	The necessary enabling systems, product, or services are identified and available for the verification actions.	The necessary enabling systems, product, or services are identified and available, but not fully utilized to support verification actions.	o
Perform verification	Perform verification actions	The verification actions are executed according to the verification plan.	The verification actions are executed according to the verification plan, but only after repeatably reminding the responsible person for verification.	o
	Develop verification reports	Verification reports are developed to provide evidence of the conformance to the requirements.	Verification reports are developed to provide evidence of the conformance to the requirements.	+
Manage results for verification	Record verification results in the verification matrix	The verification results are recorded in the Requirement Verification and Traceability Matrix.	The verification results are recorded in the verification matrix.	+
	Record anomalies observed	Anomalies encountered during the verification process are recorded. These include anomalies due to the verification strategy, enabling systems, verification execution or system definition.	Anomalies encountered during the verification processes are recorded as deviation.	+
	Maintain traceability of verified system elements	Traceability is established and maintained of the verified system elements with the verification strategy, system architecture, design and system requirements.	Traceability is established and maintain of the verified system elements with the design and system requirements.	o
	Provide baseline information	Key information items are provided that have been selected for baselines.	Baselines are created, but the project team did not act upon them.	-
	Update verification strategy and schedule	The verification strategy and schedule are updated according to the progress of the project, including redefining or rescheduling planned verification actions.	The verification management plan is updated according to the progress of the project.	+
	Coordinate verification activities	The verification activities are coordinated with the project manager, designers and the configuration manager.	The verification activities are not coordinated with the project manager, designers and configuration manager, except for subcontract B.	-

traceability was not established with the verification strategy, as theory suggests. It is important to know how the system creates the links and that one similar approach is used. For example, it was not known if evidence reported for the verification still shows the compliance to the requirement if either the evidence or the requirement itself had been changed.

Mismatches

Mismatches were found on the following activities:

- provide baseline information;
- coordinate verification activities.

The baselines of the verification process were created in the form of a management report, but the project team did not act upon them. No actions were performed after these reports were presented. People didn't feel they should be held accountable leading to minimal use of the agreed baselines. Someone should have taken the lead and be accountable for the results of these baselines, particularly when it became clear verification actions were delayed. The information shown in the exports was questioned by the employees as it could differ every time. The baselines should have been supervised.

This directly connects with the next mismatch, where verification activities are coordinated. Practice showed there is a significant advantage in coordinating the verification process. The verification activities were not coordinated and nobody was accountable for the entire verification process. The role of the verification manager was merged with the integral design manager role which didn't work. This situation was exacerbated due to the integral design manager being the project manager of a discipline at the same time. Consequently, people didn't feel the need to perform verification actions. Therefore, in addition to the technical employees, you need someone to do the monitoring and who makes sure that everyone knows how to use the tool. Communication is most important here, not only with your partners but also with the subcontractors. Involving someone from the start could make a huge difference. After a while, the need to coordinate and chase people reduces, because they now know what to do. It is essential that someone is made accountable for all requirements.

5 ANALYSING THE RESULTS

General overview

The pattern match shows that parts of the verification process were performed according to theory and parts of the verification process did not match theory. The hypotheses of this research, where problems are expected if an activity is not performed according to theory, seems correct. Every activity that partly matched or mismatched showed problems during the verification process. These experienced problems are linked with the subcontractors in next paragraph. The hypotheses also states that no problems should be expected for activities that did match theory. However, the main contractor did experience additional challenges, which do not directly relate to findings of the pattern match. In addition, as stated in the outline of the subcontractors, different kind of problems were experienced for subcontractors C, D and E. These problems are elaborated in Chapter 6.

The verification process of subcontracts

The case study outline shows that verification problems were experienced for all subcontractors, except for subcontractor B. One of the employees recognized this but states that this subcontracting probably is not the perfect example of how to perform the verification process, mainly due to the relatively low complexity of this subsystem. There was, however, a main difference with other subcontractors, which was that the responsibilities were clear and someone from the main contractor felt accountable to complete the verification process. The pattern match showed a mismatch on coordinating the verification activities. Only for this subcontractor were the verification activities coordinated, suggesting coordinating the verification activities is an essential step in the verification process.

Furthermore, the pattern match showed problems were experienced at identifying constraints, identifying necessary enabling systems and maintaining traceability of verified system elements. All three activities showed problems regarding the IMS. None of the subcontractors made use of this system. This was only experienced as a problem for subcontractor A, who had a more complex subsystem with a high number of interfaces. Similar to the evidence found for the empirical pattern of the development of the verification plans, people from both Subcontractor A and B had to be chased to perform this activity.

The lack of coordination and not sharing the same IMS also links with the mismatch, where baselines are created. As the IMS of the main contractor was used to create the baselines, there was no direct input from the subcontractors. Therefore, the baselines were not complete.

6 ADDITIONAL VERIFICATION PROBLEMS AND SOLUTIONS

The previous section discussed the verification problems experienced in accordance with the theoretical framework. However, more problems were experienced, which do not directly relate to partly matches or mismatches. Therefore, these problems are examined in more detail below and possible solutions are proposed.

