August 2019

Compliance of Designs with Requirements in Road Infrastructure Projects

Road infrastructure projects within the context of Systems Engineering

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MSc Thesis Research

Master thesis research to acquire the degree of Master of Science in the program of Civil Engineering and Management, Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands

Document:	Paper
Version:	Final
Date:	02 August 2019
Place:	Enschede, The Netherlands

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Preface

This paper is the outcome of a master thesis research conducted within the Civil Engineering and Management master's program at the University of Twente, Enschede, The Netherlands. The research was commissioned by Witteveen+Bos; a leading Dutch engineering consultancy firm. It addresses the topic of compliance of designs with requirements in road infrastructure projects, within the context of the Systems Engineering methodology.

This research represents the last step of my two-year master study journey in the Netherlands. It is with great enthusiasm that I finalize this master's program and look forward to starting the next chapter of my life. A number of years ago, enrolling in this master's program was only a dream of mine but today I look back to remember that nothing in life is impossible and that hard work always pays off. However, my dream would not be fulfilled without the help of many good-hearted people who believe in my abilities giving me a chance to prove myself.

Thanks be to God for enlightening my mind, strengthening my heart and smoothening my path.

I would like to thank the people closest to my heart, my parents and siblings, for the unlimited support and unconditional love. I would never be who I am today, and I would not be able to reach this stage if it was not for you and your encouragement. "The sky is your limit Maria" are words that are always with me. I promise to keep moving forward and never let any challenge stand in my way.

I would like to voice my appreciation for the faculty of Engineering Technology at the University of Twente for trusting in my qualifications and granting me the University of Twente Scholarship. Nothing would have been possible without this support. Additionally, I would like to thank my supervisors at the university; Robin and Mohammad, for putting in the time, effort, and consideration that tremendously helped me improve my work.

Moreover, I want to give a huge acknowledgment to Witteveen+Bos for valuing this research and for providing all the needed resources. In particular, Tim and Maarten, thank you for everything you have done to guarantee my success and that I reach what I aim for. I highly appreciate your guidance, support, and care. I also would like to thank all the interviewees who participated in this study for giving their time and effort to provide the required information.

I could never forget my loyal friends, near or far, for always being there for me whether in moments of great success or those of doubt. You never failed to be right next to my side and I can never express how much I value you. Thank you for all the pep talks, celebrating times, and all the cheerful nights. You are proof that no geographical borders can separate our hearts. I will never forget that "everything will be fine in the end. If it is not fine, it is not the end."

To the place where my dreams started, to "the land of the sun"; my home country Syria, thank you for teaching me the meaning of true strength. You taught me that giving up is never an option and that trying harder is the only solution. I cannot wait for the day that I see you more beautiful than ever. May your sun shines amazingly again.

In the end, to all those who have given me their support, sentimental has it been or tangible, I express my absolute gratitude.

Compliance of Designs with Requirements in Road Infrastructure Projects

Road infrastructure projects within the context of Systems Engineering

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Abstract:
Developing products in compliance with specifications should be realized throughout a system lifecycle to support the delivery of quality assured products. The quality of large infrastructure projects can be determined by many aspects including the extent to which the system is delivered in compliance with defined specifications. The purpose of this research has been to assess the performance of two road infrastructure projects in developing requirements and designs to be in compliance with each other so to make recommendations to improve current practices. A literature review has been conducted to develop a framework of best practices, for ensuring that designs are developed in compliance with the defined requirements throughout a design level of detail, specifically the concept design level. The framework has been applied to current practices in two case studies, which have been implementing Systems Engineering (SE) processes in the concept design phase of the project lifecycle. Pattern matching analysis, which is about testing whether theory and practice match in real life by comparing their patterns and characteristics, has been used for analyzing current practices. Pattern matching results indicate that one project has been performing better than the other project. This is in terms of matching the expected patterns for developing requirements and designs to be in compliance with each other, throughout a design level of detail. However, the findings of this research could not demonstrate if indeed one of the projects is a success project with regard to developing designs in compliance with the defined requirements throughout the concept design phase, while the other project is not. This is primarily due to the lack of evidence in one of the projects, which has been perceived in itself as an indicator of insufficient performance of that project. Certain practices are seen as reasons for the pattern matching results and are thus further discussed. On the basis of the analysis and discussions, recommendations for improving current practices are developed. Involve SE expertise, enhance required SE knowledge and skills, and ensure strict SE planning and commitment from the beginning of the projects are the recommendations suggested and supported by existing literature.

Keywords:
compliance; requirements development; designs development; systems engineering; road infrastructure projects; pattern matching

1. Introduction

Developing products in compliance[1] with specifications should be realized throughout a system lifecycle [1]. This is to support delivering quality assured products satisfying customers' wishes and needs. The quality of large infrastructure projects can be determined by how well the developed system is verified, validated, documented, and to which extent it is delivered in compliance with defined specifications, including regulations, design codes and standards [2]. Achieving efficient deliveries of projects where designs are developed in compliance with the different requirements is an important and challenging task. The recent years have witnessed many changes in the civil engineering industry supporting the implementation of new innovative methodologies to achieve such deliveries. One approach is the application of Systems Engineering (SE) methodology to design projects. The SE methodology is mostly widely spread in the defense and aerospace industries while it is relatively new to the civil engineering industry. However, it is expected to be able to receive and deliver similar benefits as in other industries [3].

[1] In keeping with the Systems Engineering handbook [1], the term compliance can be used to refer to satisfying legal, financial and other requirements but in this research, it is explicitly used to refer to satisfying the client's and stakeholders' requirements.

The International Council of Systems Engineering (INCOSE) offers the official definition of SE as "*An interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.*" [1].

Several studies among others; [3-13], give specific attention to the implementation of SE methodology and principles in the civil engineering industry. Additionally, a guide for specifically applying SE in large infrastructure projects; [2], is developed to reposition traditional SE practices applied in other industries into the context of the construction industry. The purpose of this guide is to provide professionals in the field with the needed guidance for the efficient implementation of this methodology. These references are considered as covering a large portion of the information related to the implementation of SE methodology in the civil engineering industry justifying their use in this research.

There exists an evident increase in the interest of applying SE in both the rail and road infrastructure domains [8; 11; 12]. The reasons behind the increased application of SE come from the fact that applying SE processes gives clients the opportunity to monitor and observe the whole life cycle of their projects [10]. This is especially relevant when integrated contracts are used. Organizations have perceived the advantages of applying SE principles and activities in terms of efficient management and adequate delivery of projects [11]. SE processes have gotten more and more preferred because they are carried out in an iterative way, ensuring that all the system specifications including the requirements, functions, and objects are linked and compliant with each other. This makes it easier to trace, control and adjust any phase of the project lifecycle. The interest in SE and its widespread reflect the realization of its positive influence on the market practices, resulting in improved deliveries of project assignments.

In civil engineering projects, organizations recognize designs at different levels of detail; starting with a concept design level followed by draft design, detailed design, and a technical design level. At any level of design, all the processes of the SE methodology should be followed, prior to proceeding to the next and more detailed level [5; 6]. Conducting an efficient implementation of SE principles requires following and executing several iterative activities that integrate the SE concepts and processes. As mentioned above in the official definition of SE, the goal of executing those iterative activities is to provide a quality product designed to meet the stakeholders' needs and requirements. However, developing designs that comply with stakeholders' requirements is not an easy-to-reach goal, but rather a challenging one. Several inevitable reasons like the nature of requirements [14] accompanied by the dynamic change of requirements [1] and problems in requirements documentation [15] lie behind this challenge. Additional to those, it is mentioned that time is often spent on developing requirements correctly, but not enough on ensuring that designers are developing the right designs [16]. In other words, too much time is often invested in developing requirements in comparison to verifying that they are actually satisfied in the developed designs.

Witteveen+Bos is a leading Dutch engineering consultancy firm that is specialized in the field of civil engineering. The firm has expressed having difficulties in delivering designs that comply with all the defined requirements during the concept design phase of its road infrastructure projects. Those road infrastructure projects have been defining their requirements and developing their designs within the context of the Systems Engineering methodology. The incompliance is usually discovered during the verification process where designs are checked to satisfy all the defined requirements. This leads to taking repair measures near the end of the design phase to make the designs comply with all the requirements, which makes the design verification process a stressful and lengthy process. The problem defined in this research is that *when the verification process is performed during the concept design phase of road infrastructure projects at Witteveen+Bos, it appears that designs sometimes do not meet the defined requirements. This leads to taking repair measures near the end of the design phase to make the designs fit the defined requirements, and results in stress among teams due to time and budget constraints before the deadlines*. Safeguarding that designs are in compliance with the defined requirements throughout the design process could avoid taking repair measures near the end of design phases. This would assumingly lead to carrying out the verification process more smoothly throughout a design phase of projects.

Therefore, this research is conducted to help tackle these challenges by searching for possible ways to develop designs satisfying all the client's and users' needs throughout the design process for a specific design level of detail. The main objectives of this research are twofold; to respectively benefit existing research and the firm. One objective is thus *to provide a framework of best practices based on the literature, for ensuring that designs are developed in compliance with the defined requirements throughout a design level of detail.* The other objective is *to make recommendations to improve current practices in the concept design phase of road infrastructure projects at Witteveen+Bos.*

A literature review has been conducted to develop a framework of best practices. This framework has been applied to current practices in two case studies to achieve the research objectives. The main research question is: *which possible approaches and tools – for ensuring that designs are developed in compliance with the defined requirements throughout the concept design phase of road infrastructure projects - exist in the literature, and to which extent should any of these be implemented at Witteveen+Bos?*

Chapter 2 presents the literature review conducted to develop a framework of best practices based on the literature, which will be presented in Chapter 3. Chapter 4 explains the method used in this research and is followed by Chapter 5, which presents the data collection and pattern matching results of the cases. Pattern matching analysis is presented in Chapter 6 afterward. Discussions and recommendations will be provided in Chapter 7. Limitations of this research will be presented in Chapter 8 followed by conclusions in Chapter 9.

2. Literature review

Taking into consideration the concepts and theories mentioned in the literature for applying the SE methodology; [1-13; 17-21] among others, an SE process model is derived and considered an appropriate starting point for this research [6]. The main reason for choosing this model is because it utilizes terminologies that suit the civil engineering industry regarding SE processes, and was used to assess their application in several projects. The SE process model [6], shown in Figure 1 below, is thus considered an adequate base model for this research. This model consists of nine processes composing, between the *Input* and *Output* components, the overall activities of SE within each possible design level of detail. The SE process model presents three core elements; *Requirements Analysis*, F*unctional Analysis & Allocation*, and *Design Synthesis*. It also presents six feedback elements including the Design Verification and Design Validation processes [6].

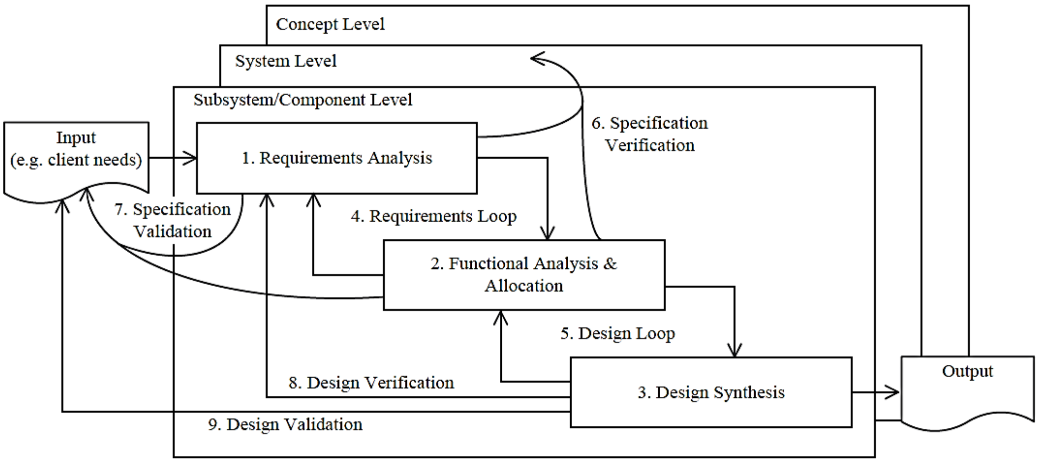

Fig. 1. SE Process Model as derived from recent literature [6] and based on, among others, a guideline used for Systems Engineering in the civil engineering sector in the Netherlands [11]

Among the objectives of the feedback processes is to ensure that the core elements are connected to each other and that every decision, improvement, change, and reason(s) behind change(s) are recognized and listed in a traceable manner (e.g. using a numbering system) and stored in a reachable place [6]. The incompliance of designs with the defined requirements is usually found when performing the Design Verification process. This feedback element is aimed at assessing whether the design meets all the defined requirements and if they are in keeping with one another [6]. The INCOSE Systems Engineering Handbook identifies the verification process as a process that "*addresses whether the system, its elements, and its interfaces satisfy their requirements. Verification ensures the conformance to those requirements.*" [1]. The purpose of the verification process is to confirm that all requirements are fulfilled by the developed designs of the system elements. Its primary function is to determine that system specifications, designs, processes, and products are compliant with requirements. In other words, the verification process answers the question "Are we building it right?" [1].

The INCOSE Systems Engineering Handbook defines the inputs needed to perform the verification activities to include baseline system requirements, verification criteria, Requirements Verification & Traceability Matrix (RVTM) and system element to be verified [1]. In other words, for fully performing the verification process, the defined requirements, the verification plans and the developed designs to be verified should be available as inputs. It is assumed that when the requirements and designs needed for the verification process are as much as possible connected and compliant with each other, verification results would be improved. This could lead to less need for repair measures, less stress among team members and more satisfaction of the overall performance of the project. In other words, it could result in having a satisfying verification process and outcomes that would be near the end of a design phase, when the final designs should be delivered to the client. This is supported by the fact that when deviations from requirements are discovered at early stages, overall project risk and cost can be reduced and a successful system can be delivered [1]. The development of requirements and designs are thus seen as main elements when aiming to improve the quality of delivered products.

In the context of this research, a *requirement* is defined as "*a statement that identifies a system, product or process' characteristic or constraint, which is unambiguous, clear, unique, consistent, stand-alone (not grouped), and verifiable, and is deemed necessary for stakeholder acceptability.*" [1]. Additionally, this research uses the term *designs* referring to the outputs of the design process, where high-level design solutions are developed. The INCOSE Systems Engineering Handbook explains design as "*the process of defining, selecting, and describing solutions to requirements in terms of products and processes. A design describes the solution (conceptual, preliminary or detailed) to the requirements of the system.*" [1]. The term *designs* is not limited to the outputs of one specific discipline but covers the other chosen solutions of the multidisciplinary deliverables. Those deliverables should be in compliance with all the defined requirements when submitted to the client.

With this in the background, in order to develop a framework of best practices, *Requirements Development*, and *Designs Development* are considered the main units of analysis. Requirements Development is the element concerned with the development of requirements to be used in the design and in the verification processes. Designs Development is the element concerned with the development of designs to be verified in compliance with all the defined requirements. Ideal characteristics of these elements along with possible approaches and tools for their efficient developments are described in more detail in the following sections.

2.1 Requirements development

As defined previously, a requirement is "*A statement that identifies a system, product or process' characteristic or constraint*" [1]. The defined requirements should be based on the wishes, requests and anticipations of the clients and stakeholders [1; 3; 5-7; 13]. From the provided definition also, a requirement should be "*unambiguous, clear, unique, consistent, stand-alone (not grouped), and verifiable, and is deemed necessary for stakeholder acceptability*" [1]. This is what several studies; [3; 5; 6; 13; 22; 23], agree on as well when they mention that the requirements should be SMART; Specific, Measurable, Acceptable, Realistic and Time-bound. The term of poor requirements is used in the literature, which stems from three sources; ambiguous requirements statements, incorrect (including unnecessary) requirements statements and incomplete (or omitted) requirements statements [22].

Following principles of the SE process model [6], shown in Figure 1, the project team should make sure that a Requirements Breakdown Structure (RBS) and Verification & Validation plans are shaped and prepared appropriately in consistency with the SMART requirements. Documenting and communicating requirements and their updates are also important matters mentioned in several studies; [3; 5-7; 9; 13; 15; 19; 22]. The incomplete documentation and inefficient communication of evolving requirements to the whole project team can lead to shifting away from the original goal. This can also lead to developing a solution incompliant with the original requirements. This "shifting away" is explained under requirements management problem [15] and demonstrated in Figure 2 below.

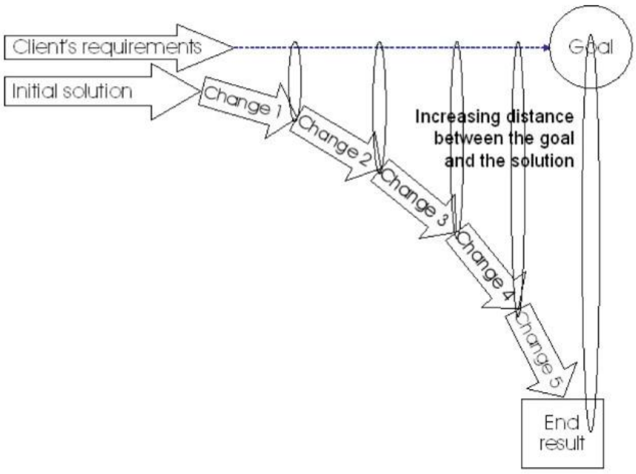

Fig. 2. Shifting away from the goal. This figure is derived from the literature; [15]

It is concluded thus, that managing and documenting requirements are essential processes for the successful development of solutions that meet stakeholders' needs. However, it is only fair to say that gathering and keeping good requirements updated and well-communicated throughout a design level is rather a challenging task. This is because of the fact that requirements are not necessarily fixed throughout the life cycle of a project. In other words, requirements change dynamically and their changes are inevitable until the final delivery is realized [1]. This is indicated in Figure 3 below.