Additional verification problems

Subcontractors C and D had quite different verification processes. The problems experienced are not related to the activities stated in the framework, but originated from the way the contractor awarded the work to the subcontractor, which is also identified as a problem in the case study of Makkinga et al. (2018). The contract of subcontractor C only included one activity: showing compliance with the requirements. However, they were not responsible for the design of this subsystem, leaving the main contractor with the task to design the subsystem without being able to verify the design solutions themselves. As the subcontractor did possess the required design knowledge for this subsystem, the subcontract should have included design activities. For subcontractor D, the work was procured in a way that allowed the subcontractor the opportunity to deduct an activity, despite delivering the design for the subsystem. Ultimately a solution was chosen that did not comply with the requirements. It is still common for parties to first chose a solution and only then check if it meets the requirements. It is preferred to use an existing solution rather than to come up with a new solution that fits all requirements. This also became apparent for the client who preferred a solution over the requirements, complicating the verification process.

Secondly, many problems were experienced regarding a lack of clear responsibilities and subsequent accountabilities. Especially for Subcontractor A, who was responsible for a big part of the subcontract, more agreements should have been made. Accountabilities and responsibilities between the parties were not clearly defined. The subcontractor was rather hesitant believing the main contractor had to take the lead, while the main contractor believed all parties should take more initiative. As a consequence, the verification activities were delayed due to the lack of clear ownership in the verification process, which was recognized by subcontractor A. They acknowledged that actually performing the verification at every design phase will benefit the entire process. However, possibly being afraid of taking too much verification responsibilities (after all, they are only a subcontractor), they still did not perform the verification actions for themselves. This suggests that the main contractor should take the lead. Performing the verification actions doesn’t have to be difficult, but it will get difficult if all verifications are delayed until the very end and without clear ownership.

Thirdly, problems were experienced regarding the IMS. As stated, the IMS was not being used by the subcontractors. This also affected the development of the verification plans. As described in the management plan, the team intended to use the IMS as the tool to create these verification plans. As a result, there was no clear format for the verification plans. This does not have to be a problem but having different approaches to plan the verification later turned out to be difficult to manage. The IMS is often seen as a way to perform the verification actions, while it should be seen as a tool to support the verification process. Practice showed there was no clear view of how and to what extent this tool should be used.

Finally, one of the bigger problems during the project occurred when a significant design change during the final design phase influenced the scope demarcation of subcontractors A and E. After this design change, many requirements belonging to the main contractor were now copied towards the scope of the subcontractors. Therefore, the subcontractor had to plan many more verifications. While this doesn’t necessarily cause a problem, the subcontractor did not possess the knowledge to perform these verification actions and to determine conformance to these new requirements. As stated in the literature review, often a subcontractor is involved in the project because they possess certain knowledge (Shafaat et al., 2014). However, when the scope change occurred, it appears the project team failed to make sure the verification knowledge was still present.

Possible solutions

The contractor should consider the combination of the contract level of detail and the selected subcontractor, also noted by Makkinga et al. (2018). If the subcontractor does not have the knowledge to design and perform the verifications, problems are likely to occur. This became apparent for subcontractor D, who did not have the knowledge to perform the verifications. Furthermore, this was not checked when the scope demarcation of subcontractors A and E changed.

Many problems were experienced regarding no clear responsibilities. Makkinga et al. (2018) note contractors should explicitly describe the scope and expectations of each subcontractor involved, including the verification process. A first step to solve this problem is related to the first activity of the framework, which is to develop a verification management plan. The verification management plan is where the strategy for the entire verification process is described. In the project, the verification management plan was written by the main contractors. The other disciplines did not see this plan and therefore had not been able to have their say in the drawing up of the plan. Although the verification management plan was performed according to theory, it could also include a detailed description of how the project team deal with the interfaces. By doing so, clear agreements can be made with the parties involved. This could have prevented multiple problems for subcontractor A, as integrating this activity would be the first step to coordinate the verification activities and to appoint someone to take the lead and take the accountability and responsibility of the verification process of the entire system.

The lack of initiative to plan the verifications delayed the entire process. With hindsight, it was seen that there were many requirements, which were not linked to a person responsible for verification. When drawing up a verification plan, it must be coordinated with the person who performs the verification. If the expertise lies with a subcontractor, you can let them determine how they plan the verification. However, care must be taken that the requirements are discussed on an integral level. In the case study, this was only done at the end of the final design phase. It is not uncommon to cajole individuals into executing the verification process of a project. It is not that they don't want to, but the primary focus is on the technical element. A lot of these problems could have been prevented by simply communicating with each other.

Lastly, the IMS should be the tool to support the verification process. The project team must make sure all employees have the knowledge to work with the tool and offer support if needed. There has to be a clear view of who is responsible for entering data in the IMS, and who is responsible for managing the data, including the traceability of the verified elements. This also includes the deviations, which were created in the IMS. In the case study, there was nobody appointed to supervise all deviations. The activity stopped right after the deviations were created, resulting in a big pile of deviations no one was working on. Instead, someone must be responsible to make sure the deviations are finished and if needed, communicated with other parties. At all stages of the process accountability needs to be clearly assigned.