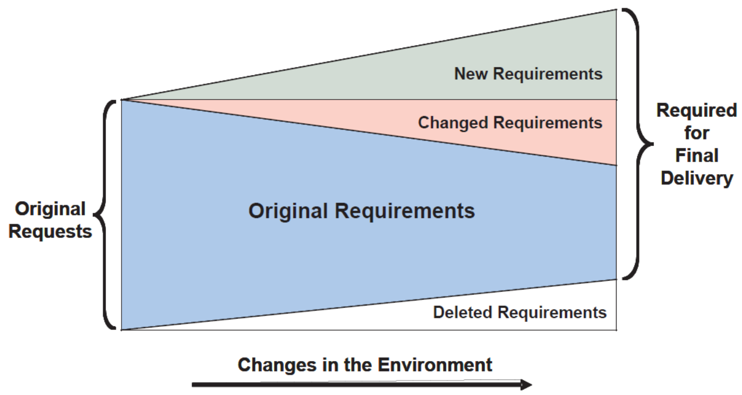

Fig. 3. Requirements changes are inevitable. This figure is derived from the literature; [1]

Moreover, requirements are information that is usually transferred to team members in a textual manner, which means that they are prone to human error due to the different possible interpretations. Examples of the characteristics that typify requirements are given in the literature such as their subjective complexity, their inconsistent use of terminologies and the complexity of their structuring and inter-relationships [24]. This and the importance of documenting not only the requirements but also the rationale behind their changes are stressed in the literature; [14]. It is mentioned that the many types of requirements, many types of spaces and many types of users and their activities form a certain complexity that designers need to deal with [14]. These complexities make managing and verifying requirements complex, prone to human error and time-consuming activities.

Managing requirements should not be a separated task from the designing activities but rather incorporated in the exploration of the design solutions, assisting the process and enhancing the verification and validation activities [25]. Several approaches and tools are mentioned in the literature to support the development of up-to-date SMART requirements to be timely incorporated into the designs. Among those are the use of requirements engineers, developing traceable products and performing structured processes, which are further explained in the following sections.

2.1.1 Requirements engineers

An approach with the aim of managing information is considered important and helpful, especially with relation to managing defined stakeholders' requirements. One way mentioned in the INCOSE Systems Engineering Handbook to maintain an archive of information produced throughout the project life cycle is by developing an Information Management Plan [1]. This plan would define the scope of information to be covered and maintained along with who and how to maintain them. Precisely in relation to managing requirements information, the literature describes the practice of requirements engineering [26]. Its definition is provided as: "*In system engineering, requirements engineering (RE) is the science and discipline concerned with analyzing and documenting requirements*." [26]. It is concluded that RE can ensure that a system can be built according to the stakeholders' requirements. Objectives of this process include the continuous management of changed and new requirements ensuring competitiveness on the market place [27].

A demonstration exists on the requirements engineer role whose core activities are to elicit requirements, model and analyze requirements, communicate requirements, agree requirements and evolve requirements [28]. These activities are rather cyclic and iterative in order to reach the outcome of the RE process, which is a requirements document defining what is to be implemented [29]. One critical feature mentioned is about a requirements engineer's skills covering social and technical skills to be able to manage requirements with consideration to both stakeholders and designers [28]. This means that multi-disciplinary training is required for reaching the intended objectives of a requirements engineer role. This role is supported and a Requirements Owner (RO) or a requirements manager, is also specified and mentioned in the literature to be a system life cycle role [19]. The idea behind this role is similar to the requirements engineer's, where the tasks cover translating customer needs into specific, well-written requirements. This is done while understanding all external interfaces and ensuring that the functional design correctly captures the defined needs [19].

2.1.2 Traceable products

The inputs for the verification process include traceable requirements and require that this traceability should be documented [1; 3; 5-7; 9; 13; 22; 23]. A prominent definition of requirements traceability is: "*Requirements traceability refers to the ability to describe and follow the life of a requirement, in both forwards and backwards direction, in other words from its origins, through its development and specification, to its subsequent deployment and use, and through all periods of on-going refinement and iteration in any of these life cycle phases.*" [23].

A realization of a grown demand for traceability in practice can be found, and a literature survey is provided identifying commonalities and differences in multiple areas; requirements engineering and model-driven development [30]. The importance of traceability is to identify what may be affected by changes to requirements and to other development components [31]. In order to be able to introduce requirements traceability, it is stated that "*traceability requires a good understanding of a clearly documented development process, with all phases and phase transitions well defined.*" [31]. One way to ensure requirements traceability is by developing a Verification Requirements Traceability Matrix (VRTM) identifying the proposed verification method and associated pass/fail criteria [22]. The VRTM is also mentioned in the INCOSE Systems Engineering Handbook among the required inputs for the execution of the verification and other processes [1]. Traceability is not an end goal in itself but rather a tool to improve the integrity and accuracy of all requirements and to allow tracking of their development and allocation. It also improves maintenance and change implementation [1].

In order to store and maintain traceable requirements, the availability of resources is considered an enabling matter. Having readily accessible sources and information to the entire project and influential parties involved, along with the ability to share and exchange data across multiple platforms and organizations is mentioned in the literature; [1]. The availability of resources; for example, Relatics[2], is mentioned in the literature as a factor affecting the implementation of Systems Engineering [13]. Requirement traceability can provide designers with various shared information and data to assess their decision-making. Additionally, measuring the performance of designs based on requirement data can be enabled with an effective requirement management framework where this data can be interfaced with computational design tools in a computer-aided design environment [25; 32]. The way of creating requirement traceability capability within a computer-aided architectural design is investigated in the literature by creating a plug-in based prototype application; *DesignTrack* [25]. This prototype can allow different users from different domains to trace, track and detect change impacts of all the requirements related to any design solution in any design session. This would assist developing designs to be in compliance with all the defined requirements regardless of their changes.

2.1.3 Structured processes

Following the concepts of the SE methodology, the iterative activities described for deriving, managing and documenting requirements and specifications should be planned. In the SE process model [6], shown in Figure 1, the ongoing iterative feedback processes between the core elements to ensure the consistency of the defined and new derived requirements are characterized [6]. The top-down and bottom-up approach is provided as an enhancer to these concepts. This approach is represented with the well-known "Vee Model" shown in Figure 4 below as derived from the literature; [9]. The left leg of the model explains how the system can be efficiently designed from the requirements. The right leg illustrates how the iterative verification and validation processes from the system components to the system level can be performed. This is done to ensure that the design meets and comply with all the stakeholders' requirements and expectations [9].

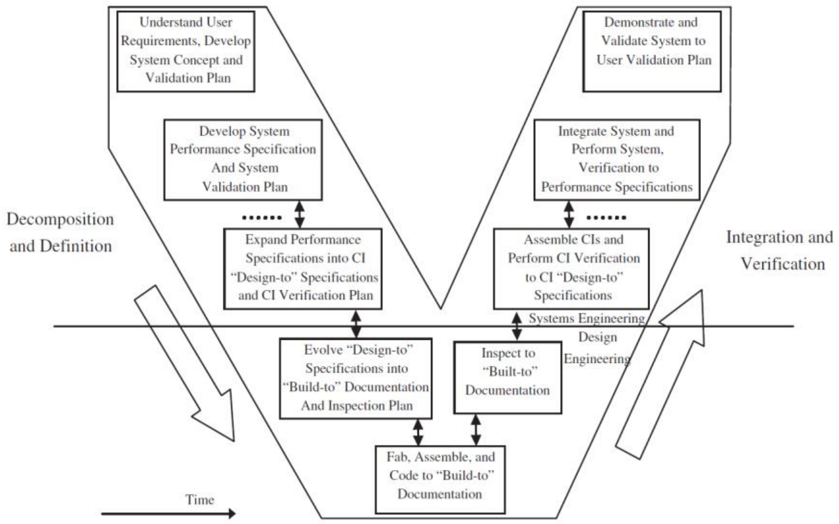

Fig. 4. Architecture Vee Model as derived from the literature; [9]

The Vee Model highlights the need and importance of developing verification plans during the first stage of the design when the requirements are being developed [1]. With relation to this, it is mentioned that the verification process flowing through the system hierarchy from the bottom up should be performed in a disciplined manner [22]. Planning for disciplined processes is consistent with what is mentioned in the literature that the project team should make sure to

[2] Relatics is a cloud platform used to control all information within a project in the construction, infrastructure, and civil engineering industry according to the Systems Engineering methodology.

appropriately shape and prepare Verification & Validation plans in consistency with the defined SMART requirements [6; 13]. Those plans contain the answers to the how, when and by whom questions accompanying later verification and validation processes throughout the design levels. The literature specifically mentions the measure of cross-referencing the verification plan to the requirements hierarchy before finalizing either of them [22]. Ongoing verification and updating of requirements are enabled in the SE process model [6], shown in Figure 1, by performing the *Requirements Loop* and *Specification Verification* feedback processes [6]. Similar suggestions are mentioned in other studies; [3; 5; 20].

Summarized, the development of requirements to be used in the design and in the verification processes has been described in the previous sections based on the conducted literature review. It is concluded that managing requirements should not be a separated task from the designing activities, but rather incorporated in the design, verification and validation processes to enhance them. However, several complexities exist and make managing and verifying requirements complex, prone to human error and time-consuming activities. Several approaches and tools are mentioned in the literature to support the development of up-to-date SMART requirements to be timely incorporated into the designs. The first approach is to employ team members with multi-disciplinary training to elicit, model and analyze, communicate, agree, and evolve requirements. Specific roles for this would be a requirements engineer, a requirements owner or a requirements manager. The second approach is to ensure requirements traceability such by developing a Verification Requirements Traceability Matrix (VRTM) or creating requirement traceability capability within computer-aided architectural design. Having readily accessible sources and information to the entire project and influential parties involved, along with the ability to share and exchange data across multiple platforms and organizations are important matters with this regard. The third approach is to plan the iterative activities described for deriving, managing and documenting requirements and specifications; following the "Vee Model" approach. In other words, it is important to prepare plans containing the answers to the how, when and by whom questions accompanying later verification and validation processes throughout the design levels. The goal is to realize ongoing management, verification, and updating of requirements.

2.2 Designs development

As defined previously, "*design is the process of defining, selecting, and describing solutions to requirements in terms of products and processes. A design describes the solution (conceptual, preliminary or detailed) to the requirements of the system*" [1]. In the context of Systems Engineering, and following the principles of the SE process model [6], shown in Figure 1, designers should convert the defined requirements and specifications into several suggestions for design solutions. This development of solutions takes place in the Design Synthesis process after having started the *Requirements Analysis* and *Functional Analysis and Allocation* processes. These design solutions should be examined and one solution should be selected by using any decision-making tool; for example, a multi-criteria analysis. Documenting and recording every step within this activity is very important to have a traceable, logical and coherent set of resolutions.

The ideal situation would be developing a design that complies with all the defined stakeholders' requirements [1; 5-7]. However, this is a challenging task due to reasons like the nature of requirements with their inventible changes [1; 14]. Additionally, problems in requirements documentation [15], and spending time on developing requirements correctly but not enough on ensuring that the right designs are being developed [16] do not make the task easier.

Designers may develop new ideas in design solutions, which may require updating the defined requirements and specifications [6]. This means that the designs are developed based on two sources; the requirements defined in earlier processes and the requirements derived during the design process. These later requirements would be based on the design decisions taken, which should be documented and used for maintenance activities, learning processes and assessment procedures [33]. They can also be reused if comparable design problems are encountered. A framework to allow extracting and classifying design decisions, as well as reasoning about decisions' rationale and other cases, is provided in the literature; [34]. These documentations will help in the linking and traceability between designs and requirements.

As in other industries, the quality of a product in the construction industry is reflected in its ability to satisfy stated or implied needs and internal characteristics as well as its external design [35]. The quality of a developed design depends on its degree of complying with the defined requirements. Several approaches and tools are mentioned in the literature to support the development of designs that can timely comply with all the defined requirements. Among those are the use of multi-disciplinary teams, developing linked products and performing organized processes, which are further explained in the following sections.

2.2.1 Multi-disciplinary teams

In the definition provided by the INCOSE, Systems Engineering is "*an interdisciplinary approach and means to enable the realization of successful systems.*" The term interdisciplinary means that it takes consideration of different domains. The systems engineering perspective is based on systems thinking, which is a method used to regard and focus on the system as a whole, rather than focusing on the sub-systems only [1]. This is essential to realize how the correlated elements influence each other so that a solution for the existing complex problems can be defined. It enables linking and involving the widely large set of skills and expertise to be able to realize suitable solutions for complex problems [9]. To allow searching and developing designs compliant with all the different technical and non-technical requirements, a multi-disciplinary approach is required. This approach can enhance successful management of the various individual elements of a complex system, which are designed, tested and supplied by different organizations throughout the project life cycle [9]. It can achieve effective collaboration [36]. Additionally, the literature defines several roles with relation to the design process such as the *System Designer* (SD), *System Analyst* (SA) and *Coordinator* (CO) [19].

In keeping with the concepts of Systems Thinking and the multidisciplinary approach, the INCOSE Systems Engineering Handbook recommends the use of an Integrated Product Team (IPT) in several SE processes including the requirements analysis and design processes [1]. Integrated Product Teams (IPTs) are multi-disciplinary teams representing an SE management technique that simultaneously integrates the various disciplines and stakeholders essential to the development of a system [5; 9]. Multiple benefits are stated regarding the use of IPTs such as bringing together the necessary expertise to analyze, review, assist with configuration issues and redesign [1]. The IPTs include all stakeholders influencing the project success. The governance based on IPTs provides the production of a design solution that satisfies customer requirements [9].

2.2.2 Linked products

As mentioned in the literature, the developed designs should comply with the defined requirements and they should both satisfy stakeholders' needs and expectations [1; 5-7]. The design data and specifics, including design decisions, should be stored and documented. The INCOSE Systems Engineering Handbook supports this by mentioning that the output of the design process should include, among others, system element detailed descriptions with documented justification for concept selections [1]. The outputs should also include requirements assigned to system elements and documented in a traceability matrix [1]. Linking designs with requirements and documenting their details along with the accompanying design decisions are noticed in multiple studies; [33; 34].

The management of designs to comply with the changing requirements is a challenging task. There are multiple conditions defined in order to manage design requirements [14]. These "must be met" conditions combine monitoring to ensure that a design solution satisfies the requirements and updating the requirements when project information affecting those requirements changes [14]. To be able to meet these conditions, a logical starting point would be to have a database where all the information can be stored and reached. One way to achieve this is by the implementation of Building Information Modeling (BIM) in the activities of an organization. As defined in the Construction manager's BIM handbook: "*Building Information Modelling is the digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it and forming a reliable basis for decisions during its life cycle, from earliest conception to demolition.*" [37]. Models and simulations allow a comprehensive analysis of system requirements and enhance communication among the different disciplines because information can be transferred quickly and design changes can be realized immediately. It is stated in the literature that models can organize, find, examine, filter, manipulate and edit information [38].

In order to allow and enhance information integration, the literature describes several technologies that can facilitate systems collaboration in architecture, engineering, construction, and facilities management [36]. Among those collaboration technologies are the web-based collaboration representing web-based systems to share construction project documents. This aims at achieving systems integration and thus improving the productivity and efficiency within the industry. One modeling language used by systems engineers is SysML, which provides a standard for systems specifications assisting the design of multi-disciplinary systems [9]. SysML can specify system requirements, structure, and parametric relationships. It allows for providing a bridge between requirements and system design levels [1].

Additionally, the INCOSE Systems Engineering Vision 2020 defines Model-Based Systems Engineering (MBSE) methodology as "*the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.*" [39]. In other words, MBSE is a methodology that utilizes the models developed within the BIM activities to verify if the design developed meets the defined requirements. This is achieved by connecting all information from the SE processes to those from the BIM activities, using a computer language as a tool; for example, SysML. This is followed by comparing the connected information to execute the verification and validation processes. Applying MBSE can enhance productivity along with quality, and it can improve communications among the system development team as well as reduce the risk [40]. It is also mentioned that modeling is an interdisciplinary work, which means that engaging other engineering disciplines is essential to realizing the added value with the MBSE. However, it is necessary to provide the needed modeling tools and languages experts to develop the system model and train other team members. This is because the MBSE approach requires a new way of thinking and a new set of skills [38].

2.2.3 Organized processes

The SE process model [6], shown in Figure 1, presents an organized process to develop designs in compliance with the defined requirements [6]. The model prescribes two feedback elements; *Design Loop* and *Design verification*, to run between the *Design Synthesis* and the other core elements. Performing the activities in these two elements can prevent developing designs that are not compliant with the defined requirements. Verification within the context of Systems Engineering should be an ongoing process throughout the lifecycle of a project and should be structured rather than spontaneous. To be able to efficiently verify the compliance of designs with the defined requirements, a structured verification plan should be developed and followed from the beginning of the project [1; 5; 6; 13]. With relation to evaluating alternative design solutions and choosing the best one, the use of a decision-making tool; a multi-criteria analysis or a trade-off analysis, is needed [1; 5; 6]. Another approach with the main objective of delivering a product that meets or exceeds stakeholders' requirements and expectations, and it is related closely to the verification process is the quality assurance approach. Failure testing, statistical control, and total quality control are activities generally associated with quality assurance [1]. For the management of quality assurance, a model used vastly among organizations is the Plan-Do-Check-Act procedure, which is a structured problem-solving process to drive improvement [41].

Summarized, the development of designs to be verified in compliance with all the defined requirements has been described in the previous sections based on the conducted literature review. It is concluded that designers should convert the defined requirements and specifications into several suggestions for design solutions. However, designers may develop new ideas when designing solutions. Therefore, the designs should be developed based on the already defined requirements and the requirements derived during the design process. These design solutions, decisions and rationales behind the decisions should be documented and stored in accessible sources. Several approaches and tools are mentioned in the literature to support the development of designs that can timely comply with all the different technical and non-technical requirements. The first approach is the use of multi-disciplinary teams such as integrated product teams. Additionally, several roles with relation to the design process can be defined such as the system designer, system analyst, and coordinator. The second approach is linking designs with requirements utilizing a database where all the information can be stored and reached. This can be achieved such by implementing web-based collaboration, Building Information Modeling or Model-Based Systems Engineering. The third approach is to develop and follow a structured verification plan from the beginning of the project. Verifying the compliance of designs with the defined requirements should be structured rather than spontaneous. Additionally, the use of a decision-making tool; a multi-criteria analysis or a trade-off analysis, is needed for evaluating alternative design solutions and choosing the best one. Another approach found is the quality assurance approach. The goal is to realize a design that complies with all the defined stakeholders' requirements.

3. The framework of best practices

This chapter describes the framework of best practices, which is developed based on the literature review presented in Chapter 2 above. To facilitate structuring the desired framework, the main elements; *Requirements Development* and *Designs Development*, are divided into sub-elements. These sub-elements are derived from the findings of the literature review and categorized into three categories; *people*, *products* and *processes*. These points can be found common in the collected data about the ideal characteristics of the main elements and the possible approaches and tools for achieving them. Categorizing the findings of the literature review into the *people*, *products* and *processes* categories is just an endeavor towards structuring the framework for the continuity of this research project. An acknowledgment of the possible overlapping and dependent natures between these, and other, elements in real life remains clear regardless of this categorization.

The use of these categories is inspired from the INCOSE Systems Engineering Handbook, where it is mentioned that "*Verification encompasses the tasks, actions and activities performed to evaluate the progress and effectiveness of the evolving system solutions (people, products and process) and to measure compliance with requirements.*" [1]. It is concluded that these tasks, actions, and activities are not limited to the verification process but exist in other SE processes. Therefore, it is perceived that activities represent the processes generated to organize the tasks, which are executed by the people to take actions on the designed products. These elements are seen as interconnected and dependent on one another.

By definition, these elements comprise any system as "*An integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements.*" [1]. Other elements mentioned in this definition may influence the development of the requirements and designs but searching explicitly for them is considered out of the scope of this research project. Consequently, *people*, *products* and *processes* are considered the sub-elements embedded in the previously defined main elements and will provide their characteristics. The characteristics describing best practices for developing designs to be in compliance with all the defined requirements throughout a design level of detail are presented in Table 1 and Table 2 below.

Table 1. The framework of best practices for developing requirements throughout a design level

Main element	Sub-element	Expected pattern	Sources
Requirements Development	People	There should be multi-disciplinary teams responsible for: • Eliciting client's and stakeholders' requirements • Analyzing client's, stakeholders' and derived requirements (including design constraints) for clarity, completeness, and consistency • Documenting client's, stakeholders' and derived requirements • Communicating client's, stakeholders' and derived requirements among the different stakeholders and team members • Evolving requirements in response to stakeholders' needs and/or design processes (e.g. Requirements Engineer role, Requirements Owner role)	[1; 19; 28]
	Products	The defined requirements should be based on the wishes, requests, and anticipations of the clients and stakeholders	[1; 3; 5-7; 13]
		The defined requirements should be SMART (i.e. Specific, Measureable, Acceptable, Realistic and Time-bound)	[1; 3; 5; 6; 13; 22; 23]
		The defined requirements should be documented The updated requirements should be documented	[3; 5-7; 9; 13; 15; 19; 22]
		The defined and updated requirements should be traceable (e.g. using a numbering system, Verification Requirements Traceability Matrix (VRTM))	[1; 3; 5-7; 9; 13; 22; 23; 25; 32]
		The defined requirements information should be stored in accessible sources (e.g. Relatics)	[1; 13; 25; 32]
	Processes	Managing and verifying requirements should be ongoing (not restricted to one moment in time) Managing and verifying requirements should be iterative (whenever changes in requirements/designs occurred) Managing and verifying requirements should be disciplined processes (e.g. V&V plans with specific and clear roles and responsibilities)	[1; 3; 5; 6; 9; 13; 20; 22]

Table 2. The framework of best practices for developing designs throughout a design level

Main element	Sub-element	Expected pattern	Sources
Designs Development	People	There should be multi-disciplinary teams to: Search for, define and analyze design solutions satisfying the defined client's and stakeholders' requirements (e.g. Integrated Product Teams, System Designer role, System Analyst role, Coordinator role)	[1; 9; 19; 36]
	Products	The design solutions should be developed based on the defined requirements and specifications	[1; 5-7; 35]
		The design solutions descriptions should be documented The design solutions descriptions should be stored in accessible sources	[5; 6; 9; 36-38; 40]
		There should be documentation of design decisions There should be documentation of the rationales of the design decisions	[1; 5; 6; 33; 34]
	Processes	Evaluating alternative design solutions should be performed carefully (e.g. using a multi-criteria analysis, a trade-off analysis) Choosing one design solution should be performed with consideration of the defined requirements	[1; 5; 6]
		Verifying designs with the defined requirements should be ongoing (not restricted to one moment in time) Verifying designs with the defined requirements should be iterative (whenever changes in requirements/designs occurred) Verifying designs with the defined requirements should be a disciplined process (e.g. V&V plans with specific and clear roles and responsibilities)	[1; 5; 6; 13]

4. Method

In order to answer the research question, current practices at Witteveen+Bos should be compared with the framework of best practices presented in Chapter 3 above. In this research project, using case studies is the chosen strategy for revealing the details of the way current practices are carried out in projects. This is facilitated by the use of case studies since they provide profound insights into one or several processes restricted in time and space [42]. In other words, preferring depth over breadth for understanding the real practices and gaining a holistic vision of the situation in the firm. Additionally, a case study strategy is considered appropriate for this research since the research question is of exploratory nature, the studied projects are contemporary and the researcher has no control over the events [43].

The case studies have been chosen depending on two main criteria; both cases are of a road infrastructure specification and both have been implementing SE processes in the concept design phase of the project life cycle. This selection of projects is made in direct relation to the interest and scope of this research. In both projects, the final deliverables of the concept design phase have not been delivered to the client yet. However, a preliminary evaluation of the performance of each project can be made based on team members' observations and personal interpretations. Based on the impression within Witteveen+Bos, one of the projects is perceived as a success project developing designs in compliance with the defined requirements throughout the concept design phase, while the other project is supposedly not. This assumption can provide added value to the research when comparing the findings of both projects to realize the main differences. A brief description of each project is as follows:

- Project A is an extension of a road from two by two lanes to two by three lanes, which resolves in changing within the interchanges of the road. Witteveen+Bos is responsible for delivering the concept design of the road and its surroundings; the integral design of the new highway. This integral design includes the designs of all related surroundings of the area; the bridges, viaducts, waterways, nature, landscape, etc. The design documents with verification and validation reports and the system specification are among the expected deliverables. The project started in September 2017.
- Project B is an extension of a road from two by two lanes to two by three lanes. Witteveen+Bos is responsible for delivering the concept design and environmental impact analysis of the road while a third party is responsible for the landscape design. The design reports with the system specification and the environmental impact assessment matching the developed designs are among the expected deliverables. The client will manage to transform the deliverables from Witteveen+Bos to contract specification, but this is out of the scope of the current assignment. The project started in April 2018.

4.1 Data collection

In this research, data from two case studies have been collected only by means of interviews with personnel involved in the chosen projects. People are chosen as the main and most suitable source of information for this research. Sources like project documents and databases cannot be analyzed because they are provided in Dutch, and the researcher lacks the needed understanding of this language. Other reasons for choosing the people as a source of information are the diversity of the information to be gathered along with the speed of collecting that information. Different people with different roles in performing the current practices at the firm can provide different information and details, which is considered an advantage. Personnel could be respondents giving information about themselves, could be informants providing data about current practices or situations, or could be experts acting as suppliers of knowledge or experience due to their high expertise, role and/or position at the hosting organization [42].

Therefore, semi-structured interviews with personnel from different working teams with different positions and different working experiences are conducted. A structured outline was used for all the interviews but some space was left for additional questions that seemed informative during the interview. This semi-structured process could result in a deeper understanding of the situation due to the possibility of identifying new factors that could be affecting the current practices. The interviews lasted for approximately seventy-five minutes and all were in a face-to-face setting of the interviewee and the interviewer. Face-to-face interviews enabled clarifying possible doubts by repeating or rephrasing statements when certain responses or questions were not understood properly [44]. In total, 9 interviews with team members from both projects are executed; 5 from project A and 4 from project B. Specific roles and responsibilities involved in the development and management of requirements and designs in the projects were considered essential for understanding the current practices. The technical managers, leaders of the disciplines responsible for developing the concept designs and systems engineers responsible for delivering the system specifications from both projects are interviewed.

Following the suggestions mentioned in the relevant literature, the interviews started with broad questions initially and continued with narrowed ones regarding the developed framework of best practices [44]. In other words, the interviewees were first asked to generally describe how current practices are being carried out with relation to developing requirements and designs in the projects. Such broad questions would be like "*how was the process of developing requirements and designs in general?*." The problem defined in this research project was then presented to the interviewees. They were asked whether they thought this problem existed in their projects, to which extent it did and the reason behind its (non)existence. An example of such a question would be "*how would you assess the process in general? And how would you look at these points, when you are actually doing the full verification, what is the percentage of compliance between the defined requirements and the designs?*"

The developed framework of best practices was then presented to the interviewees and structured questions about its characteristics were asked. This allowed gathering descriptive data of the current practices for the comparison with the best practices. Evidence supporting the interviewees' answers, and reasons behind the current ways of working in the projects were collected from their personal inputs. In the end, the interviewees were asked for their suggestions to improve current practices for developing requirements and designs. The general approach for developing requirements and designs within each project is summarized and presented in Chapter 5.

4.2 Data analysis

Analyzing data collected from the literature review and the conducted interviews has been performed by means of pattern matching, which is a strategy considered as the core procedure of theory-testing with case studies [45]. The main concept of pattern matching is to test whether an expected pattern deduced from theory matches with the actual pattern that exists in the current testing context. In other words, pattern matching is about testing whether theory and practice match in real life, by comparing their patterns and characteristics.

The framework of best practices for developing designs to be in compliance with all the defined requirements throughout a design level of detail of projects has been considered the *expected pattern*. This expected pattern combines the possible main elements, sub-elements and their characteristics embedded in the proposed best practices. These elements and characteristics have been provided in a qualitative manner, as shown in Table 1 and Table 2 presented in Chapter 3, and have been compared to the characteristics of current practices performed at Witteveen+Bos regarding the specified elements. The current practices, the *observed pattern*, have been analyzed and compared with the expected pattern, and the final status of *matching*, *quasi-matching* or *mismatching* results have been given to every specified element in the framework; the *expected pattern*.

The status of (mis)matching characteristics between the two patterns have been analyzed within and cross-case study respectively. This has been demonstrated by giving values to them on a three-point scale; -, 0, +, where the researcher's interpretation of theory has been used in defining specific criteria for evaluating the patterns. These criteria can be found in Appendix D attached to this paper. A - status means that there is no state of matching between the expected and observed patterns. A + means a complete matching and a 0 means that there is some kind of matching but it does not cover all characteristics defined in the specified element. The status of matching is assessed based on meeting the patterns evaluation criteria and the ability to provide evidence. The lack of evidence to support statements would result in not giving a status to the observed pattern. The result in this situation would be not available; N/A. This is because the lack of evidence to support a certain statement is seen as an obstacle for an efficient evaluation but is not necessarily an indicator that the observed pattern under evaluation matches, quasi-matches or mismatches the expected pattern.

The pattern matching results have been presented in a table combining the elements, sub-elements and their characteristics in the expected pattern, the qualitative data collected about the observed pattern and the status of their pattern matching. Appendices A and B present tables of the within cases pattern matching results with their explanations. Matching patterns within cases has enabled analyzing each project and understanding its particular characteristics for developing requirements and designs. The cross-case analysis has enabled comparing the characteristics of both projects to have a more comprehensive understanding of the current practices and the needed improvements. This analysis has provided insights into the differences and similarities between the patterns of the two projects in a qualitative manner. The outcomes of these comparisons have been the basis for explaining the (in)compliance between the developed requirements and designs among both projects.

5. Case study results

This chapter presents the cross-case data collection results and the pattern matching results respectively. An analysis of these results will be provided later in Chapter 6.

5.1 Data collection results

This section presents information about the general approach for developing requirements and designs within each project as collected by means of the interviews. These data collection results typify the current practices at Witteveen+Bos and will be used later to perform the pattern matching analysis.

5.1.1 Project A

Witteveen+Bos has planned different design loops, gates and baselines for delivering the concept design of the new highway. At the firm, there are four internal design loops for developing the designs at different levels of detail. These design loops are carried out before the final designs are delivered to the client to be presented to the public. At the end of every design loop, there is a gate and a baseline of which the dates are planned in advance. A gate date is a deadline specified for every discipline to deliver their products for the internal integral verification and decision-making processes to take place by the discipline leaders. A baseline date is a deadline for submitting the developed products, including the advice provided by Witteveen+Bos, to the client for its validation and final decisions.

There are three main teams in the organization of the project, which together form the project management team; environmental impact team, design and innovation team, and planning team. The planning team is responsible for managing the legislation and legal matters related to the project. Within the environmental impact team exists the stakeholder participation team responsible for managing stakeholders' demands and wishes. The design and innovation team includes, among others, the multidisciplinary design sub-teams and the system specification team. The system specification team is responsible for building the system specification suitable for every baseline, and for maintaining the Relatics database with existing, changed and/or new requirements. Design discipline leaders would send the requirements resulting from developing the designs to the system specification team via emails to be stored and maintained in the Relatics database. A design discipline leader is generally a team member representing a discipline of certain expertise and skills and is responsible for the management and delivery of the designs of that discipline; a design sub-team manager. Examples of design disciplines are, among others, phasing and construction discipline, road design discipline, spacial quality discipline, etc.

The three main teams work in parallel during the design loop until they reach the gate point, where all disciplines deliver a version of their products individually to be verified by the project team. At the gate, all the disciplines formally review and verify all the deliverables integrally at Witteveen+Bos. The gate meeting would consist of the managers of the three teams; the project management team, all the discipline leaders and some of the designers from the lower level, because of their knowledge of the design details. The needed adjustments on the developed products would be made so that the project team reaches the final delivery of a design loop; at the baseline, where the client receives the deliverables and validates them.

Additionally, the project has activated a digital Participation Platform managed by Witteveen+Bos, but under the client's name. This platform allows people to react and give requirements while seeing the status of the requirements that are met already in the design or not yet, and with reasons behind those (un)meetings. All these requirements are then entered in the Relatics database. This was one of the offers provided in the tender documents. The reason for using this platform, as mentioned by the technical manager, is that Relatics is just a database, not a way of communicating with stakeholders. It is a way to communicate with the client, but not smoothly either while the participation platform is a way to communicate with the client and stakeholders in a simple and easy way. Additionally, Witteveen+Bos wanted to take into consideration other stakeholders' opinions who are possibly not able to attend evening discussion meetings; provide availabilities to react for different ages and different opinions.

5.1.1.1 Developing requirements and designs

There was a strict project plan delivered to the client before the start of the project, where themes and information were specified to be defined and fixed for every baseline. In other words, there were essential requirements that needed to be defined for a specific baseline and then fixed before moving forward to the following baselines. The project plan also consisted of verification and validation plans delivered to the client.

The lifecycle of a requirement in this project starts when the stakeholder participation team and specialists from the design team elicit and collect stakeholders' demands and wishes in group sessions. Stakeholders' demands are then communicated with the project team by assigning them to the responsible discipline leader(s) and design specialists to analyze them. The specialists then advise the project management team whether a demand can be included in the designs or not. The project management team checks, agrees or denies and then advises the client depending on this second evaluation. The client receives the advice and sends a final reply with a decision to Witteveen+Bos. Finally, depending on the client's decision, a stakeholder's demand is either accepted and included as a system requirement or denied. When accepted, the system specification team then checks the client's decisions and links the accepted requirements in the system requirements already made or makes new requirements. The communication between team members from the three main teams and the client is done using the Relatics database along with having meetings. The communication between the stakeholder participation team and the discipline leaders is done either via the Relatics database, emails or by having meetings.

If a requirement would be incorporated in the system specification, the system specification team would decide whether verification of the requirement with the designs would be required for the current baseline or not yet. If the answer were no, then no verification would be planned in the system and it would be rather postponed until reaching the suitable baseline. If the answer were yes, then the verification process would be planned including how, when and by whom the verification would take place. The system specification team would make the V&V plans before the requirements would go to the design. When the system specification team would allocate requirements to functions and objects deciding whether they were function-related, aspect-related or interface-related requirements, they would also think at that moment how the verification should happen. The team members responsible for verifying the requirements with the designs; discipline leaders, would then have to execute the verification and provide evidence of the positive results in the Relatics database.

5.1.1.2 Relation to the defined problem

With relation to the defined problem of this research, it appears that indeed, there were moments during the verification process when the teams faced their designs with the defined requirements, they realized they were not in compliance with each other. This is mentioned to happen in the later design loops more than in the earlier ones. Among the several reasons mentioned for this incompliance is the late arrival of stakeholders' requirements in the process and/or the inadequate SMART formulation of those requirements. Additionally, digital communication between team members from the three main teams, rather than face-to-face communication, was mentioned by one design discipline leader as a reason for this incompliance due to possible misinterpretations at several points throughout the design process.

Moreover, multidisciplinary design leaders having different points of view and different ways of approaching design-related matters is another mentioned reason. For example, a discipline leader wanted to strictly follow the guidelines when designing, while another discipline leader thought following the guidelines would result in extra costs that should be avoided. There was enough communication between the discipline leaders about those conflicting points of view when designing but still, clear agreements were not always made. However, the project team appears to manage these challenges well and make the necessary adjustments on the developed products in time so that they satisfy the defined requirements before a baseline delivery to the client. It is mentioned that between the gate and the baseline is where the discipline leaders evaluate the developed alternative design solutions from all the disciplines and together decide on the most beneficial alternative so they can provide advice to the client in their deliveries.