Integrating the verification process

Integration and communication seem to become more important for subcontractors that have a large impact on the project. The findings of this case study showed the verification process of subcontracts having few interfaces did not trigger big problems. However, the verification process of the subcontract that had a large impact on the outcome of the project showed multiple problems. Preventing all problems is difficult, especially when design decisions are made which impacts other parties. The way you deal with these design decisions integrally determines whether the verification process goes smoothly or not. Therefore, it seems that integration directly affects the verification process. With the expertise of the people interviewed, two main solutions are proposed to support the integration of the verification process. However, like the verification process, the integration process is complex and consists of multiple activities. A similar study which includes the integration process could verify the proposed solutions.

The first solution is that all disciplines work together to integrally perform all verification activities. Therefore, all disciplines must agree on the approach of the verification process. The verification management plan is compiled together and only one IMS will be used. Care must be taken that the information management system has all the functionalities that the process needs. For example, it must be possible to allocate multiple people responsible for verification and multiple verification methods or phases. Every few weeks, depending on the stage of the project, all disciplines should come together to discuss the progress. The downside of this method is that every discipline needs the expertise and dedication to perform the verifications.

The second solution involves appointing a verification manager. This person manages the IMS and makes sure that all disciplines perform their verification activities. The verification approach of the subcontractors is agreed with this verification manager. Once a party wants to perform verification actions, the verification manager must be contacted. This person is then able to review these actions on an integral level. The downside of this method is that the responsibility of having an integrated system is completely shifted to one person. Therefore, this person must have basic knowledge of all aspects of the system to understand the consequences of all separate verification actions.

7 DISCUSSION

In this section, the findings will be considered with the existing knowledge. The research showed that the verification process consists of multiple activities, which have been tailored to civil engineering. Problems were indeed experienced for verification activities that were not matching theory. Therefore, the framework seems to be useful as a first guide to make sure the verification process is performed successfully. However, a precondition is found that the competences of the selected subcontractor must match the contract level of detail, as also noted by Makkinga et al. (2018). The case study showed that a mismatch result in verification problems not directly related to activities in the framework. Another precondition seems to be that the party who is responsible for the design of a (sub)system, should also be responsible for the verification of that (sub)system. Therefore, as acknowledged by Makkinga et al. (2018) and Shafaat et al. (2014), the subcontractor must have the necessary design and verification knowledge.

Furthermore, many of the findings are related to the integration process. Problems were often experienced where requirements have interfaces with other disciplines. However, subcontractors were hesitant to take more initiative as they did not want to have the full responsibility of the verification process. Makkinga et al. (2018) note that contractors should explicitly describe the scope and expectations of each supplier involved. In addition to that finding, this study shows the main contractor should appoint someone to take responsibility for the entire verification process. From there, the activities can be coordinated. Care must be taken that physical divisions of the project do not affect the process. This research found solutions to coordinate the process. However, the solutions seem to depend on the impact of the subcontractor, relating to the factors found in literature indicating to what extent subcontractors should be involved. Coordinating the verification activities for less complex subsystems seems sufficient for a successful verification process, whereas the verification process must be fully integrated for subsystems that are complex and have many interfaces. The contractor should consider the desired degree of responsibility held by the subcontractor, also noted by Wynstra and Pierick (2000).

8 LIMITATIONS

This research does have some limitations that must be addressed. Firstly, the research was carried out in the civil engineering industry in the Netherlands and may not be directly applicable in other industries or countries. This is enhanced by the theoretical framework, which is specifically tailored to this industry.

Secondly, the research was limited to only one civil engineering project. More projects at different main contractors should be studied to improve the generalizability of the research.

Thirdly, the pattern match was performed with the intention to only find problems which can be related to activities of the framework, but this was not the case. Additional problems were found. Therefore, a successful verification process might not be guaranteed when all activities are performed according to the framework. More case studies should be performed to determine the completeness of the framework and to potentially find more problems or solutions.

9 CONCLUSION

This research aimed to identify the verification problems experienced by contractors when subsystems are outsourced to subcontractors and to propose solutions for these problems. A framework has been developed which includes a list of activities to perform as part of the verification process. The case study showed problems were experienced for activities not matching theory. Coordinating verification activities is an essential part of the verification process. Furthermore, the case study suggests that if a main contractor does not perform the verification activities according to theory, this will directly impact the verification activities performed by the subcontractors. The subcontractors expect the higher-level organisation to take the lead in the verification process. A subcontractor may agree to perform the verification actions and deliver documentation, but the main contractor must make sure they have the necessary verification knowledge. Without a person to take both responsibility and accountability for the verification of the entire system, the progress of the verification process will stagnate. It is the responsibility of the main contractor to appoint a person to oversee and complete this verification process ensuring all parties complete their verification activities. The main contractor is ultimately responsible to deliver a system that meets all requirements. In addition, the main contractor must ensure the level of detail in the contract aligns with the capabilities of the selected subcontractor. At all stages of the project accountability must be clearly assigned. This includes the use of an IMS, where clear communication throughout the process is essential between the main contractor and subcontractors. There are no official guidelines for the verification process within civil engineering projects however this case study demonstrates the need for such structure and processes as utilised in other industries including clearly defined responsibilities and accountabilities between contractors and subcontractors.

10 REFERENCES

Bemelmans, J., Voordijk, H., & Vos, B. (2012). Supplier-contractor collaboration in the construction industry: A taxonomic approach to the literature of the 2000-2009 decade. *Engineering, Construction and Architectural Management*, *19*(4), 342–368.

Dainty, A. R. J., Briscoe, G. H., & Millett, S. J. (2001). Subcontractor perspectives on supply chain alliances. *Construction Management and Economics*, *19*(8), 841–848.

de Graaf, R. S. (2014). *Basisboek Systems Engineering in de bouw*. Brave New Books.

de Graaf, R. S., Voordijk, H., & van den Heuvel, L. (2016). Implementing Systems Engineering in Civil Engineering Consulting Firm: An Evaluation. *Systems Engineering*, *19*(1), 44–58.

Department of Transportation. (2009). *Systems Engineering Guidebook for Intelligent Transportation Systems Version 3.0*.

Gil, N., Tommelein, I. D., Kirkendall, R. L., & Ballard, G. (2001). Leveraging specialty-contractor knowledge in design-build organizations. *Engineering, Construction and Architectural Management*, *8*(5/6), 355–367.

Hätönen, J., & Eriksson, T. (2009). *30+ years of research and practice of outsourcing – Exploring the past and anticipating the future*. *15*, 142–155.

Hirshorn, S. R. (2016). *NASA System Engineering Handbook Revision 2*. 297.

Hofman, E., Voordijk, H., & Halman, J. (2009). Matching supply networks to a modular product architecture in the house-building industry. *Building Research and Information*, *37*(1), 31–42.

INCOSE, Walden, D. D., Roedler, G. J., Forsberg, K., Hamelin, R. D., & Shortell, T. M. (2015).

Systems engineering handbook: A guide for system life cycle processes and activities.

Insinga, R. C., & Weije, M. (2000). Linking outsourcing to business strategy. *The Academy of Management Executive*, *14*(4), 58–77.

ISO/IEC 15288: Systems Engineering—System Life Cycle Processes. (2015). *International Organization for Standardization, Geneva, Switzerland*.

Liker, J. K., Kamath, R. R., & Nazli Wasti, S. (1998). Supplier involvement in design: A comparative survey of automotive suppliers in the USA, UK and Japan. *International Journal of Quality Science*, *3*(3), 214–238.

Makkinga, R., de Graaf, R., & Voordijk, H. (2018). Successful verification of subcontracted work in the construction industry. *Systems Engineering*, *21*(2), 131–140. https://doi.org/10.1002/sys.21425

ProRail. (2015). *Handboek Systems Engineering (SE)* (Nummer April).

ProRail, Rijkswaterstaat, Vereniging van Waterbouwers, NLingenieurs, Uneta VNI, & Bouwend Nederland. (2013). *Leidraad voor Systems Engineering binnen de GWW-sector versie 3*.

Rijkswaterstaat, & Bouwend Nederland. (2015). *Verificatie & Validatie Management Plan—Template* (1.0). https://www.leidraadse.nl/assets/files/downloads/Publicaties/Verificatie_en_Validatie_Mngt_Plan_v_1.0.pdf

Shafaat, A., Mahfouz, T., Jackson, C., & Kandil, A. (2014). Decision Making Model by Specialty Subcontractors in Construction Project. *Construction Research Congress 2014*, 867–876.

Voordijk, H., & Vossebeld, N. (2013). Samenwerking tussen bouwbedrijf en toeleverancier: Gepland knuffelen als kritische succesfactor. In R. Kok, H. Lekkerkerk, & P. Vermeulen (Red.), *Versterking van innovatie: Liber Amicorum voor Ben Dankbaar* (pp. 189–200). Boom Lemma.

Wynstra, F., & Pierick, E. T. (2000). Managing supplier involvement in new product development: A portfolio approach. *European Journal of Purchasing and Supply Management*, *6*(1), 49–57.

Yin, R. K. (2003). *Case Study Research: Design and Methods* (Vol. 5). SAGE Publications.