The percentage of compliance between the defined requirements and developed designs is estimated to be around 80% as an average for all design loops, being higher in the first design loops than in later ones. In other words, all the interviewees estimated that the developed designs have been around 80% in compliance with all the defined requirements. However, the interviewees estimated the highest percentage of compliance being in the first design loops due to the low number of requirements to be verified in that stage, and because they were mostly the client's requirements. Other reasons mentioned for the estimated high percentage of compliance:

- There were a previous evaluation and selection of the requirements before formally starting designing, which was executed by the specialists. In other words, a stakeholder need would not be considered a system requirement unless it would be accepted to be fulfilled. Additionally, many of the requirements are standards and the designers have knowledge of the client's standards and guidelines, which have been used in developing the designs.
- From the start, the team defined which requirements they were going to verify at which baseline. This meant that there were verification and validation plans answering the questions of how, when and by whom, so that team members only verified requirements planned for the specific baseline. There was a really well-organized process for verifying and validating stakeholders' requirements and many team members with specific responsibilities were involved with this regard. The technical requirements; the client's requirements from the guidelines, were verified by the designers and the specialists.
- After analyzing existing designs from previous stages and knowing the problems, Witteveen+Bos made a list of the design decisions to be taken regarding those problems. Design decisions were inserted into the Relatics database with the alternative design solutions that the designers had in mind. The designers then evaluated the alternative design solutions to solve the problems from the beginning. In other words, in addition to the stakeholders' requirements that the designers took into account, they were prepared with alternative design solutions and design decisions regarding already existing problems.
- The coordination between the system specification team and the designers was mentioned as a possible reason for the high percentage of compliance between the defined requirements and developed designs. For example, in a design loop, the system specification leader or his assistant would regularly participate in the design team meetings to discuss, explain and update them about the requirements. Those regular meetings would be held on a weekly basis with the design team, where existing problems or misunderstandings regarding the requirements would be disclosed.
- Every two/four weeks, (some of) the discipline leaders had an informative meeting with informal internal verifications performed during. This was done throughout a design loop, before reaching the gate. However, these meetings were not fixed but rather dependent on the discipline leaders and were issue-based.

Concisely, when the technical manager was asked about his satisfaction with the developed designs, quoting him: "*This is the most integral design we ever made.*" He mentioned that the percentage of compliance was not necessarily very high because some requirements could not be met. However, the requirements specified to be necessary and SMART enough to be met were all included in the designs.

5.1.2 Project B

Witteveen+Bos' approach was to plan the deliverables internally before the final delivery to the client, where an external preliminary check of the integral design with the environmental impact analysis takes place. Depending on this check, the decision would be made on the design whether it could be presented to the public or not yet. Witteveen+Bos' plan has four design loops; four design levels of detail, from broad to more in detail. At the end of every design loop, there is a baseline and the date of it is planned. However, no specific gate date accompanying is planned; there is no smart gate point. In other words, there was no gate date specified for performing formal internal integral verification and decision-making processes. On the other hand, there were baseline dates specified for submitting the developed products, including the advice provided by Witteveen+Bos, to the client for its validation and final decisions.

There are two main teams at Witteveen+Bos responsible for delivering the assignment; the environmental impact specialists' team and the designers' team. One team member from the environmental specialists; the environmental manager, is responsible for eliciting and communicating the stakeholders' requirements to the technical manager and the environmental specialists at fixed times by batches in Excel sheets. The Excel sheets contain the name, the process, the function of the requirement along with the object it is related to, a question behind it and the impact analysis of it. For every baseline, it is mentioned in the project plan in which week of the project the specialists will receive these Excel sheets and in which week they have to return their assessments, which will be then incorporated in the main Excel sheet that will be used to provide the final advice to the client. The technical manager filters the requirements and gives advice on which requirements can be accepted and included in the designs and which cannot. The client takes the final decisions and then the accepted requirements are communicated to the designers in a design meeting or by email to include them in the designs.

The use of GRIP; an application based on the Relatics database, is required by the client. The information related to the defined requirements are not inserted directly in the GRIP but the environmental manager imports the Excel sheets to the application. A systems engineer is currently transforming the documents already made by the designers into system requirements stored in the Relatics database along with the standard requirements from the client. In other words, everything is going afterward; after the design has been made, the systems engineer is looking back at the design and the decisions made and is inserting them in the database. At this moment, in the 4th design loop, the systems engineer is storing the design solutions, decisions, and rationales behind those decisions from all the previous loops in the Relatics database. The alternative design solutions with their advice are now being inserted in the Relatics database where the client makes a decision again. Noteworthy to mention is that both team members assigned as systems engineers were involved relatively near the end of the project to perform such tasks. This happened after the previous systems engineer who was involved in the project had left the company. Among the expected systems engineers' deliverables are system specification documents and a maintained Relatics database with linked requirements, functions, objects, and design decisions.

5.1.2.1 Developing requirements and designs

The project team is structured in a way that every role at Witteveen+Bos has a counterpart at the client's organization. In other words, there are two environmental managers, a representative of Witteveen+Bos and a representative of the client attending the interviews with the stakeholders. In this case, the project can be covered from the technical aspects of the designs; Witteveen+Bos representative's input, and from the other aspects related to the overall policy; the client's representative's input. The environmental manager from Witteveen+Bos, the client's environmental manager and three team members from the external landscape design company all attend meetings with the stakeholders. With the progress of the project to the following baselines, the meetings with the stakeholders get more informative as the design is being developed.

The lifecycle of a requirement in this project starts with the first meeting about customer's requirements when the environmental manager asks the stakeholders questions that are more specific about their demands and tries to make them SMART. The environmental manager writes them in the notes of the meetings and sends a version to the client's environmental manager, who attended the same meetings, to validate the conclusions for correct interpretations. These notes are stored in a joint IT system with the rest of the team members at Witteveen+Bos. Once the report of a meeting is definite, it is sent with the defined requirements to the stakeholders who attended that meeting for their validation and input. This contact between the environmental manager and the stakeholders happens until there is a definite confirmation from the stakeholders that the requirements defined in the report are good representations of their wishes and demands.

The environmental manager documents the defined stakeholders' SMART requirements in Excel sheets containing the name, the process, the function of the requirement, the object it is related to, a question behind it and the impact analysis of it. The environmental manager first assesses the requirements whether they fit in the scope of the project, can be covered in the budget or are technically feasible depending on his experience. Afterward, the environmental manager assigns verification responsibilities to specialists in the project team at Witteveen+Bos to assess and analyze which requirements can be included and which cannot. The technical manager afterward filters the requirements and gives advice to the client who makes the final decisions, and thereafter the accepted requirements are communicated to the designers to be included in the designs.

5.1.2.2 Relation to the defined problem

With relation to the defined problem of this research, the technical manager of the project stated that indeed, sometimes there was incompliance between the defined requirements and the developed designs. This incompliance, however, is justified by working with the third party responsible for the landscape design and the different approaches followed, but not because of Witteveen+Bos' practices. Nevertheless, this statement could not be supported and the problem defined in this research could not be entirely assessed from the interviews. This is because no explicit proof of the verification has been found yet.

When the technical manager was asked about the designs and the requirements whether they were meeting each other or there was a huge gap between them, he said: "I think they were meeting, and if you ask me to prove it, we do not have a verification list … no …".

Noteworthy to mention is that neither of the systems engineers was involved in the verification processes and neither of them could estimate the percentage of compliance between the defined requirements and the developed designs.

5.2 Pattern matching results

This section presents the pattern matching results cross cases. The results can be seen in Table 3 and Table 4 below for both Projects A and B. These results represent the comparisons between the expected and observed patterns for developing designs to be in compliance with all the defined requirements throughout a design level of detail. An analysis of these results is provided later in Chapter 6.

Noteworthy to mention that - stands for mismatching patterns, 0 for quasi-matching patterns and + for matching patterns. The status of matching is assessed based on two main conditions; meeting the patterns evaluation criteria and the ability to provide evidence. In other words, the patterns evaluation criteria developed by the researcher, as provided in Appendix D, are used as the first assessment for giving a practice the status of matching, quasi-matching or mismatching. The final assessment is based on the (non)existing evidence provided by the interviewees supporting their statements.

However, if one observed pattern was assumed to be matching the expected pattern but there was no evidence to support such a statement, no status would be given to the observed pattern, and thus the result would be not available; N/A. This is because, as mentioned before, the lack of evidence to support a certain statement is seen as an obstacle for an efficient evaluation but is not necessarily an indicator that the observed pattern under evaluation matches, quasi-matches or mismatches the expected pattern. In all cases, each given status is further justified in Appendices A and B, where tables of the within cases pattern matching results accompanied with elaborated explanations are presented.

Table 3. Pattern matching results of requirements development cross Projects A and B

Main element	**Sub-element**	**Expected pattern**	**Status of matching Project A**	**Status of matching Project B**
Requirements Development	People	There should be multi-disciplinary teams responsible for: • Eliciting client's and stakeholders' requirements • Analyzing client's, stakeholders' and derived requirements (including design constraints) for clarity, completeness, and consistency • Documenting client's, stakeholders' and derived requirements • Communicating client's, stakeholders' and derived requirements among the different stakeholders and team members • Evolving requirements in response to stakeholders' needs and/or design processes (e.g. Requirements Engineer role, Requirements Owner role)	+	+
	Products	The defined requirements should be based on the wishes, requests, and anticipations of the clients and stakeholders	+	+
		The defined requirements should be SMART (i.e. Specific, Measurable, Acceptable, Realistic and Time-bound)	0	0
		The defined requirements should be documented	+	+
		The updated requirements should be documented	+	+

		The defined and updated requirements should be traceable (e.g. using a numbering system, Verification Requirements Traceability Matrix (VRTM))	+	0
		The defined requirements information should be stored in accessible sources (e.g. Relatics)	+	+
	Processes	Managing and verifying requirements should be ongoing (not restricted to one moment in time)	0	-
		Managing and verifying requirements should be iterative (whenever changes in requirements/designs occurred)	0	-
		Managing and verifying requirements should be disciplined processes (e.g. V&V plans with specific and clear roles and responsibilities)	+	0

- mismatching patterns, 0 quasi-matching patterns, + matching patterns, N/A not available results

Table 4. Pattern matching results of designs development cross Projects A and B

Main element	Sub-element	Expected pattern	Status of matching Project A	Status of matching Project B
Designs Development	People	There should be multi-disciplinary teams to: Search for, define and analyze design solutions satisfying the defined client's and stakeholders' requirements (e.g. Integrated Product Teams, System Designer role, System Analyst role, Coordinator role)	+	+
	Products	The design solutions should be developed based on the defined requirements and specifications	+	+
		The design solutions descriptions should be documented	+	+
		The design solutions descriptions should be stored in accessible sources	+	+
		There should be documentation of design decisions	+	+
		There should be documentation of the rationales of the design decisions	+	0
	Processes	Evaluating alternative design solutions should be performed carefully (e.g. using a multi-criteria analysis, a trade-off analysis)	+	+
		Choosing one design solution should be performed with consideration of the defined requirements	+	+
		Verifying designs with the defined requirements should be ongoing (not restricted to one moment in time)	+	N/A
		Verifying designs with the defined requirements should be iterative (whenever changes in requirements/designs occurred)	+	N/A
		Verifying designs with the defined requirements should be a disciplined process (e.g. V&V plans with specific and clear roles and responsibilities)	+	0

- mismatching patterns, 0 quasi-matching patterns, + matching patterns, N/A not available results

6. Pattern matching analysis

As it can be seen in the pattern matching results presented in Table 3 and Table 4 in Chapter 5, it appears that Project A is performing better than Project B. This is in terms of matching the expected patterns for developing requirements and designs to be in compliance with each other, throughout a design level of detail. However, more analysis is needed for such evaluation because the observed patterns reflecting current practices in both projects can be justified with several explanations. Appendix C presents the tables that include the analysis of the pattern matching results with more insights on the current practices in both Projects A and B. This analysis is based on the data collected from the interviews and the researcher's evaluation of the information, statements, and evidence provided. The following sections serve as a summary of the analysis presented in those analysis tables provided in Appendix C.

6.1 Requirements development

The pattern matching analysis indicates that both projects involve multi-disciplinary teams for eliciting, analyzing, documenting, communicating and evolving requirements. Both projects appear to understand the importance of involving different disciplines for performing the defined tasks as they are related to the whole project. This way of working is justified as embedded in the general practices of Witteveen+Bos in such projects, where an acknowledgment exists that a requirement from one discipline can affect more than one discipline. Both projects appear to acknowledge the need to consider and satisfy the client's and stakeholders' desires when developing requirements and designs. Both projects document the defined and updated requirements and appear to understand the importance of this pattern. While requirements documentation in Project A is mostly done utilizing the Relatics database, the documents of the clients' and stakeholders' requirements are not integrated in Project B. A reason mentioned for this is the lack of experience and lack of advice from the previous systems engineer who was involved in the project. Another finding is that not all of the defined requirements in both projects are SMART. This is because, among other reasons, some requirements cannot be as SMART in certain design loops or with relation to specific disciplines, and stakeholders are not professionals in making their requirements SMART. It was mentioned in Project A that it is time-consuming to contact back and forth with the stakeholders to make their requirements SMART.

Regarding the traceability of requirements, Project A proves that all the defined requirements in the system have numbers and codes related to functions, objects and system elements. It came across as a mutual acknowledgment within the team of the need to make every object and function unique, traceable and linkable to one another. On the other hand, not all of the defined requirements in Project B are traceable with a numbering system. Stakeholders' requirements are traceable with a numbering system but the client's requirements are documented in a different manner in the design reports, without a numbering system. It was mentioned that using the Relatics database actively only at the end of the project can be a reason for this.

Both projects store the defined requirements information in accessible sources for the team members involved in the project and for the client. In Project A, accessible sources are the Relatics database for the client and all team members from Witteveen+Bos, and the digital Participation Platform for the other stakeholders. Project B stores the requirements information in a joint IT system with all team members from Witteveen+Bos, and uploads those documents in the GRIP; an application based on the Relatics database. However, the information related to the defined requirements is not inserted directly in GRIP but rather the Excel sheets are imported to the application. The reason behind this could be the environmental manager's personal preference to use the Excel sheets and a lack of experience in using the application. In addition to this information, the technical manager of Project B mentioned that the Relatics database is accessible but not all the designers access it. He justified his statement by explaining that designers are only interested in what is important for their designs so they receive the conclusions from the design manager in Excel sheets.

Regarding managing and verifying requirements, Project A performs them during the design loops but rather informally during regular meetings between members from the stakeholder participation, design and system specification teams. The processes were formally performed at the gate so to avoid that planning and milestones would not be met due to time consumed in the ongoing processes. The processes were iterative but not whenever changes in requirements or designs occurred. On the other hand, Project B performs the processes of managing and verifying requirements at the end of a design loop and they are not considered iterative. One justification mentioned for this practice was to get an easier and better manageable process. However, it was mentioned that not all team members are ready to implement Systems Engineering principals and methodology. Regarding managing and verifying requirements to be disciplined processes, Project A provides specific and clear roles and responsibilities for managing and verifying requirements in the project plans and during the design loops. It was mentioned that strict planning of the project from the beginning is needed so that the whole system functions well. On the other hand, there have been roles and responsibilities for managing and verifying requirements in Project B but they have been really active only recently. A reason for this, as the technical manager mentioned, is that the previous team member responsible for this did not perform it enough. Noteworthy to mention is that both systems engineers of the project could not give a clear evaluation of several characteristics regarding the patterns of developing requirements in Project B because they both have been involved as systems engineers only at the end of the project.

6.2 Designs development

The pattern matching analysis indicates that both projects involve multi-disciplinary teams for searching, defining and analyzing design solutions. Both projects appear to understand the importance of involving different disciplines to perform the defined tasks in order to develop design solutions satisfying the defined client's and stakeholders' requirements. Both projects develop design solutions based on the defined requirements and specifications, and both projects appear to acknowledge the importance of this pattern. Additionally, both projects document design solutions descriptions and store them in accessible sources, and both appear to recognize the value of this practice. Both projects document design decisions but only Project A documents all the rationales of the design decisions. It comes across that team members in Project A, share a mutual realization of the impacts of (not)documenting the rationales of design decisions. On the other hand, only some of the rationales of the design decisions in Project B are documented, although it also comes across that Project B understands the importance of justifying why a decision is integrated into the design. This could be attributed to the fact that using the Relatics database has been active only at the end of the project; linking the design decisions with the requirements started recently using the Design Decisions module in the Relatics database.

Both projects evaluate alternative design solutions carefully using a multi-criteria analysis and then choose one design solution with consideration of the defined requirements. Both projects appear to acknowledge the importance of these patterns. Regarding the processes of verifying designs with the defined requirements, Project A performs them in ongoing and iterative manners with V&V plans including specific roles and responsibilities developed. It comes across that team members in Project A are convinced that these processes should be performed in this structured manner in order to deliver designs in compliance with the defined requirements. On the other hand, there is no explicit proof in Project B for performing these processes in ongoing and iterative manners, and the team started recording them recently. This is why no result could be given regarding the ongoing and iterative processes of verifying the designs with the defined requirements. There exist pre-developed plans describing the processes, and responsibilities are being assigned to specialists now, so they are considered quasi-disciplined. The reason mentioned for this is the lack of integrated files to refer to when performing this verification, which was because of the lack of experience and lack of advice from the previous systems engineer who was involved in the project. This was the justification mentioned by the technical manager of Project B. Noteworthy to mention is that both systems engineers of the project could not give a clear evaluation of several characteristics regarding the patterns of developing designs in Project B because they both have been involved as systems engineers only at the end of the project.