APPENDIX I

Activity	Operationalisation	Theoretical pattern	Sources
Prepare for verification	Develop a verification strategy	The verification strategy includes a list of the items for verification and the corresponding actions, verification constraints that could impact the implementation of the verification actions, and verification scope.	Establish a list of items for verification, including requirements, architectural characteristics, or design properties, and define corresponding verification actions. (INCOSE et al., 2015)
			Establish a list of verification constraints that need to be considered and could impact the implementation of the verification actions. (INCOSE et al., 2015)
			Establish the scope of the verification. (INCOSE et al., 2015)
			A verification master plan is included in the Project Plan to establish general guidelines for the verification process. A strategy is developed which is compatible with the system concept and the deployment objectives (Department of Transportation, 2009)
			The verification strategy includes trading off what will be verified (scope) against the constraints or limits, and deduces what verification actions to use. ('ISO/IEC 15288', 2015)
			The contractor lays down the strategy for verification and validation in a verification and validation management plan. In doing so, the contractor continues the specification process that has been performed by the client. (ProRail et al., 2013)
	Develop verification procedures	The verification procedure identifies the purpose of the verification, the verification technique to be applied, the environmental conditions and the verification schedule.	Develop the verification procedures that support the verification actions. Schedule the execution of the verification actions in the project steps and define the configuration of submitted items to verification actions. (INCOSE et al., 2015)
			The verification procedure identifies the purpose of the verification with success criteria (expected results), the verification technique to be applied, the necessary enabling systems, and the environmental conditions to perform the verification procedures. ('ISO/IEC 15288', 2015)
			The verification plan will give guidance for all verification activities, including the identification of all verification participants, descriptions of their roles and responsibilities, and a schedule for verification activities. (Department of Transportation, 2009)
			The second activity is to determine the verification moments. Thereafter, the verification matrix should indicate who is responsible for the verification. (de Graaf, 2014)
	Identify verification constraints	Verification constraints are identified that arise from the verification strategy, that relate to system requirements, architecture or design elements.	Identify verification constraints on the system or system elements, arising from the verification strategy, that relate to specific system requirements, architecture elements, or design elements. Typical constraints include performance characteristics, accessibility, and interface characteristics. (INCOSE et al., 2015)
			Identify system constraints from the verification strategy to be incorporated in the system requirements, architecture, or design. This includes practical limitations of accuracy, uncertainty, repeatability that are imposed by the verification enablers, the associated measurement methods, the need for system integration, and the availability, accessibility and interconnection with enablers. ('ISO/IEC 15288', 2015)
	Identify necessary enabling systems	The necessary enabling systems, product, or services are available for the verification actions.	Ensure that the necessary enabling systems, products, or services required for the verification actions are available, when needed. The planning includes the identification of requirements and interfaces for the enablers. (INCOSE et al., 2015)
			Identify and plan for the necessary enabling systems or services needed to support verification. Verification enabling systems include verification equipment, simulators, test automation tools facilities, etc. ('ISO/IEC 15288', 2015)
			Obtain or acquire access to the enabling systems or services to be used to support verification. The acquisition of the enabling systems can be done through various ways, such as rental, procurement, development, reuse, subcontracting; usually it is a mix of these ways. ('ISO/IEC 15288', 2015)
			In order to verify in a structured way, the first activity is to create a verification matrix. (de Graaf, 2014)

Perform verification	Perform verification actions	The verification actions are executed according to the verification procedures.	Using the verification procedures, execute the verification actions and record the results. A verification action describes what must be verified, on which item, the expected result, the verification technique to apply, and on which level of decomposition of the system. (INCOSE et al., 2015)
			Perform the verification procedures. The verification, in accordance with the verification strategy, occurs at the appropriate time in the schedule. ('ISO/IEC 15288', 2015)
			If verification is performed as described in the verification matrix, the results of the verification will follow. (de Graaf, 2014)
			When all resources are ready, verification is performed according to the approved procedures. (Department of Transportation, 2009)
	Analyse verification results	The verification results are analysed to determine conformance to the requirement.	Analyse the verification results against established expectation and success criteria to determine whether the element being verified indicates conformance. (INCOSE et al., 2015)
			The performance of a verification action consists of capturing a result from the execution of the verification procedure; comparing the obtained result with the expected result; and deducing a degree of correctness of the submitted element. ('ISO/IEC 15288', 2015)
Manage results for verification	Identify and record verification results	The verification results are recorded in the Requirement Verification and Traceability Matrix.	Identify and record verification results and enter data in the Requirement Verification and Traceability Matrix. Maintain the records per organizational policy. (INCOSE et al., 2015)
			Record verification results. ('ISO/IEC 15288', 2015)
			The verification results should be included in the verification matrix. (de Graaf, 2014)
			Document verification results; prepare a verification report for each verification step. (Department of Transportation, 2009)
			The results of the verifications and validations are recorded in verification and validation reports. (ProRail et al., 2013)
	Record anomalies observed	Anomalies encountered during the verification process are recorded. These include anomalies due to the verification strategy, enabling systems, verification execution or system definition.	Record anomalies observed during the verification process, and analyse and resolve the anomalies. (INCOSE et al., 2015)
			Record any anomalies encountered. This includes anomalies due to the verification strategy, enabling systems, execution of verification, or incorrect system definition. ('ISO/IEC 15288', 2015)
	Maintain traceability of verified system elements	Traceability is established and maintained of the verified system elements with the verification strategy, system architecture, design and system requirements.	Establish and maintain bidirectional traceability of the verified system elements with the system architecture, design, and system and interface requirements that are needed for verification. (INCOSE et al., 2015)
			Maintain traceability of the verified system elements. Bi-directional traceability is maintained between the verified system elements and the verification strategy, system architecture, design, and system requirements. ('ISO/IEC 15288', 2015)
	Provide baseline information	Key information items are provided that have been selected for baselines.	Provide baseline information for configuration management (INCOSE et al., 2015)
			Provide key information items that have been selected for baselines. The configuration management process is used to establish and maintain configuration items and baselines. This process (verification) identifies candidates for the baseline, and then provides the information items to configuration manager. For this process, the verification strategy is a typical information item that is baselined. ('ISO/IEC 15288', 2015)
	Update verification strategy and schedule	The verification strategy and schedule are updated according to the progress of the project, including redefining or rescheduling planned verification actions.	Update the verification strategy and schedule according to the progress of the project; in particular, planned verification actions can be redefined or rescheduled as necessary. (INCOSE et al., 2015)
			The verification strategy and schedule are updated according to the progress of the project in particular planned verification actions are redefined or rescheduled when unexpected events or system evolutions occur. ('ISO/IEC 15288', 2015)
			It is quite possible that a change in requirements, the design or the realized product leads to (re)performing verification and/or validation activities. (ProRail et al., 2013)
	Coordinate verification activities	The verification activities are coordinated with the project manager, designers and the configuration manager.	Coordinate verification activities with the project manager, the architect or designers, and the configuration manager. (INCOSE et al., 2015)