7. Discussions and recommendations

The purpose of this research has been to assess the performance of Projects A and B in developing requirements and designs to be in compliance with each other, to make recommendations to improve current practices in the concept design phase of road infrastructure projects at Witteveen+Bos. Having analyzed the pattern matching results cross projects, the comparisons reveal several findings that are seen as crucial for discussion. A starting point for discussion is concerned with the problem defined in the research; *when the verification process is performed during the concept design phase of road infrastructure projects at Witteveen+Bos, it appears that designs sometimes do not meet the defined requirements. This leads to taking repair measures near the end of the design phase to make the designs fit the defined requirements, and results in stress among teams due to time and budget constraints before the deadlines.*

The research problem has been evaluated and it appears that indeed, for both projects there were moments during the verification process when the teams faced their designs with the defined requirements, they realized they were not in compliance with each other. Both projects justified this incompliance with several reasons, of which some could be described as inevitable or hard-to-control reasons. Such reasons in Project A cover, among others, the late arrival of stakeholders' requirements in the process and/or the inadequate SMART formulation of those requirements. Digital communication between team members rather than face-to-face communication, and multidisciplinary design leaders having different points of view and different ways of approaching design-related matters are other reasons mentioned for the incompliance. Project B justified the possible incompliance by working with the third party responsible for the landscape design and the different approaches followed, but not because of Witteveen+Bos' practices.

However, the projects appear to have managed these challenges somehow and made the necessary adjustments on the developed products in time so that they satisfy the defined requirements before a baseline delivery to the client. Both projects considered their designs to be in compliance with the defined requirements but only Project A was able to estimate in each design loop, the percentage of (in)compliance between the designs and requirements. Project A did not only explain why and how the designs are to a high percentage in compliance with the defined requirements, but also was able to provide evidence supporting such statements. Project B, on the other hand, could not support its statement because no explicit proof of the verification has been found yet. Project B could not provide evidence of documentation with verification reports or lists to clearly prove that the designs developed in the project are in compliance with the defined requirements. This came as a surprising finding of this research and led to reaching multiple arguments.

On the one hand, the lack of concrete evidence resulted in an incomplete evaluation of current practices in Project B. However, the incomplete evaluation of current practices in Project B does not necessarily mean that the observed patterns are mismatching the expected ones. It can be the case that, regarding the processes of verifying the developed designs with the defined requirements, the patterns are quasi-matching or even matching the expected patterns. It can be that the processes have been indeed ongoing and iterative, which maybe can be found with further research and document analysis. However, project documents and databases could not be analyzed for more details during this research because they are provided in Dutch, and the researcher lacks the needed understanding of this language. Therefore, the accurate and complete assessment of the problem statement defined in this research is currently not possible due to the lack of evidence in one of the projects. Therefore, the preliminary evaluation of the performance of each project that could be made based on team members' observations and personal interpretations within Witteveen+Bos could not be accurately proven. The findings of this research could not demonstrate if indeed one of the projects; Project A, is a success project developing designs in compliance with the defined requirements throughout the concept design phase, while the other project; Project B, is not.

On the other hand, the fact that Project B could not provide concrete evidence of performing the verification processes can be perceived in itself as an indicator of insufficient performance of structured processes. This indicator does not necessarily reflect an entirely negative judgment on the performance of Project B but it gives an impression that Project B has not followed very structured processes. This is important because structured and organized processes are presented as an essential element for ensuring that requirements and designs are developed in compliance with each other. This is explicitly according to the framework of best practices, which is developed in this research based on the existing literature, and presented in Chapter 3 above. Therefore, even though Project B could not be accurately assessed to not have developed designs in compliance with the defined requirements, its performance can be seen as less sufficient in terms of ensuring and proving the required compliance with structured processes.

With this in the background, the analysis of the pattern matching results cross projects, which is presented in Chapter 6 and Appendix C, revealed specific differences and commonalities in current practices of both projects, which could indicate a need for several improvements. In comparison to Project A, the lack of evidence along with the inability of several team members to evaluate certain characteristics of current practices of Project B are considered critical matters and can be attributed back to certain practices. These certain practices are seen as reasons for the pattern matching results and are related to the three main elements of people, products and processes for developing designs in compliance with the defined requirements throughout a design level of detail. The following sections will provide more explanations about these certain practices along with recommendations for future improvements supported by existing literature.

7.1 People improvement – involve SE expertise from the beginning

Carrying out projects within the context of the Systems Engineering methodology means that certain principles need to be implemented so that requirements and designs can be developed in compliance with each other. Among these principles are the efficient development and management of the system specification documents with linked requirements, functions, objects, and design choices from the beginning of the project. Multi-disciplinary teams are seen as an important element for implementing such principles and performing the expected patterns. However, it appears from the pattern matching analysis cross projects that other matters should be taken into consideration with this regard.

Even though both Projects A and B matched the expected patterns and involved multi-disciplinary teams in performing tasks related to the development of requirements and designs to be in compliance with each other, differences within current practices cross projects can be noticed. For example, from the beginning of the project, Project A involved an experienced Systems Engineering advisor to help the system specification team with building the functions tree and defining the objects of the project, based on his experience in other projects.

On the other hand, Project B assigned two team members relatively near the end of the project to perform such tasks after the previous systems engineer who was involved in the project had left. However, both team members were not very experienced with SE principles and practices before being involved in the project. It was also mentioned that the previous systems engineer who left the project lacked the needed experience and advice for efficiently performing such tasks. This was mentioned as a reason for the absence of integrated requirements and designs information and a well-maintained database, which apparently affected the verification processes within the project.

Involving experienced systems engineers from the beginning of the projects and in an ongoing manner is one difference between projects, and is considered an essential matter. This could facilitate managing the information of requirements and designs throughout a design level and could enhance their developments. Safeguarding SE expertise and involving team members experienced with SE in projects are mentioned in the literature to have a positive impact on the implementation of SE principles, by incorporating and sharing their enriching experiences with other team members [5]. The literature also mentions that teams should have an enabling structure where team members have a moderately stable membership and good communication to enable efficient teamwork [7].

7.2 Products improvement – enhance required SE knowledge and skills from the beginning

Analyzing the characteristics of the developed requirements and designs shows that there is a distinctive variation between practices within both Projects A and B. Specifically, with relation to guaranteeing traceable requirements and documentation of the rationales of the design decisions, it appears that Project B could not fully match the expected patterns. Among several reasons behind this way of performance, it was mentioned that the active use of the Relatics database starting only at the end of the project could be a sound reason.

In comparison to Project A, where all the information has been inserted in the Relatics database and linked with preserved traceability, Project B started relatively late with fully utilizing the GRIP application and maintaining the database. This could be justified by two main reasons; the lack of experience and advice from the previous systems engineer who was involved in the project, and the environmental manager's personal preference who is responsible for the stakeholders' requirements. Both of these reasons could be attributed back to the lack of knowledge and skills regarding the implementation of SE principles because differences in the knowledge and skills between the team members of both projects could be noticed.

For example, the environmental manager of Project B did not have any experience with using the GRIP application before the project, but he had several meetings with specialists from Witteveen+Bos and the client to learn the basics. Before the environmental manager started working on the project, he attended multiple courses about the basic principles of Systems Engineering to learn about it in general and to know what to focus on. However, in comparison to the situation in Project A, it is noticed that team members are more familiar with the Relatics database and take responsibility to manage the accompanying tasks. It should be mentioned that not all team members in Project A find the application easily manageable but they all arrange the needed effort and help so to perform the tasks required from them. This willingness could be explained with their knowledge about the SE methodology and principles. For Project B, it is considered that if the environmental manager and the previous systems engineer who was involved in the project had the required SE knowledge and skills, the information about the requirements and designs could be inserted and linked in the database earlier in the project. This would have probably saved the time and effort being consumed now by the new systems engineers to prepare the final documents and maintain the database before the final delivery to the client.

Therefore, enhancing the required SE knowledge and skills from the beginning of the projects is seen as an enabling factor that can facilitate developing requirements and designs to be in compliance with each other throughout a design level. The literature also supports this by suggesting hiring SE experts for training purposes, implementing rewarding principles, using concrete and practical SE examples along with systematic guides. All of these can enhance and aid the learning and understanding goals among the multi-disciplinary teams, leading to improved SE knowledge and skills [3; 5; 6; 20].

7.3 Processes improvement – ensure strict SE planning and commitment from the beginning

With relation to the processes followed when developing requirements and designs in the analyzed projects, preparing project plans with specific and clear roles and responsibilities is seen as a very important matter. This is regarded as a significant enabler for smoothly managing and verifying the defined requirements and developed designs. For example, it was obvious in the observed practices of Project A that strict planning and commitment from the technical manager and the discipline leaders facilitated the structured way of working. Project plans with verification plans along with examples on how, when and by whom verifying a requirement would be done were developed from the beginning of the project. These were provided with the document where the results of verification would be inserted once executed at the already planned gate points. On the other hand, strict planning in Project B appears to be missing with regards to arranging which specific processes should be performed and when to perform them. This could be a reason for the lack of evidence of performing the verification processes throughout a design level of detail. For example, it was mentioned that there was no gate date specified for performing formal internal integral verification and decision-making processes. However, it is perceived that if there were strict plans with specific dates and clear roles and responsibilities for the verification activities and their documentation, there would probably be evidence of performing those activities accompanied with their outcomes. Those could be used in later stages for many purposes such as facilitating decision-making processes. The technical manager of Project B supports this when stating: "*I think that is one of the issues to make a decision because there was not a smart gate point.*"

Therefore, ensuring strict SE planning and commitment from the beginning of the projects is seen as an enabling factor, to successfully perform processes of developing designs in compliance with the defined requirements throughout a design level of detail. Existing literature supports this and mentions how structured verification and validation plans should be developed and followed from the beginning of the project [1; 5; 6; 13]. It is mentioned to be necessary that the verification process flows through the system hierarchy in a disciplined manner [22].

Summarized, this chapter has provided several discussion points regarding the current practices performed within both Projects A and B. The preliminary evaluation of the performance of each project that could be made based on team members' observations and personal interpretations within Witteveen+Bos could not be accurately proven. The findings of this research could not demonstrate if indeed one of the projects; Project A, is a success project developing designs in compliance with the defined requirements throughout the concept design phase, while the other project; Project B, is not. However, even though Project B could not be accurately assessed to not have developed designs in compliance with the defined requirements, its performance can be seen as less sufficient in terms of ensuring and proving the required compliance with structured processes. This is because, in comparison to Project A, there exist lack of evidence and inability of several team members to evaluate certain characteristics of current practices within Project B. These are considered critical matters and are attributed back to certain practices. One of these practices is assigning two team members relatively near the end of the project to perform tasks related to providing integrated requirements and designs information and a well-maintained database. Another practice in Project B is related to the team members' possible lack of knowledge and skills regarding the implementation of SE principles. In addition, strict planning in Project B appears to be missing with regards to arranging which specific processes should be performed and when to perform them. These practices are seen as reasons for the pattern matching results and are related to the three main elements of people, products and processes for developing designs in compliance with the defined requirements, throughout a design level of detail.

With this in the background, and on the basis of the elaborated analysis and discussions, recommendations for improving current practices specifically at Witteveen+Bos are developed. The findings of this research provide a recommendation for Witteveen+Bos to involve experienced systems engineers from the beginning of the projects and in an ongoing manner. This could facilitate managing the information of requirements and designs throughout a design level and could enhance their developments. The findings also indicate that Witteveen+Bos should pay specific attention to the SE knowledge and skills required from team members when carrying out projects within the context of the SE methodology. Moreover, Witteveen+Bos should ensure strict SE planning and commitment from the beginning of the projects, especially in relation to preparing verification plans answering the how, when and by whom questions along with clear planning of the documenting process of the results. Implementing these recommendations could facilitate developing designs in compliance with the defined requirements throughout a design level of detail.

8. Limitations

This research encounters several limitations, which are in need of mentioning. The first limitation concerns the framework of best practices, for developing designs to be in compliance with the defined requirements, based on the literature. The framework focused on three elements covering the people, products, and processes but did not explicitly cover other elements that could be related to the development of requirements and designs. Such elements could be techniques, services, facilities or other support elements. Additionally, it is possible that not all the characteristics related to the defined elements are included in the used framework. For example, the framework does not mention validation processes or describe specific profiles for team members involved in requirements and designs developments. Future research with broader scope that can cover other elements and characteristics is advised to improve the developed framework and enhance the results.

A second limitation is regarding the generalization of the findings of this research. Civil Engineering projects other than those of a road infrastructure specification and the concept design phase of the project life cycle need to be studied and analyzed to generalize the findings. Additionally, the fact that in both studied projects the final deliverables of the concept design phase have not been delivered to the client yet is a restriction to reaching a final conclusion whether the problem statement defined in this research could be supported with evidence or not. This is in addition to the lack of evidence in one project along with the fact that project documents and databases could not be analyzed for more details during this research because they are provided in Dutch, and the researcher lacks the needed understanding of this language. These all are significant limitations that future research should take into consideration.

This brings another limiting point, which is related to the criteria for choosing the case studies to include a preliminary evaluation of the performance of each project being based on team members' observations and personal interpretations. Based on the impression within Witteveen+Bos, one of the projects was perceived as a success project developing designs in compliance with the defined requirements during the concept design phase, while the other project was supposedly not. However, since this statement was not fully supported with evidence in the findings of this research, the evaluation and selection of projects at the beginning of this research were not well-founded because they were not fully based on sharp selection criteria. This should be taken into account in future research to enable a complete assessment of the research problem statement.

A fourth limitation is linking the research only to the effect of current practices on the compliance between the defined requirements and the developed designs but not on other outcomes of projects. Examples of such missing linkages could be the relation between the current practices for developing requirements and designs and the time and budget needed for their deliveries. These relations along with the stress levels faced among team members until the final delivery of products could support or deny the findings of this research and are recommended for future research.

A fifth limitation is related to the qualitative data collected and analyzed, which is prone to different interpretations. This is because most of the data collected are based on personal statements and perceptions provided by team members who are still working on the projects, which could possibly be subjective to their practices. This means that many of the provided information could be debatable. Further research with quantitative data, such as the compliance between the defined requirements and the developed designs provided in percentages could support the findings of this research. This is specifically mentioned because none of the interviewees is a native English speaker and a possibility exists that they could have been able to express themselves better in their Dutch mother tongue. This applies to the researcher conducting the research as well, with the difficulty of translating Dutch documents and records of current practices to English in short periods.

A final limitation concerns the fact that this research is restricted to a duration of six months as a master thesis research to acquire the degree of Master of Science. Time restriction is a considerable limitation in relation to the data collection results, which could be expanded with more research to cover more aspects and insights from both theory and practice. Time limitation was also the reason for not being able to conduct a neutral validation session, with specialists not involved in the projects, to support or deny the findings in other projects. This session could add value to the findings of this research had it been conducted as it was previously planned. Further research with a broader scope and more time is needed to be able to cover the described limitations.

9. Conclusions

This research is conducted with two main objectives of which the first has been to provide a framework of best practices based on the literature, for ensuring that designs are developed in compliance with the defined requirements throughout a design level of detail. The other objective has been to make recommendations to improve current practices in the concept design phase of road infrastructure projects at Witteveen+Bos. A literature review has been conducted to develop the framework of best practices, which has been applied to current practices in two case studies implementing Systems Engineering processes in the concept design phase of the project life cycle. Based on the employees' impression within Witteveen+Bos, one of the projects was perceived as a success project developing designs in compliance with the defined requirements throughout the concept design phase, while the other project was supposedly not.

The performance of both projects in developing requirements and designs to be in compliance with each other has been assessed. It appeared that for both projects there were moments during the verification process when the teams faced their designs with the defined requirements, they realized they were not in compliance with each other. Pattern matching analysis has been used to analyze current practices and the results indicate that one project has been performing better than the other project, in terms of matching the expected patterns. However, the findings of this research could not demonstrate if indeed one of the projects is a success project with regard to developing designs in compliance with the defined requirements throughout the concept design phase, while the other project is not. This is primarily due to the lack of evidence in one of the projects, which came as a surprising finding of this research and resulted in an incomplete evaluation of current practices across projects.

Even though the incomplete evaluation of current practices in one project does not mean that its observed patterns are mismatching the expected ones, the lack of evidence in the project has been perceived in itself as an indicator of insufficient performance of structured processes. On the basis of the analysis and discussions, recommendations for improving current practices at Witteveen+Bos have been developed and supported by existing literature. Among the recommendations provided is to involve experienced systems engineers from the beginning of the projects and in an ongoing manner. Another recommendation is to pay specific attention to the SE knowledge and skills required from team members when carrying out projects within the context of the SE methodology. A final recommendation is to ensure strict SE planning and commitment from the beginning of the projects, especially in relation to preparing verification plans answering the how, when and by whom questions along with clear planning of the documenting process of the results.

In conclusion, there exist different ways that can be followed to get to the final delivery of projects but the question remains about the most efficient one. It appears from this research that both projects have their own approaches for developing designs satisfying the client's and stakeholder's requirements. Both projects appear to have managed existing challenges and have developed their products satisfying enough to the client to pass the previous design loops and reach their current stage of the design phase. However, implications of the difference between the followed approaches could be more apparent when investigating the repair measures taken and the stress levels experienced until achieving the final delivery before the deadlines. The difference between the approaches of the projects could be one of the reasons for longer and more stressful procedures.

It can be concluded from this research that when following SE activities and applying its principles more strictly in a project, while safeguarding that the people with the right skills and expertise are in the right positions throughout the process, there is a likelihood that the compliance between requirements and designs can increase. The findings of the case studies provide reasons to believe that strictly following SE principles can enhance performing iterative verifications of requirements and designs with traceable evidence to prove their required compliance throughout a design process. This would assumingly lead to carrying out the processes more smoothly and less stressfully with less need for repair measures throughout a design phase of projects. Efficient performance of projects would thus be facilitated taking into consideration that evaluating the performance of a project does not only depend on the compliance degree between the final delivered requirements and designs, but it also covers, among others, the time and budget aspects as well as team members' well-being conditions.

References

[1] Haskins, C., Forsberg, K., Krueger, M., Walden, D., & Hamelin, D. (2006). *Systems engineering handbook.* Paper presented at the INCOSE.

[2] Group, I. I. W. (2012). Guide for the Application of Systems Engineering in Large Infrastructure Projects. *San Diego, US-CA: INCOSE*.

[3] Farnham, R., Aslaksen, E. W., & Merz, S. K. (2009). *Applying systems engineering to infrastructure projects.* Paper presented at the INCOSE Spring Conference, Nottingham, UK.

[4] Blockley, D. (2013). Do civil engineering systems need systematising? Tackling complexity–top 10 issues for civil engineering systems. *Civil Engineering and Environmental Systems, 30*(3-4), 199-210.

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

[6] De Graaf, R., Vromen, R., & Boes, J. (2017). Applying systems engineering in the civil engineering industry: an analysis of systems engineering projects of a Dutch water board. *Civil Engineering and Environmental Systems, 34*(2), 144-161.

[7] de Graaf, R. S., & Loonen, M. L. (2018). Exploring Team Effectiveness in Systems Engineering Construction Projects: Explanations Why Some SE Teams Are More Effective than Others. *Systems Research and Behavioral Science, 35*(6), 687-702.

[8] Elliott, B., O'Neil, A., Roberts, C., Schmid, F., & Shannon, I. (2012). Overcoming barriers to transferring systems engineering practices into the rail sector. *Systems engineering, 15*(2), 203-212.

[9] Locatelli, G., Mancini, M., & Romano, E. (2014). Systems engineering to improve the governance in complex project environments. *International Journal of Project Management, 32*(8), 1395-1410.

[10] Makkinga, R., de Graaf, R., & Voordijk, H. (2018). Successful verification of subcontracted work in the construction industry. *Systems engineering, 21*(2), 131-140.

[11] Prorail, R. (2008). Bouwend-Nederland, and Onri. *Guideline Systems Engineering for Public Works and Water Management*.

[12] Schreinemakers, P. (2015). *An application of System Architecture in the Rail and Road Infrastructure.* Paper presented at the INCOSE International Symposium.

[13] Van den Houdt, S. (2013). Identifying and Managing the Success Factors behind the implementation of Systems Engineering.

[14] Kim, T. W., Kim, Y., Cha, S. H., & Fischer, M. (2015). Automated updating of space design requirements connecting user activities and space types. *Automation in construction, 50*, 102-110.

[15] Kiviniemi, A., & Fischer, M. (2004). Requirements management interface to building product models.

[16] Larsen, R. F., & Buede, D. M. (2002). Theoretical framework for the continuous early validation (CEaVa) method. *Systems engineering, 5*(3), 223-241.

[17] Efatmaneshnik, M., & Reidsema, C. (2010). A complex system engineering design model. *Cybernetics and Systems: An International Journal, 41*(8), 554-576.

[18] Gräßler, I., & Hentze, J. (2018). Application Potentials of Systems Engineering for Small and Middle-sized Enterprises. *Procedia CIRP, 67*, 510-515.

[19] Sheard, S. A. (1996). *Twelve systems engineering roles.* Paper presented at the INCOSE International Symposium.

[20] Sheard, S. A., Lykins, H., & Armstrong, J. R. (2000). Overcoming barriers to systems engineering process improvement. *Systems engineering, 3*(2), 59-67.

[21] Terry Bahill, A., & Henderson, S. J. (2005). Requirements development, verification, and validation exhibited in famous failures. *Systems engineering, 8*(1), 1-14.

[22] Marchant, A. B. (2010). Obstacles to the flow of requirements verification. *Systems engineering, 13*(1), 1-13.

[23] Sparrius, A. (2014). *The Life Cycle of a Requirement.* Paper presented at the INCOSE International Symposium.

[24] Malsane, S., Matthews, J., Lockley, S., Love, P. E., & Greenwood, D. (2015). Development of an object model for automated compliance checking. *Automation in construction, 49*, 51-58.

[25] Ozkaya, I., & Akin, Ö. (2007). Tool support for computer-aided requirement traceability in architectural design: The case of DesignTrack. *Automation in construction, 16*(5), 674-684.

[26] Kauppinen, M., Vartiainen, M., Kontio, J., Kujala, S., & Sulonen, R. (2004). Implementing requirements engineering processes throughout organizations: success factors and challenges. *Information and Software Technology, 46*(14), 937-953.

[27] Carlshamre, P., & Regnell, B. (2000). *Requirements lifecycle management and release planning in market-driven requirements engineering processes.* Paper presented at the Proceedings 11th International Workshop on Database and Expert Systems Applications.

[28] Nuseibeh, B., & Easterbrook, S. (2000). *Requirements engineering: a roadmap.* Paper presented at the Proceedings of the Conference on the Future of Software Engineering.

[29] Sommerville, I. (2005). Integrated requirements engineering: A tutorial. *IEEE software, 22*(1), 16-23.

[30] Winkler, S., & von Pilgrim, J. (2010). A survey of traceability in requirements engineering and model-driven development. *Software & Systems Modeling, 9*(4), 529-565.

[31] Tvete, B. (1999). *Introducing efficient requirements management.* Paper presented at the Proceedings. Tenth International Workshop on Database and Expert Systems Applications. DEXA 99.

[32] Ozkaya, I., & Akin, Ö. (2005). Use of requirement traceability in collaborative design environments. *CoDesign, 1*(3), 155-167.

[33] Capilla, R., Nava, F., & Duenas, J. C. (2007). *Modeling and documenting the evolution of architectural design decisions.* Paper presented at the Proceedings of the Second Workshop on SHAring and Reusing architectural Knowledge Architecture, Rationale, and Design Intent.

[34] Bhat, M., Shumaiev, K., & Matthes, F. (2017). *Towards a framework for managing architectural design decisions.* Paper presented at the Proceedings of the 11th European Conference on Software Architecture: Companion Proceedings.

[35] Chen, L., & Luo, H. (2014). A BIM-based construction quality management model and its applications. *Automation in construction, 46*, 64-73.

[36] Shen, W., Hao, Q., Mak, H., Neelamkavil, J., Xie, H., Dickinson, J., . . . Xue, H. (2010). Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review. *Advanced engineering informatics, 24*(2), 196-207.

[37] Eynon, J. (2016). *Construction manager's BIM handbook*: John Wiley & Sons.

[38] Ramos, A. L., Ferreira, J. V., & Barceló, J. (2011). Model-based systems engineering: An emerging approach for modern systems. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), 42*(1), 101-111.

[39] INCOSE, T. (2007). Systems engineering vision 2020. *INCOSE, San Diego, CA, accessed Jan, 26*, 2019.

[40] Hause, M., Buitelaar, J., van de Ven, M., & Burgers, E. (2015). *The Use of MBSE in Infrastructure Projects--An MBSE Challenge Team Paper.* Paper presented at the INCOSE International Symposium.

[41] Lundkvist, R., Meiling, J. H., & Sandberg, M. (2014). A proactive plan-do-check-act approach to defect management based on a Swedish construction project. *Construction Management and Economics*, *32*(11), 1051-1065.

[42] Verschuren, P., Doorewaard, H., & Mellion, M. (2010). *Designing a research project* (Vol. 2): Eleven International Publishing The Hague.

[43] Yin, R. K. (1994). Case study research, applied social research methods series. *Publications S, ed. Beverly Hills*.

[44] Bougie, R., Sekaran, U., Riemer, F. J., Kostelis, K. T., Quartaroli, M. T., Niku, S. B., . . . Matthews, T. D. (2017). *Research Methodology & Academic Skills*: John Wiley & Sons.

[45] Hak, T., & Dul, J. (2009). Pattern matching.

Appendix A. Tables of pattern matching results within Project A

Table A1. Pattern matching results of requirements development within Project A

Main element	Sub-element	Expected pattern	Observed pattern	Status of matching	Explanation
Requirements Development	People	There should be multi-disciplinary teams responsible for: • Eliciting client's and stakeholders' requirements • Analyzing client's, stakeholders' and derived requirements (including design constraints) for clarity, completeness, and consistency • Documenting client's, stakeholders' and derived requirements • Communicating client's, stakeholders' and derived requirements among the different stakeholders and team members • Evolving requirements in response to stakeholders' needs and/or design processes (e.g. Requirements Engineer role, Requirements Owner role)	There are multi-disciplinary teams responsible for • Eliciting client's and stakeholders' requirements • Analyzing client's, stakeholders' and derived requirements • Documenting client's, stakeholders' and derived requirements • Communicating client's, stakeholders' and derived requirements among the different stakeholders and team members • Evolving requirements in response to stakeholders' needs and/or design processes	+	There exists evidence of team members from different disciplines involved in performing all of these tasks. Additional to prepared project plans, for example: • Minutes of stakeholders' meetings show how the stakeholder participation team and design discipline leaders are part of eliciting stakeholders' requirements. • Stakeholders' requirements are also collected using the participation platform, which is accessed by all disciplines. • Design reports show the different designers eliciting the client's requirements from the guidelines. • Design reports prove how designers from different disciplines are involved in analyzing requirements. This can also be shown utilizing a specific option to view the history of a requirement in the Relatics Database. • The Relatics database and design reports along with the emails exchanged between the stakeholder participation team and the system specification team with the discipline leaders are evidence proving the different disciplines involved in documenting, communicating and evolving requirements.
	Products	The defined requirements should be based on the wishes, requests, and anticipations of the clients and stakeholders	The defined requirements are based on the wishes, requests, and anticipations of the clients and stakeholders	+	• Regarding the client's requirements: the Relatics database includes source documents showing from where the wishes are extracted. It is also proven in the design reports, where the client's guidelines are referenced. • Regarding the stakeholders' requirements: this is evident in the Relatics database where every requirement included in the SYS goes back to the requirement verified and accepted by the client. It can also be proven in the documents of the stakeholder design validation sessions along with the minutes and emails of the defined requirements during the sessions. The participation platform is another evidence, where the public's reactions are translated into new entries in the Relatics database.
		The defined requirements should be SMART (i.e. Specific, Measurable,	Some of the defined requirements are SMART but not all of them	0	In general, the requirements entered in the system requirements are as SMART as they can be; keeping in mind that it is very hard to make innovation ambitions SMART. It is mentioned

	Acceptable, Realistic and Time-bound)			to be hard to make requirements related to some disciplines SMART; aesthetics related requirements. The history of a requirement in the Relatics database proves the endeavors to make a requirement SMART. Client's requirements are mostly SMART because they are design regulations and they are confirmed. Stakeholders' requirements are not necessarily SMART because they are from the stakeholders who are not professionals with making requirements SMART. Even though it is a time-consuming task, there exists evidence of emails with discussions about requirements to make them SMART. This is another reason why not all requirements are SMART. Also minutes of meetings proving the evolvement of a wish to a SMART formulation. Another evidence is the traceable sticky notes in the digital participation platform. It is also stated that not all the letters in SMART can be met, especially with the high requirements in the system breakdown structure covering many requirements below; those are generally not that SMART, they are more general. This is because not all requirements can be time-bound or measurable; some can only be made measurable by making the lower requirements related to them measurable.
	The defined requirements should be documented	The defined requirements are documented	+	Explicit evidence for this is the Relatics database, where the requirements are documented per baseline. The digital participation platform, minutes of meetings and design reports are other proofs.
	The updated requirements should be documented	The updated requirements are documented	+	Explicit evidence for this is the Relatics database, where the changed requirements between baselines are documented again with changes. This can be seen easily when browsing the history of a requirement showing its lifecycle. Design reports are other proofs.
	The defined and updated requirements should be traceable (e.g. using a numbering system, Verification Requirements Traceability Matrix (VRTM))	The defined and updated requirements are traceable	+	The Relatics database with a verification matrix shows that all the defined requirements in the system have numbers and codes related to functions, objects and system elements. Every requirement in the SYS is related to the KES with a number and it should be traced back to the source of its origin; from which part of the KES it came. Another evidence is minutes of meetings with a date and a theme; wishes discussed.
	The defined requirements information should be stored in accessible sources (e.g. Relatics)	The defined requirements information are stored in an accessible network	+	Explicit evidence is the Relatics database, which is accessible to all team members involved in the project from the firm and from the client. It is mentioned that Relatics is generally applied by other companies and clients with the biggest benefit that it is an adaptable program that can be adjusted to add extra fields, extra relations, etc. For the stakeholders' accessibility, the digital participation platform could be seen as a network (managed by Witteveen+Bos under the client's name) where people could react and give requirements (with status of the requirements that are met already in the design or not yet, and with reasons behind those (un)meetings).
Processes	Managing and verifying requirements should be ongoing (not restricted to one moment in time)	Managing and verifying requirements have been ongoing informally during the design loops but formally at the gate	0	There were several moments in time where the team members got communicated and updated about the requirements (not only one moment), proving it was somewhat ongoing. However, they have been formally done at the gate. The justification for this is that planning and milestones would not be met due to the time consumed in the ongoing processes; too time-consuming and costly. Additionally, it is seen that the quality of the different products would not be the same because of changes on requirements that are done individually (not integral design anymore). This is why the verification would be at the gate where everybody can know the issues and which ones to be solved so that at the end all teams enter the baseline together.

					A discipline leader mentioned that the efficiency of the frequency of managing and verifying requirements dropped in at least the 3rd design loop in comparison to the other loops; they could have been done better in the 1st and 3rd design loops
		Managing and verifying requirements should be iterative (whenever changes in requirements/designs occurred)	Managing and verifying requirements have been iterative but not whenever changes in requirements/designs occurred	0	Managing and verifying requirements have been iterative during each baseline; at the gate, there are the new system requirements with functions and objects verified but no changes happen to previous baselines. This can be shown in the minutes of the gate meetings and design reports. Additionally, the Relatics database with the changes made on requirements so they are accepted (same function but a different requirement is entered). It can be seen that there is no concrete evidence for this but with the most important requirements, there has been a new requirement with the same text at each baseline to verify it and check whether it was still applicable or needed checking back for what had changed. A discipline leader mentioned that the processes have been iterative but not the same way in all the design loops; it could have been improved in certain design loops or moments during the project.
		Managing and verifying requirements should be disciplined processes (e.g. V&V plans with specific and clear roles and responsibilities)	Managing and verifying requirements have been disciplined processes	+	There have been specific and clear roles and responsibilities for managing and verifying requirements provided in the project plans and the Relatics database. There exist project plans with verification plans uploaded in the Relatics database with examples on how, when and by whom verifying a requirement would be done. These are also with the document where the results of verification would be inserted and explanations on the use of the Relatics database; a plan of how verification would be done using the Relatics database.

Table A2. Pattern matching results of designs development within Project A

Main element	**Sub-element**	**Expected pattern**	**Observed pattern**	**Status of matching**	**Explanation**
Designs Development	People	There should be multi-disciplinary teams to: Search for, define and analyze design solutions satisfying the defined client's and stakeholders' requirements (e.g. Integrated Product Teams, System Designer role, System Analyst role, Coordinator role)	There are multi-disciplinary team members to search for, define and analyze design solutions satisfying the defined client's and stakeholders' requirements	+	There exists evidence of team members from different disciplines involved in performing all of these tasks. Prepared project plans with the structure of the design team and traceable maps, which are verifiable with dates and fixed at certain moments. Integral design report, emails and meetings between the designers to fix problems and develop alternatives to discuss during the meetings with the discipline leaders are all considered proofs of this.
	Products	The design solutions should be developed based on the defined requirements and specifications	The design solutions are developed based on the defined requirements and specifications, provided they are the accepted ones	+	Explicit evidence is the Relatics database with the SYS. It is mentioned that when requirements would be excluded, the reasons for this would be stated and motivated. The integral design report and the geometrical design report to explain to which extent the design met the guidelines. The special report is a proof to show the client's reviewers how the designs meet the requirements.
		The design solutions descriptions should be documented	The design solutions descriptions are documented	+	Explicit evidence for this are the design reports on each baseline.
		The design solutions descriptions should be stored in accessible sources	The design solutions descriptions are stored in accessible sources	+	Explicit evidence for this is the Relatics database; which is accessible for all the team members involved in the project from the firm and client.

				Dated models in Civil3D, MX and other softwares accessible by the related disciplines, and the designs are converted to neutral formats. For example, Illustrator is used with APS formats, which can be opened in AutoCAD so that other disciplines can open and use the designs. The other disciplines put their designs in GIS. It is mentioned that the integral design report is in the Relatics database but it is of 100 pages or more with many other reports; finding the files can take a while.
	There should be documentation of design decisions	There is documentation of design decisions	+	Explicit evidence for this are the design reports on each baseline, where designers would write all the design decisions. There exists a tool in the Relatics database explicitly for inserting separately the important design decisions made (because it would be too much information otherwise). Additionally, minutes of formal meetings with the discipline leaders, stakeholder participation team's leader and sometimes with the client along with meetings with the Q-team are proofs for this.
	There should be documentation of the rationales of the design decisions	There is documentation of the rationales of the design decisions	+	Explicit evidence for this is the Relatics database with the integral design report and the design choices tool. For example, the design report of the landscape design is built in the why, how and what structure corresponding with the top-eis, system-eis, and component-eis.
Processes	Evaluating alternative design solutions should be performed carefully (e.g. using a multi-criteria analysis, a trade-off analysis)	Evaluating alternative design solutions has been performed carefully	+	Design reports include explanations that evaluating alternative design solutions has been performed using a multi-criteria analysis. However, it is mentioned that these have only been for the decisions that affect/influence other disciplines. The decisions that do not affect or influence other disciplines are made depending on experience and only the advice is written down.
	Choosing one design solution should be performed with consideration of the defined requirements	Choosing one design solution has been performed with consideration of the defined requirements	+	There exists a written document specifically about the design choice in the Relatics database linked to the requirements. Additionally, minutes of validation meetings with the client, where choosing a design solution is based on the defined requirements that are accepted by the client. The client chooses the final design solution. It is mentioned that not all alternatives meet all requirements and the trade-off matrices are made to analyze which is the preferred solution but it does not necessarily include all defined requirements, the matrices show which requirements are most important and which are not. Some requirements are wishes not all are really requirements.
	Verifying designs with the defined requirements should be ongoing (not restricted to one moment in time)	Verifying designs with the defined requirements has been ongoing but not always formalized	+	Verifying designs with the defined requirements has been an ongoing process but formally performed and recorded at the gates. However, there are minutes of a technical meeting between the discipline leaders every two weeks, where informal verifications with the defined requirements can be proven. This proves that the process has been happening more than only multiple times. There are also minutes of meetings between the discipline leaders and the stakeholder participation team's leader.
	Verifying designs with the defined requirements should be iterative (whenever changes in requirements/designs occurred)	Verifying designs with the defined requirements has been iterative	+	Explicit evidence for this is the Relatics database with the SYS with verifications and browsing history. Additionally, there is a list of requirements verified at every baseline again.
	Verifying designs with the defined requirements should be a disciplined process (e.g. V&V plans with specific and clear roles and responsibilities)	Verifying designs with the defined requirements has been a disciplined process	+	There have been specific and clear roles and responsibilities for verifying designs with the defined requirements provided in the project plans and the Relatics database. There exist project plans with verification and validation plans to be executed at the gates uploaded in the Relatics database. Additionally, there exist emails, at every gate or baseline, to remind team members who should do what, and when the tasks should be done.