APPENDIX II

Activity	Theoretical pattern	Empirical pattern	Match	Evidence	Explanation
Develop verification management plan	The verification management plan is developed, which defines the strategy of the verification process, the organisation of the verification activities, agreements on starting principles, the verification methods to be used (per project phase), phasing and agreements on the verification status and verification reporting.	The verification management plan is developed, which defines the strategy of the verification process of both system and management requirements, the organisation of the verification activities, starting principles, verification methods to be applied and verification reporting.	+	The verification strategy has been described in chapter 2.1 and 3.1 of the verification management plan. [IMS; Project management plan; Verification management plan] The strategy for verifying the system entities has been defined in the verification management plan [IMS] The verification management plan should include an integrated verification strategy including the verification methods to be applied in design, construction and maintenance. This is included in the verification management plan. [IMS] The verification management plan includes the verification strategy of both system and management requirements. For both requirement types, the verification methods to be used are defined. Furthermore, the verification matrix is introduced, which includes drafting the verification plan and verification report. [Verification management plan] The verification strategy determines how you deal with the verification process and in what phases you perform those activities [Quote] The verification strategy is described in the verification and validation management plan. [Quote] The Project Management Plan refers to the verification and validation management plan. This document defines the approach for the verification process. [Quote]	The verification and validation management plan has been developed as part of the Project Management Plan. Strategies are developed for the verification of system requirements, and for the verification of management requirements. The verification management plan has been approved by the client. While theory suggest to state verification methods per project phase, this strategy describes separate methods for different types of requirements. Furthermore, the theory suggests to state agreements on the status of the verification. This is not stated in the management plan. Concluding, the empirical study shows the management plan has indeed been developed, sharing most sections suggested by theory. Match: +
Develop verification plan	The verification plan is developed, which identifies for each requirement the verification technique to be applied, the verification schedule, criteria and the responsible party or person for verification.	The verification plan is developed, which identifies for each requirement the technique to be applied, the verification schedule, criteria and the responsible party or person for verification.	+	A verification plan is defined in the verification process "plan verifications". [IMS] The requirements will be linked to a phase in which the verification should take place. The applicable phases are defined in the Project Management Plan. System requirements are linked to a technical phase, management requirements are linked to a project phase. [IMS, process plan verification]	Similar to what theory suggests, verification plans are developed to determine the person responsible for verification, followed by the phase the verification should be conducted, what method is used and verification criteria. This process is primarily conducted with the help of IMS, asking four questions for each requirement: verification phase; verification technique (with an optional comment

				The planned verifications are laid down in the verification plan in IMS. By linking the requirements to objects or processes, it is clear within which Work Package the verification must take place. At the latest at the start of a Work Package/process, the requirements are provided with a verification method and the person responsible for the verification. [IMS process plan verification] At the start of a design phase, the verification plan will define the requirements to be verified in this phase and by which verification method. [Verification management plan; IMS] The verification plan defines which requirements should be verified in that phase. [Quote] For each requirement, you can add data to create a verification plan, which is then linked to a person responsible for verification, who will see in which phase he has to conduct the verification. [Quote]	section), criteria, and the responsible person for verification. Match: +
Identify verification constraints	Verification constraints are identified that arise from the verification strategy, that relate to system requirements, architecture or design elements.	Verification constraints are identified by identifying risks arising from other process.	o	The verification constraints are identified by identifying risks arising from other processes. Risks that are a constraint to design decisions are assigned to the work package owner of the design in question and are linked to the work package in IMS. [IMS] What you essentially need is that the management system meets all requirements, regardless of the type of contract. In this project, it was evident that the intended processes did not match the tooling. [Quote]	Verification constraints were identified, but not specifically arising from the verification strategy, as suggested by theory. Furthermore, the tooling had several constraints, which should have been resolved (earlier). Concluding, the empirical pattern partly matches theory: o
Identify necessary enabling systems	The necessary enabling systems, product, or services are identified and available for the verification actions.	The necessary enabling systems, product, or services are identified and available, but not fully utilized to support verification actions.	o	To ensure that the enabling system for verification is available for verification, a Test Readiness Review in conducted according to the Test Management Plan. [IMS] The Test Readiness Review includes a determination that all test facilities and tools are ready and functioning properly (verification environment, simulators, test automation tools, measuring equipment, etc.) [Test Management plan; IMS]	In order to make sure the necessary facilities and tools are ready, a Test Readiness Review is conducted. Furthermore, an information management system is used to support several processes, including the verification process. However, multiple problems were experienced with this management system, reducing the benefits of the tools. For example, the personnel did not know how to work with the tool. Concluding, the empirical pattern does not completely match theory due to the lack of expertise with the supporting systems: o.