Appendix B. Tables of pattern matching results within Project B

Table B1. Pattern matching results of requirements development within Project B

Main element	Sub-element	Expected pattern	Observed pattern	Status of matching	Explanation
Requirements Development	People	There should be multi-disciplinary teams responsible for: • Eliciting client's and stakeholders' requirements • Analyzing client's, stakeholders' and derived requirements (including design constraints) for clarity, completeness, and consistency • Documenting client's, stakeholders' and derived requirements • Communicating client's, stakeholders' and derived requirements among the different stakeholders and team members • Evolving requirements in response to stakeholders' needs and/or design processes (e.g. Requirements Engineer role, Requirements Owner role)	There are multi-disciplinary team members responsible for • Eliciting client's and stakeholders' requirements • Analyzing client's, stakeholders' and derived requirements • Documenting client's, stakeholders' and derived requirements • Communicating client's, stakeholders' and derived requirements among the different stakeholders and team members • Evolving requirements in response to stakeholders' needs and/or design processes	+	There exists evidence of team members from different disciplines involved in performing all of these tasks. Reports of meetings, emails and Excel sheets with a history of team members from different disciplines adjusting the requirements.
	Products	The defined requirements should be based on the wishes, requests, and anticipations of the clients and stakeholders	The defined requirements are based on the wishes, requests, and anticipations of the clients and stakeholders	+	• Regarding the client's requirements: reports of meetings with the client. Requirements stated in the offers and documents from the previous phases of the project are shared during meetings. • Regarding the stakeholders' requirements: reports of meetings with the stakeholders. The Relatics database with the uploaded batches of the stakeholders' requirements. Every requirement from the stakeholder is documented with the stakeholder's original demands for it, the SMART representation of it and a document link leading to the requirement within the system
		The defined requirements should be SMART (i.e. Specific, Measurable, Acceptable, Realistic and Time-bound)	Some of the defined requirements are SMART but not all of them	0	In general, the requirements entered in the system requirements are as SMART as they can be (not all requirements can be SMART at the same level of design detail. Some requirements cannot be SMART at the current design loop). However, There exist Excel sheets with discussions by specialists to make a requirement SMART.

				There are also Excel sheets with adjustments on un-SMART requirements to make them SMART by the environmental manager and his counterpart from the client. It is also mentioned that not all stakeholders are used to the system and know how to make their requirements SMART. It is mentioned that the client's requirements are not SMART yet since they are derived from guidelines. Regarding the stakeholders' requirements, the focus was on making the planning product. Now the process of making all requirements SMART is being performed.
	The defined requirements should be documented	The defined requirements are documented	+	For every baseline, there is an approved and controlled textual document that includes the already double-checked requirements signed by the project leader to deliver them to the client. These are five documents combining a collection of all the requirements. The Relatics database with the uploaded Excel batches of the stakeholders' requirements. The Excel sheets are for stakeholders' requirements and the starting-point documents are for client's requirements but these are not integrated. The lack of integrated files is because of a lack of experience and a lack of advice from the previous systems engineer who was involved in the project. The SYS is now being prepared almost at the end of the project.
	The updated requirements should be documented	The updated requirements are documented	+	The updated requirements are documented but it is mentioned that the history of updating a requirement cannot be found in the Excel sheets or design reports. The use of the Relatics database has been active only at the end of the project.
	The defined and updated requirements should be traceable (e.g. using a numbering system, Verification Requirements Traceability Matrix (VRTM))	Some of the defined requirements and updated are traceable but not all of them	0	Stakeholders' requirements are traceable with a numbering system but the client's requirements are documented in a different manner in the design reports without a numbering system. The Relatics database with the uploaded Excel batches of the stakeholders' requirements proves their traceability. However, not all the defined requirements are traceable with a numbering system.
	The defined requirements information should be stored in accessible sources (e.g. Relatics)	The defined requirements information are stored in an accessible network	+	Evidence for this are the Excel sheets and the design reports shared with team members. The Relatics database, with the uploaded Excel batches of the stakeholders' requirements, is accessible to all team members involved in the project from the firm. It is mentioned though that not all the designers access it because designers are only interested in what is important for their designs so they receive the conclusions from the design manager in Excel sheets.
Processes	Managing and verifying requirements should be ongoing (not restricted to one moment in time)	Managing and verifying requirements have not been ongoing	-	For the stakeholders' requirements, it is mentioned that there exist many versions of the function tree reflecting how it is in development all the time, which proves that the process is somewhat ongoing. However, this management and verification take place at the end of a design loop (like a gate) by the environmental manager and technical manager. It is also mentioned that other requirements are drafted at the end of the project and the design is checked every design loop by the road design guidelines. Noteworthy to mention is that both systems engineers of the project did not give a clear evaluation of this characteristic because they both have been involved as systems engineers only at the end of the project.
	Managing and verifying requirements should be iterative (whenever changes in requirements/designs occurred)	Managing and verifying requirements have not been iterative	-	Quoting the technical manager: "Not everybody is used and ready for true Systems Engineering already" It is mentioned that stakeholders' requests are checked every design loop and other requirements are drafted at the end of the project. Further is the road design checked every loop by the road design guidelines. Noteworthy to mention is that both systems engineers of the project did not give a clear evaluation of this characteristic because they both have been involved as systems engineers only at the end of the project.

					The environmental manager also did not know if managing and verifying requirements have been iterative. No specified reason was justified for this.
		Managing and verifying requirements should be disciplined processes (e.g. V&V plans with specific and clear roles and responsibilities)	Managing and verifying requirements have been disciplined processes	0	There exists the project plan that was developed at the beginning of the project including when and who the specialists are needed for verifying the requirements. Additionally, during the processes using Excel, responsibilities are assigned to specialists depending on the expertise needed. It is mentioned that there have been roles and responsibilities for managing and verifying requirements but they have been really active only recently. This, as the technical manager mentioned, is because the previous team member responsible for this did not perform it enough. Noteworthy to mention is that both systems engineers of the project did not give a clear evaluation of this characteristic because they both have been involved as systems engineers only at the end of the project.

Table B2. Pattern matching results of designs development within Project B

Main element	Sub-element	Expected pattern	Observed pattern	Status of matching	Explanation
Designs Development	People	There should be multi-disciplinary teams to: Search for, define and analyze design solutions satisfying the defined client's and stakeholders' requirements (e.g. Integrated Product Teams, System Designer role, System Analyst role, Coordinator role)	There are multi-disciplinary team members to search for, define and analyze design solutions satisfying the defined client's and stakeholders' requirements	+	There exists evidence of team members from different disciplines involved in performing all of these tasks. Additional to the project plan with an outline of the design team responsible for developing the designs, reports of team meetings, design reports and memos are considered proves for this. It is mentioned that team members involved in the designs are from different backgrounds and with different specialties.
	Products	The design solutions should be developed based on the defined requirements and specifications	The design solutions are developed based on the defined requirements and specifications	+	Evidence for this are the design reports with the requirements that have been used to make the choices. The project plan with the explained approach of the firm is also mentioned as a proof for this. It is also mentioned that the design solutions are developed based on the possible solutions within the related guidelines.
		The design solutions descriptions should be documented	The design solutions descriptions are documented	+	Explicit evidence for this are the design reports, advice reports, and Excel sheets. The design solutions are written in reports and memos for the different design decisions or design phases. The design solutions are presented in those documents with descriptions and figures.
		The design solutions descriptions should be stored in accessible sources	The design solutions descriptions are stored in accessible sources	+	Explicit evidence for this is the shared folder with the design reports, which is accessible for all team members involved in the project from the firm. AutoCAD and Civil3D are softwares used in the design process.
		There should be documentation of design decisions	There is documentation of design decisions	+	Explicit evidence for this are the Excel files, design reports, memos, and the Relatics database. Reports of meetings are also mentioned as proof for this.
		There should be documentation of the rationales of the design decisions	There is documentation of some of the rationales of the design decisions	0	Evidence for this are the Excel files and design reports. Explicit evidence is the Relatics database but the use of it has been active only at the end of the project. Linking the design decisions with the requirements started in February using the Design Decisions module in the Relatics database. Reports of meetings are also mentioned as proof for this.

Processes	Evaluating alternative design solutions should be performed carefully (e.g. using a multi-criteria analysis, a trade-off analysis)	Evaluating alternative design solutions has been performed carefully	+	There exist design reports, memos and Excel files, which include explanations that evaluating alternative design solutions has been performed using a multi-criteria analysis.
	Choosing one design solution should be performed with consideration of the defined requirements	Choosing one design solution has been performed with consideration of the defined requirements	+	There exist decisions notes of the client's decisions recorded.
	Verifying designs with the defined requirements should be ongoing (not restricted to one moment in time)	N/A	N/A	It is mentioned that the defined requirements are drafted based on the design at the end of the project and the stakeholder requirements are checked at the different phases/loops of the project. It is also mentioned that the road design is checked every loop by the road design guidelines. The processes are mentioned to be ongoing, iterative and disciplined. However, there is no explicit proof for performing these processes and the team started recording them recently. The reason for this, as the technical manager mentioned, is the lack of integrated files to refer to when performing this verification, which was because of a lack of experience and a lack of advice from the previous systems engineer who was involved in the project. There is no explicit proof for performing these processes but it is mentioned that it could be in the emails (for ongoing), project team meeting reports (for iterative), pre-developed plans describing the processes (for disciplined) but without assigned specific responsibilities because the environmental manager is assigning responsibilities to specialists now. Noteworthy to mention is that both systems engineers of the project did not give a clear evaluation of this characteristic because they both have been involved as systems engineers only at the end of the project.
	Verifying designs with the defined requirements should be iterative (whenever changes in requirements/designs occurred)	N/A	N/A	
	Verifying designs with the defined requirements should be a disciplined process (e.g. V&V plans with specific and clear roles and responsibilities)	Verifying designs with the defined requirements has not been explicitly a disciplined process	0	

Appendix C. Analysis of pattern matching results cross Projects A and B

Table C1. Analysis of pattern matching results of requirements development cross Projects A and B

Main element	Sub-element	Analysis of pattern matching results
Requirements Development	People	The pattern matching analysis indicates that both projects score matching patterns regarding the people responsible for eliciting, analyzing, documenting, communicating and evolving requirements. This score has been given because both projects prove to have team members from the different disciplines involved in performing all of these tasks. One basic reasoning mentioned for this is the fact that Witteveen+Bos is a multi-disciplinary company that does not take on monofunctional projects, which means that this way of working is embedded in the general practices of the company. Both projects appear to understand the importance of involving different disciplines for performing the defined tasks as they are related to the whole project. Both projects seem to acknowledge that, in such projects, a requirement from one discipline can affect more than one discipline. This can be seen as a reasonable justification for this practice. Therefore, since both projects are able to provide evidence of matching the expected pattern, the evaluation of this characteristic is a positive one.
	Products	• **The defined requirements should be based on the wishes, requests, and anticipations of the clients and stakeholders** Both projects are able to provide evidence that the defined requirements are based on the wishes, requests, and anticipations of the clients and stakeholders. It sounds only logical that the client takes the final decisions on which requirements are to be honored and decides on contradicting, hard to realize or out-of-budget wishes and requirements. Therefore, the observed pattern in both projects matches the expected pattern as they both appear to acknowledge the need to consider and satisfy the client's and stakeholders' desires when developing requirements and designs. Additionally, it came across that Project A took this behavior a step further by activating the digital Participation Platform to communicate with the client and stakeholders in a simple and easy way. • **The defined requirements should be SMART (i.e. Specific, Measurable, Acceptable, Realistic and Time-bound)** Regarding all the defined requirements being SMART, both projects received a quasi-matching result. This is because not all of the defined requirements in both projects are SMART. This is justified in both projects with several reasons as mentioned; some requirements cannot be as SMART in certain design loops or with relation to specific disciplines, and stakeholders are not professionals in making their requirements SMART. It was also mentioned that not all the letters in SMART can be met, especially with the high requirements in the system breakdown structure covering many requirements below; those are generally not that SMART, they are more general. This is because not all requirements can be time-bound or measurable; some can only be made measurable by making the lower requirements related to them measurable. Additionally, it was mentioned in Project A that it is time-consuming to contact back and forth with the stakeholders to make their requirements SMART. • **The defined and updated requirements should be documented** Both projects document the defined and updated requirements, which means that their observed patterns match the expected ones. Project A provides justifications for this practice by, among others, the need for traceability of changes, avoiding to miss or forget what has been (and needs to be) done, and the ability to motivate the already performed work. The technical manager of Project A mentioned that it can be an administrative burden but it is important not only for the client as an accountant but also for Witteveen+Bos. He mentioned that it is important to keep the requirements safeguarded in the future to justify their works by showing the documentation and changes. In other words, documentation is considered important to reserve proofs that the decisions taken have been the right ones providing answers to questions about why and where something was done and/or changed. Requirements documentation in Project A is mostly done utilizing the Relatics database. It appears that Project B shares similar ideas regarding the importance of documenting defined and updated requirements. Project B also documents defined and updated requirements but in a different manner; using Excel sheets for stakeholders' requirements and starting-point documents with design reports for the client's requirements. Even though there exists evidence of all requirements being documented, this approach appears to be problematic especially knowing that those documents are not integrated. One of the systems engineers responsible for developing the System Specification documents of Project B mentioned that the history of updating a requirement could not be found easily in the Excel sheets or design reports. He expressed that using the Relatics database actively only at the end of the project can be a reason for this. The lack of integrated files, as mentioned by the technical manager, is because of a lack of experience and a lack of advice from the previous systems engineer who was involved in the project. • **The defined and updated requirements should be traceable (e.g. using a numbering system, Verification Requirements Traceability Matrix (VRTM))** Regarding the traceability of requirements, Project A has a high score matching the expected pattern where all the defined requirements in the system have numbers and codes related to functions, objects and system elements. Among the justifications mentioned for this practice is to differentiate every requirement with a number, code, and date to avoid misunderstandings or miscommunications among team members about requirements in different design loops of the project. Another justification mentioned is to have an overview and control of everything in the system. The technical manager of the project supported these ideas stating that the reason for this traceability of requirements is the need to make every object and function unique, traceable and linkable to one another.

Project B on the other hand scores quasi-matching on this characteristic because not all of the defined requirements are traceable with a numbering system. Stakeholders' requirements are traceable with a numbering system but the client's requirements are documented in a different manner in the design reports, without a numbering system. Quoting the technical manager of Project B, when asked for the reason behind this practice: "It is just the way our product is built." He added: "I am not convinced it is really necessary, it can be …" One of the systems engineers responsible for developing the System Specification documents of Project B mentioned that using the Relatics database actively only at the end of the project can be a reason for this.

- **The defined requirements information should be stored in accessible sources (e.g. Relatics)**

Both projects store the defined requirements information in accessible sources, which matches the expected pattern and results in matching scores. In Project A, accessible sources are the Relatics database for the client and all team members from Witteveen+Bos, and the digital Participation Platform for the other stakeholders. Among the justifications mentioned for this practice are to minimize different understandings by looking at the same information and to provide traceability of why things changed over time. However, it was mentioned that not all disciplines utilized the Relatics database as actively as others did, or they provided the complete information about the requirements; their influence, days before the deadline. This resulted in making the influence on the designs too late to be managed. A possible reason mentioned for this is that Relatics is not easily manageable or accessible that some people do not want to use it; some team members are resistant and do not like to deal with texts. Reacting to the active use of Relatics instead of other softwares, the technical manager of Project A stated: "Excel is forbidden". This is, as he mentioned, because Excel is not a database and requirements cannot be managed in Excel; no history or changes can be found. He added that there is no definition of the data in Excel; for example, forgetting or changing requirements identification numbers, which could make all the linkages disappear. This is also supported by one of the design discipline leaders mentioning that Excel is not suitable and that Relatics is generally applied by other companies and clients with the biggest benefit that it is an adaptable program, which can be adjusted to add extra fields, extra relations, etc.

On the other hand, Project B stores the requirements information in a joint IT system with all team members from Witteveen+Bos, and uploads those documents in the GRIP; an application based on the Relatics database. The use of GRIP is mentioned to be a contract condition as a requirement from the client. However, the environmental manager responsible for the stakeholders' requirements does not insert the information related to the defined requirements directly in GRIP; he imports the Excel sheets to the application. The reason behind this, as he mentioned, is that he finds it easier to handle the Excel sheets in terms of time consumption and efficiency. Noteworthy to mention is that the environmental manager did not have any experience with using the GRIP application before the project, but he had several meetings with specialists from Witteveen+Bos and the client to learn the basics. Before the environmental manager started working on the project, he had a flash course; a quick session, about the basic principles of Systems Engineering, to learn about it in general and to know what to focus on. He also attended an expert course offered by Witteveen+Bos on the same topic. In addition to this information, the technical manager of Project B mentioned that the Relatics database is accessible but not all the designers access it. He justified his statement by explaining that designers are only interested in what is important for their designs so they receive the conclusions from the design manager in Excel sheets.

Processes

- **Managing and verifying requirements should be ongoing and iterative**

In comparison to the expected pattern where managing and verifying requirements processes should be ongoing and iterative, Project A scores as quasi-matching while Project B scores mismatching. Project A performs managing and verifying requirements during the design loops but rather informally during regular meetings between members from the stakeholder participation, design, and system specification teams. Such meetings could be for discussing, explaining or updating about the requirements. One discipline leader described these meetings as a verification tool and mentioned that cutting them at a certain point resulted in making the processes less ongoing. The processes were formally performed at the gate so to avoid that planning and milestones would not be met due to time consumed in the ongoing processes. The processes were iterative but not whenever changes in requirements/designs occurred. The technical manager of Project A mentioned that it would be too time-consuming and costly to have these processes ongoing and iterative. He also mentioned that the quality of the different products would not be the same because of changes on requirements that are done individually; not integral design anymore. This is why the verification would be at the gate where everybody can know the issues and which ones to be solved so that at the end all teams enter the baseline together.

On the other hand, Project B performs the processes of managing and verifying requirements at the end of a design loop and they are not considered iterative. For the stakeholders' requirements, it is mentioned that there exist many versions of the function tree reflecting how it is in development all the time, which proves that the process is somewhat ongoing. However, this management and verification take place at the end of a design loop (like a gate) by the environmental manager and technical manager. It is also mentioned that other requirements are drafted at the end of the project and the design is checked every design loop by the road design guidelines. One justification mentioned for this practice was to get an easier and better manageable process. However, "Not everybody is used and ready for true Systems Engineering already" is a statement from the technical manager of Project B disclosing the reason for the mismatching of this pattern with the expected pattern. Noteworthy to mention is that both systems engineers of the project did not give a clear evaluation of this pattern because they both have been involved as systems engineers only at the end of the project.

- **Managing and verifying requirements should be disciplined processes**

Regarding managing and verifying requirements to be disciplined processes, Project A scores a matching result with the expected pattern while Project B scores quasi-matching. Project A receives a matching score for having specific and clear roles and responsibilities for managing and verifying requirements provided in the project plans and during the design loops. As a reason behind this observed pattern, it was mentioned that strict planning of the project from the beginning is needed so that the whole system functions well.

		On the other hand, Project B scores quasi-matching regarding this pattern. It is mentioned that there have been roles and responsibilities for managing and verifying requirements but they have been really active only recently. A reason for this, as the technical manager mentioned, is that the previous team member responsible for this did not perform it enough. Noteworthy to mention is that both systems engineers of the project did not give a clear evaluation of this characteristic because they both have been involved as systems engineers only at the end of the project.

Table C2. Analysis of pattern matching results of designs development cross Projects A and B

Main element	**Sub-element**	**Analysis of pattern matching results**
Designs Development	People	The pattern matching analysis indicates that both projects score matching patterns regarding the people responsible for searching, defining and analyzing design solutions. This score has been given because both projects prove to have team members from the different disciplines involved in performing all of these tasks. Among the reasons mentioned for this practice is that integrated designs and functions result in efficiency in surface, materials, money and time, which require multi-disciplinary expertise. It was also mentioned that the only way to come to a multi-disciplinary optimal design choice, is by including the benefits from different disciplines in it. Both projects appear to understand the importance of involving different disciplines for performing the defined tasks in order to develop design solutions satisfying the defined client's and stakeholders' requirements. This can be seen as a reasonable justification for this practice. Therefore, since both projects are able to provide evidence of matching the expected pattern, the evaluation of this characteristic is a positive one.
	Products	• **The design solutions should be developed based on the defined requirements and specifications** Both projects are able to provide evidence that the design solutions are developed based on the defined requirements and specifications. Among the justifications mentioned for this practice is mainly because this is what the client is interested in knowing. Other justifications are to make sure that nothing is forgotten and to motivate why things are done or not; transparency. Therefore, the observed pattern in both projects matches the expected pattern as both projects appear to acknowledge the need to incorporate the defined requirements and specifications when developing design solutions. • **The design solutions descriptions should be documented and stored in accessible sources** Both projects document design solutions descriptions and store them in accessible sources. Project A provides explicit evidence for this as the design reports on each baseline and the Relatics database; which is accessible for all the team members involved in the project from the firm and client. Project B also provides explicit evidence for this as the design reports, advice reports and Excel sheets and the shared folder, which is accessible for all team members involved in the project from the firm. Among the justifications mentioned for these practices are to trace, find and retrieve why certain decisions have been made. To be able to find the solutions being investigated is another justification mentioned. Therefore, the observed pattern in both projects matches the expected pattern and both projects receive matching scores. • **There should be documentation of design decisions and the rationales of the design decisions** Both projects document design decisions, which makes them match the expected pattern. However, only Project A scores a matching result regarding the documentation of the rationales of the design decisions while Project B scores quasi-matching. Among the reasons mentioned by Project A for documenting rationales are traceability, transparency, updating the team members who could not attend the meeting to understand other disciplines' values. In other words, justifying decisions that can affect other disciplines and thus avoiding conflicting opinions or disagreements between disciplines. In other words, presenting text with why decisions are taken with their necessity, and how impacts on other disciplines are minimized, can provide better support from other disciplines. Additionally, there is a need for a reference line to motivate the decisions and provide proofs for justifications. On the other hand, only some of the rationales of the design decisions in Project B are documented. This could be referred to the fact that actively using the Relatics database has been only at the end of the project. Even though it comes across that Project B understands the importance of justifying why a decision is integrated into the design, not all the rationales of the design decisions are documented. Linking the design decisions with the requirements started in February using the Design Decisions module in the Relatics database. This delay in linking could be, as mentioned by one of the systems engineers of the project, that the main focus was not on documenting the decisions but on getting those decisions to be able to make the design. However, now it is a necessity. Therefore, the observed pattern in Project B receives a quasi-matching score against the expected pattern.
	Processes	• **Evaluating alternative design solutions should be performed carefully (e.g. using a multi-criteria analysis, a trade-off analysis), and choosing one design solution should be performed with consideration of the defined requirements** Both projects evaluate alternative design solutions carefully using a multi-criteria analysis and then choose one design solution with consideration of the defined requirements. Both projects appear to acknowledge the importance of these patterns. Among the justifications mentioned for these practices are to make an integral design decision, to efficiently weigh all aspects avoiding subjectivity or double-counting of issues, and to notice which matters are more important than others; laws vs. wishes. It is mentioned that the outcome should be well-

thought over and balanced in perspective to different components; to ensure priorities are clear and included. Taking into consideration (less)important aspects, major impacts, minor influences, and costly solutions and decisions is another reason mentioned for these practices. The multi-criteria analyses are made to analyze which is the preferred solution showing which requirements are most important and which are not. The technical manager of Project A provides a comprehensive explanation for these practices saying that the start of a project should always be with defining the criteria for decision-making processes to be performed with the same criteria set, in order to guarantee good decisions. These criteria are defined based on experience and project ambitions, goals and objectives along with the more technical parts. Additional reasons mentioned again are to trace, find and retrieve why certain decisions have been made. As both projects are able to provide evidence supporting their statements, scores of matching with the expected patterns are given to both projects.

- **Verifying designs with the defined requirements should be ongoing, iterative and disciplines processes**

Regarding the processes of verifying designs with the defined requirements, Project A performs them in ongoing and iterative manners with V&V plans including specific roles and responsibilities developed. Therefore, Project A scores a matching result with the expected pattern. These practices are justified with the goal of generating transparency; traceable and verified design process helps in providing credibility to decisions. Ongoing verification processes are mentioned to ensure fulfilling the needs of the person on the other side of the table because otherwise the solutions would be based on misunderstandings in the beginning. If verification does not happen in the meanwhile, as mentioned by one of the design discipline leaders, the solution at the end might fulfill the person's question but not his needs. Additionally, it was mentioned that changing design can lead to meeting a requirement that was not met before, or the other way around, which is why verifying iteratively is needed. In a statement regarding the specific and clear roles and responsibilities for the verification process, one design discipline leader mentions that it is needed to make it clear who should do it because otherwise, nobody will do it. However, one discipline leader still mentioned that the processes are not as ongoing as they should be due to time constraints. The technical manager of Project A states that there is not much time between the gates and baselines so it is better to avoid fixing many problems between the gate and the baseline, and rather find the problems earlier and prevent issues on the gate.

On the other hand, Project B scores a quasi-matching result regarding the disciplined processes but no result could be given regarding the ongoing and iterative processes of verifying the designs with the defined requirements. The quasi-matching score is given because there exist pre-developed plans describing the processes, and the environmental manager is assigning responsibilities to specialists now. The undefined scores; N/A, are given because in Project B, there is no explicit proof for performing these processes in ongoing and iterative manners, and the team started recording them recently. The reason mentioned for this is the lack of integrated files to refer to when performing this verification, which was because of the lack of experience and lack of advice from the previous systems engineer who was involved in the project. This was the justification mentioned by the technical manager of Project B. Noteworthy to mention is that both systems engineers of the project did not give a clear evaluation of these patterns because they both have been involved as systems engineers only at the end of the project.

Appendix D. Patterns evaluation criteria

Table D1. Patterns evaluation criteria for developing requirements throughout a design level

Main element	Sub-element	Expected pattern	Patterns evaluation criteria
Requirements Development	People	There should be multi-disciplinary teams responsible for: • Eliciting client's and stakeholders' requirements • Analyzing client's, stakeholders' and derived requirements (including design constraints) for clarity, completeness, and consistency • Documenting client's, stakeholders' and derived requirements • Communicating client's, stakeholders' and derived requirements among the different stakeholders and team members • Evolving requirements in response to stakeholders' needs and/or design processes (e.g. Requirements Engineer role, Requirements Owner role)	• **Match:** Multi-disciplinary teams are responsible for performing all of these tasks • **Quasi-match:** Only some of these tasks are performed by multi-disciplinary teams • **Mismatch:** A team from one discipline is responsible for performing all of these tasks
	Products	The defined requirements should be based on the wishes, requests, and anticipations of the clients and stakeholders	• **Match:** The defined requirements are based on the wishes, requests, and anticipations of the clients and stakeholders • **Quasi-match:** The defined requirements are based on only some of the wishes, requests, and anticipations of the clients and stakeholders • **Mismatch:** The defined requirements are not based on the wishes, requests, and anticipations of the clients and stakeholders
		The defined requirements should be SMART (i.e. Specific, Measurable, Acceptable, Realistic and Time-bound)	• **Match:** The defined requirements are SMART • **Quasi-match:** The defined requirements are partly SMART (i.e. only some requirements are SMART) • **Mismatch:** The defined requirements are not SMART
		The defined requirements should be documented	• **Match:** The defined requirements are documented • **Quasi-match:** The defined requirements are partly documented (i.e. only some requirements are documented) • **Mismatch:** The defined requirements are not documented
		The updated requirements should be documented	• **Match:** The updated requirements are documented • **Quasi-match:** The updated requirements are partly documented (i.e. only some updated requirements are documented) • **Mismatch:** The updated requirements are not documented
		The defined and updated requirements should be traceable (e.g. using a numbering system, Verification Requirements Traceability Matrix (VRTM))	• **Match:** The defined and updated requirements are traceable • **Quasi-match:** The defined and updated requirements are partly traceable (i.e. only some requirements are traceable) • **Mismatch:** The defined and updated requirements are not traceable
		The defined requirements information should be stored in accessible sources (e.g. Relatics)	• **Match:** The defined requirements information are stored in accessible sources • **Quasi-match:** The defined requirements information are partly stored in accessible sources (i.e. only some requirements information are stored in accessible sources) • **Mismatch:** The defined requirements information are not stored in accessible sources

	Processes	Managing and verifying requirements should be ongoing (not restricted to one moment in time)	• **Match:** Managing and verifying requirements are ongoing processes (i.e. they are not restricted to one moment in time) • **Quasi-match:** Managing and verifying requirements are partly ongoing processes (i.e. they are performed only multiple times) • **Mismatch:** Managing and verifying requirements are not ongoing processes (e.g. they are restricted to one moment in time)
		Managing and verifying requirements should be iterative (whenever changes in requirements/designs occurred)	• **Match:** Managing and verifying requirements are iterative processes (i.e. whenever changes in requirements/designs occur, the already defined requirements are managed and verified again) • **Quasi-match:** Managing and verifying requirements are partly iterative processes (i.e. only when some changes in requirements/designs occur, the already defined requirements are managed and verified again) • **Mismatch:** Managing and verifying requirements are not iterative processes (i.e. the already defined requirements are not managed and verified whenever changes in requirements/designs occur)
		Managing and verifying requirements should be disciplined processes (e.g. V&V plans with specific and clear roles and responsibilities)	• **Match:** Managing and verifying requirements are disciplined processes (i.e. there are plans with specific and clear roles and responsibilities to when these processes should be performed) • **Quasi-match:** Managing and verifying requirements are partly disciplined processes (i.e. there are specific and clear roles and responsibilities for team members to perform these activities but not to when they should be performed) • **Mismatch:** Managing and verifying requirements are not disciplined processes (i.e. there are no plans with specific and clear roles and responsibilities to when these processes should be performed)

Table D2. Patterns evaluation criteria for developing designs throughout a design level

Main element	**Sub-element**	**Expected pattern**	**Patterns evaluation criteria**
Designs Development	People	There should be multi-disciplinary teams to: Search for, define and analyze design solutions satisfying the defined client's and stakeholders' requirements (e.g. Integrated Product Teams, System Designer role, System Analyst role, Coordinator role)	• **Match:** Multi-disciplinary teams are responsible for performing all of these tasks • **Quasi-match:** Only some of these tasks are performed by multi-disciplinary teams • **Mismatch:** A team from one discipline is responsible for performing all of these tasks
	Products	The design solutions should be developed based on the defined requirements and specifications	• **Match:** The design solutions are developed based on the defined requirements and specifications • **Quasi-match:** The design solutions are developed based only on some of the defined requirements and specifications • **Mismatch:** The design solutions are not developed based on the defined requirements and specifications
		The design solutions descriptions should be documented	• **Match:** The design solutions descriptions are documented • **Quasi-match:** The design solutions descriptions are partly documented (i.e. only some design solutions descriptions are documented) • **Mismatch:** The design solutions descriptions are not documented

	The design solutions descriptions should be stored in accessible sources	• **Match:** The design solutions descriptions are stored in accessible sources • **Quasi-match:** The design solutions descriptions are partly stored in accessible sources (i.e. only some design solutions descriptions are stored in accessible sources) • **Mismatch:** The design solutions descriptions are not stored in accessible sources
	There should be documentation of design decisions	• **Match:** Design decisions are documented • **Quasi-match:** Design decisions are partly documented (i.e. only some design decisions are documented) • **Mismatch:** Design decisions are not documented
	There should be documentation of the rationales of the design decisions	• **Match:** The rationales of the design decisions are documented • **Quasi-match:** The rationales of the design decisions are partly documented (i.e. only some rationales of the design decisions are documented) • **Mismatch:** The rationales of the design decisions are not documented
Processes	Evaluating alternative design solutions should be performed carefully (e.g. using a multi-criteria analysis, a trade-off analysis)	• **Match:** Evaluating alternative design solutions is performed carefully (i.e. the decision-making process is performed using a multi-criteria analysis or a trade-off analysis) • **Quasi-match:** Evaluating alternative design solutions is performed partly carefully (i.e. the decision-making process is not always performed using a multi-criteria analysis/a trade-off analysis) • **Mismatch:** Evaluating alternative design solutions is not performed carefully (i.e. the decision-making process is not performed using a multi-criteria analysis or a trade-off analysis)
	Choosing one design solution should be performed with consideration of the defined requirements	• **Match:** Choosing one design solution is performed with consideration of the defined requirements (i.e. the chosen design solution includes the defined requirements) • **Quasi-match:** Choosing one design solution is performed partly with consideration of the defined requirements (i.e. the chosen design solution includes only some of the defined requirements) • **Mismatch:** Choosing one design solution is not performed with consideration of the defined requirements (i.e. the chosen design solution does not include the defined requirements)
	Verifying designs with the defined requirements should be ongoing (not restricted to one moment in time)	• **Match:** Verifying designs with the defined requirements is an ongoing process (i.e. it is not restricted to one moment in time) • **Quasi-match:** Verifying designs with the defined requirements is partly an ongoing process (i.e. it is performed only multiple times) • **Mismatch:** Verifying designs with the defined requirements is not an ongoing process (e.g. it is restricted to one moment in time)
	Verifying designs with the defined requirements should be iterative (whenever changes in requirements/designs occurred)	• **Match:** Verifying designs with the defined requirements is an iterative process (i.e. whenever changes in requirements/designs occur, designs are verified again) • **Quasi-match:** Verifying designs with the defined requirements is partly an iterative process (i.e. only when some changes in requirements/designs occur, designs are verified again) • **Mismatch:** Verifying designs with the defined requirements is not an iterative process (i.e. designs are not verified whenever changes in requirements/designs occur)

	Verifying designs with the defined requirements should be a disciplined process (e.g. V&V plans with specific and clear roles and responsibilities)	• **Match:** Verifying designs with the defined requirements is a disciplined process (i.e. there are plans with specific and clear roles and responsibilities to when this process should be performed) • **Quasi-match:** Verifying designs with the defined requirements is a partly disciplined process (i.e. there are specific and clear roles and responsibilities for team members to perform this activity but not to when it should be performed) • **Mismatch:** Verifying designs with the defined requirements is not a disciplined process (i.e. there are no plans with specific and clear roles and responsibilities to when this process should be performed)