				The corporation chooses to use IMS as the information management system, but the problem was that the employees did not know how to use the tool. The design of the system was not sufficiently thought through and no work instructions were given. [Quote] The systems provided for verification must be consistent with what is described in the processes. This was not the case for this project. [Quote]	
Perform verification actions	The verification actions are executed according to the verification plan.	The verification actions are executed according to the verification plan, but only after repeatably reminding the responsible person for verification.	o	Verification actions of a Work Package or process are performed in accordance with the verification plan. For the system requirements, this is done in connection with the technical processes, for the management requirements this is linked to the configuration of the management system. Verification can only take place once the requirements analysis has been completed. [IMS; IMS process perform verification] People had to be continuously directed to complete the verification tasks. [Quote] The person responsible for verification often makes little or minimal use of the information management system. Many people don't like to perform the verifications, so you must chase them every time to make sure they do. I am willing to take over some of the work, but the responsibility remains with them. [Quote] People weren't really engaged in the verification process. They rather wanted to continue with the project itself. So there was a need for someone to chase them. [Quote]	The verification actions were performed according to the verification plan. However, people had to be pushed to actually perform these verifications. Once people were chased and offered help to complete them, the verification actions were performed according to the verification plans (except for the schedule). Concluding, the fact that people had to be chased to actually perform the verifications, this empirical pattern partly matches theory: o.
Develop verification reports	Verification reports are developed to provide evidence of the conformance to the requirements.	Verification reports are developed to provide evidence of the conformance to the requirements.	+	The verification report is the output of the processes 'verify requirement' and 'verify design'. The verification report provides objective evidence that the realized product satisfies the system requirements. [IMS] The verification reports ensure the verification data is available on the system [IMS] Verification results are recorded in a verification report [IMS process perform verification] It was hard work to ensure that the verification reports were made. There was a lot of work to be	The empirical study shows verification reports were used to provide evidence of the requirements. Similar to the empirical pattern above (perform verification actions…), in order to collect sufficient evidence, people had to be chased. Although it took hard work to eventually complete the reports, it was rather due to delay in performing the verification actions. Concluding, the empirical pattern matches theory: +.

				done before all those reports were finally completed. [Quote]	
Record verification results in the verification matrix	The verification results are recorded in the Requirement Verification and Traceability Matrix.	The verification results are recorded in the verification matrix.	+	The verification actions are registered in a verification register. The verification plans and verification reports are recorded in IMS. [IMS; IMS process design verification approach] The current verification status of the verification is recorded in IMS. [IMS] The verification matrix is organised in IMS for the verification of the requirements. [Verification management plan] The information management system IMS is used to manage and verify the requirements. [Quote] The verifications are recorded in the verification matrix or in IMS. [Quote]	The verification results were recorded in the information management system used. The system, based on Relatics, has the possibility to create links between requirements and add information to requirements for the verification process, resulting in a verification matrix. Concluding, the empirical pattern matches theory: +.
Record anomalies observed	Anomalies encountered during the verification process are recorded. These include anomalies due to the verification strategy, enabling systems, verification execution or system definition.	Anomalies encountered during the verification processes are recorded as deviation.	+	If it is expected that a requirement cannot be met and the issue cannot be resolved within the relevant work package, this will be reported as deviation. [IMS process follow up on verification results] Interfaces, changes, deviations, risks, opportunities and design decisions are created, linked, controlled and handled within IMS. [Configuration management plan] In practice, once you encounter a requirement that you cannot verify or that you would like to have it changed, you quickly enter the deviation process. [Quote]	Anomalies encountered were recorded and reported as deviation in IMS. Any person responsible for the verification was able to create these deviations, which the client was able to view. Concluding, the empirical findings match theory: +.
Maintain traceability of verified system elements	Traceability is established and maintained of the verified system elements with the verification strategy, system architecture, design and system requirements.	Traceability is established and maintain of the verified system elements with the design and system requirements.	o	The planned verifications are laid down in the verification plan for the system and management requirements in the information management system. [IMS process plan verification] Mutual traceability is maintained between specified design and system requirements by combining the design process and verification process, resulting in the output verification report. [IMS]	Traceability of the system elements are established in IMS, by combining the design and verification processes. This outputs in the verification reports, linking the requirements with system elements and the design. Theory suggests to establish traceability with the verification strategy as well, but this was not the case. Concluding, this empirical pattern partly matches theory: o.
Provide baseline information	Key information items are provided that have been selected for baselines.	Baselines are created, but the project team did not act upon them.	-	Baselines are created and exported from IMS, which will be used in the gate-reviews [Configuration management plan] Baselines were created in the form of a management report. However, people didn't feel	Baselines were created but appeared to be little to no use. Therefore, the pattern is considered to not match theory: -.

				accountable for these results. The reports had little added value because no future actions were established. [Quote] The reports were discussed with the management team. These reports showed many verifications had to be planned, but then the communication stopped. No one will feel accountable if the person is not directly addressed. [Quote]	
Update verification strategy and schedule	The verification strategy and schedule are updated according to the progress of the project, including redefining or rescheduling planned verification actions.	The verification management plan is updated according to the progress of the project.	+	The plan no longer fitted in with what happened in practice. [Quote] A total of four revisions of the verification management plan were created. One of the changes includes the addition of appointing three roles for every system requirement: person responsible for the requirement, person responsible for performing the verification actions, person authorized to disclose the verification. [Revisions verification management plan]	Theory suggests the verification strategy should be updated according to the progress of the project. In this project, the strategy has been defined in the verification management plan. This document has been updated three times, mainly because the plan no longer fitted with what happened in practice. Apparently, the plan was not sufficient at first, but got updated. Concluding, the empirical pattern matches theory: +.
Coordinate verification activities	The verification activities are coordinated with the project manager, designers and the configuration manager.	The verification activities are not coordinated with the project manager, designers and configuration manager, except for subcontract B.	-	There is an extreme gain to be made in coordinating the verification process [Quote]. The role of verification and validation manager was merged with the integral design manager and that didn't work. At the same time, the integral design manager was the project manager of a discipline, which caused the other disciplines to work on their own. [Quote] It was difficult to manage and to have an overview of all the requirements. There should have been more steering and control using the verification matrix. [Quote] It was evident that the verification process went well where somebody felt responsible and accountable for the verification process. [Quote]	In general, the verification activities were not coordinated. There was no person who took the responsibility for the entire verification process. Consequently, people didn't feel the need to perform the verifications. Except for subcontractor B, where somebody did feel responsible, the verification activities were coordinated. Concluding, the lack of coordination of the verification activities resulted in a lot of problems. As the verification process was only coordinated at one subcontractor, the empirical pattern mismatches: -.

NEDERLANDSE SAMENVATTING

In de civiele techniek zijn in de laatste jaren verantwoordelijkheden verschoven van de opdrachtgever naar de aannemer. In deze integrale projecten kunnen aannemers niet meer uitsluitend richten op de bouwwerkzaamheden, omdat zij ook verantwoordelijk zijn voor het ontwerp. Met deze verschuiving is de aannemer ook verantwoordelijk voor het verificatieproces. Echter worden verificatieproblemen vaak ervaren wanneer delen van het project door onderaannemers worden uitgevoerd. Het doel van dit onderzoek is om deze problemen te identificeren en om mogelijke oplossingen te vinden voor aannemers.

Om dit doel te bereiken is allereest een literatuurstudie uitgevoerd, waarna een theoretisch framework is opgesteld. In dit framework worden de activiteiten weergegeven die in het kader van het verificatieproces moeten worden uitgevoerd, bestaande uit drie hoofdactiviteiten: voorbereiding op de verificatie, uitvoering van de verificatie en het beheren van de verificatieresultaten. Vervolgens is een case study uitgevoerd, waarin het verificatieproces is onderzocht van een civieltechnisch project. De uitkomsten van de case study en het literatuuronderzoek zijn vergeleken en geanalyseerd met behulp van de onderzoeksmethode *pattern matching*. Hieruit is gebleken dat er problemen verwacht kunnen worden als verificatieactiviteiten niet volgens de theorie worden uitgevoerd. Een voorbeeld hiervan uit de case study is dat meerdere problemen werden veroorzaakt door een gebrek aan coördinatie van de verificatieactiviteiten, wat een essentieel onderdeel is van het verificatieproces.

Echter toonde de case study ook aan dat er problemen werden ervaren die niet direct verband hadden met het theoretische framework, maar voortkwamen uit de samenwerking met de onderaannemer. De case study suggereert dat de wijze waarop het verificatieproces wordt uitgevoerd door de hoofdaannemer, dit rechtstreeks invloed heeft op de verificatieactiviteiten van de onderaannemer. Zij verwachten namelijk dat de hogere organisatie in de keten het voortouw neemt in het verificatieproces. Alhoewel een onderaannemer ermee in kan stemmen om verificatieactiviteiten uit te voeren en documentatie te leveren, moet de hoofdaannemer ervoor zorgen dat zij ook over de benodigde verificatiekennis beschikken. Als er niet een persoon is die actief de verantwoordelijkheid op zich neemt van de verificatie van het gehele systeem, zal de voortgang van het verificatieproces stagneren. Het is de taak van de hoofdaannemer om die persoon aan te wijzen die toezicht houdt op het proces en ervoor zorgt dat alle partijen zijn verificatieactiviteiten voltooien. De hoofdaannemer is uiteindelijk verantwoordelijk voor het leveren van een systeem dat voldoet aan alle gestelde eisen. Daarnaast moet de hoofdaannemer ervoor zorgen dat het detailniveau in het contract in overeenstemming is met de capaciteiten van de onderaannemer. In alle fases van het project moeten de verantwoordelijkheden duidelijk worden toegewezen. Hieronder valt ook het gebruik van een informatie managementsysteem, wat vaak gebruik wordt als hulpmiddel om het proces overzichtelijk uit te voeren. Hierbij is het essentieel dat er gedurende het gehele project duidelijke communicatie is tussen de hoofdaannemer en de onderaannemers.

Er zijn geen officiële richtlijnen voor het verificatieproces binnen civieltechnische projecten, maar dit onderzoek toont de noodzaak aan van een dergelijke structuur. Het uitvoeren van de verificatieactiviteiten volgens het framework is een eerste richting in het succesvol uitvoeren van het verificatieproces. Daarnaast moet gezorgd worden voor een duidelijke afbakening van de verantwoordelijkheden tussen de hoofdaannemers en onderaannemers. Dit onderzoek stelt voornamelijk twee mogelijke oplossingen voor. De eerste is dat de onderaannemer volledig meegenomen wordt in het verificatieproces en samen ervoor zorgt dat de activiteiten uitgevoerd worden. De tweede optie is dat de hoofdaannemer een verificatiemanager aanwijst die verantwoordelijk is voor het gehele verificatieproces en ervoor zorgt dat alle partijen zijn verificatietaken uitvoeren. Per project en per onderaannemer moet onderzocht worden welke optie mogelijk is en het meest bruikbaar is.