MASTER THESIS

IMPROVING THE SATISFACTION WITH SYSTEMS ENGINEERING AT A GENERAL CONTRACTOR: AN APPLICATION OF SYSTEMS ENGINEERING IN THE CONSTRUCTION INDUSTRY

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Improving the satisfaction with Systems Engineering at a general contractor
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ABSTRACT

This study explores the bottlenecks faced by general contractors in the construction industry when applying the technical processes of Systems Engineering (SE). The goal is to clarify the dissatisfaction among SE experts of a general contractor regarding SE application and to offer advise on how to improve it. To assess the SE application at general contractors, a single case study is conducted through interviewing 8 respondents on the bottlenecks experienced at their organisation and the associated causes and consequences, using the Delphi method. From this study, 6 main bottlenecks have appeared as the greatest sources of dissatisfaction, being (1) partners performing their SE tasks too late, (2) shortage of management support, (3) knowledge shortage of on-site employees, (4) employees performing the verification too late, (5) uncertainty about validation and (6) difficulties with the use and operation of the RMS. This paper also advises on proposals for the improvement of the indicated bottlenecks, so the level of dissatisfaction regarding SE application can be reduced.

Keywords: systems engineering, technical processes, application, construction industry, non-residential buildings, Delphi method, bottlenecks

1. Introduction

Systems Engineering (SE) is receiving increasing attention in the construction industry. Scientific papers, professional magazines, handbooks and guidelines have appeared on this topic. The growing complexity and multidisciplinarity of construction projects and their environment is what gives rise to this. The transition from traditional contracts to integrated contracts, most of which takes place in the public sector, has led to an increasing extent of the responsibility for contractors and a mandatory or voluntary application of Systems Engineering in projects (de Graaf, Voordijk, & van den Heuvel, 2016; de Graaf, Vromen, & Boes, 2017; Makkinga, de Graaf, & Voordijk, 2018; SEBoK Editorial Board, 2019; Ugurlu, Bougain, Nigischer, & Gerhard, 2016; Walden, Roedler, Forsberg, Hamelin, & Shortell, 2015).

Issues regarding the efficiency of projects are still common in the construction sector. It regularly occurs that budgets are exceeded, projects take longer than expected and projects fail in performance. Systems Engineering should reduce the problems that lead to this lack of efficiency. This means that, conversely, a less efficient SE application will lead to failure in terms of cost, time planning and performance. Although there is a good foundation of the theory of SE and its application, the application in practice often proves to be challenging (Hardman & Colombi, 2012; Makkinga et al., 2018; Ugurlu et al., 2016).

In this research, a Dutch general contractor is interested in analysing the SE application in its organisation, after receiving signals of dissatisfaction from the SE experts among its employees regarding this topic. Here, the focus lies on the department of the general contractor that is involved in the construction of non-residential buildings, such as offices, government buildings, hospitals, schools and factories. The exact content and causes of this dissatisfaction, however, still remain unclear and give reason for research. This general contractor will serve as the case of the single case study research strategy used in here. Its attention is specifically aimed at the Technical Processes of Systems Engineering as defined in the ISO standard NEN-ISO/IEC/IEEE 15288:2015 Systems and software engineering – System life cycle (ISO/IEC-IEEE, 2015). Furthermore, this study concentrates on large projects with a total value that exceeds 10 million euros, since these projects usually encompass the highest risk and complexity, wherefore the application of Systems Engineering is most frequent, essential and useful.

The goal of this research is to provide the general contractor with an advice to improve the application of the technical processes of Systems Engineering and to reduce dissatisfaction among its SE experts where possible. Most existing literature about SE and its application describes it in general or for industries like aerospace, defence, information technology and healthcare, whereas this research covers the construction industry. Moreover, little existing literature is focused on the construction of non-residential buildings specifically. So besides the importance of this study for the general contractor itself, it also contributes to literature and the lessons-learned can serve other organisations in this sector in their SE application and improvement.

To reach the goal of this research, the following research question should be answered: What are possible solutions for removing the dissatisfaction experienced at the general contractor regarding the application of the technical processes of Systems Engineering and which solutions are most suitable for the general contractor?

In this paper, first, a theoretical framework is established by conducting a literature review and presented in section 2. The first part of this section describes the applicable knowledge as it intends to give better insight in the concepts of the research question, being "Systems Engineering" and "Technical processes according to ISO 15288". The second part of this section elaborates on the existing bottlenecks for applying these technical SE processes in the construction of non-residential buildings according to literature. Section 3 explains the methods used for data collection and data analysis in this research, followed by section 4 that presents the results of the data collection. In the fifth section the results are compared to literature and discussed by the researcher. Finally, a conclusion is drawn and the research question is reviewed in section 6 and in section 7 the limitations of this research and future research are discussed.

2. Theoretical Framework

In this section a theoretical framework is drawn up to gain insight into the various concepts included in the research question based on existing literature. Section 2.1 describes the concept of Systems Engineering and in section 2.2 the technical processes according to ISO 15288 are presented. Subsequently, section 2.3 of the literature review aims to gain insight into the application of these technical SE processes in the construction of non-residential buildings. Common bottlenecks, related causes and effects and potential solutions will be listed here and are summarized in table 1. This theoretical framework will set the starting point for identifying the bottlenecks encountered at the general contractor when applying Systems Engineering along with their causes, effects and potential solutions and therefore will form the input for the data collection. The literature review has shown that little literature is available specifically relating to non-residential buildings and technical processes, and moreover to the application thereof, which implies results outside the exact scope of the research question have been included as well.

2.1 Systems Engineering

Systems Engineering is described differently by various organisations, institutions and industries and an official, unambiguous definition is lacking. According to the International Council on Systems Engineering (INCOSE), which is considered the world's largest organization for Systems Engineering, Systems Engineering can be described as follows: "Systems Engineering is 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, then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing and disposal. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. 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" (Walden et al., 2015).

The INCOSE definition is commonly used in scientific research on Systems Engineering in the civil engineering industry and will therefore also be used in this study (de Graaf et al., 2016; de Graaf et al., 2017). Some key characteristics of Systems Engineering that can be deduced from this definition are that SE is interdisciplinary, social, technical and complete, but also iterative, concurrent, recursive, transparent and traceable (ISO/IEC-IEEE, 2015; Walden et al., 2015).

2.2. Technical processes according to ISO 15288

The most commonly used standard for the application of Systems Engineering is the one of the International Organization for Standardization (ISO), named NEN-ISO / IEC / IEEE 15288: 2015 Systems and software engineering - System life cycle processes (ISO/IEC-IEEE, 2015). This standard is used by default for the application of SE in the Netherlands and its use is therefore required by public clients such as Rijkswaterstaat and ProRail. The ISO 15288 is well applicable to project-based organizations, such as in the construction sector and will serve as a basis for this research (de Graaf et al., 2017).

The ISO 15288 describes 30 processes that can be followed during the lifecycle of a system, which are divided into four categories: (1) Agreement processes, (2) Organizational Project-Enabling processes, (3) Technical Management processes and (4) Technical processes. The standard explicitly states that the described processes do not exclude the use of processes added by the organisation and that the order in which they are presented can also be seen as an advice which can be deviated from. However, in many literature and manuals it is assumed that the sequence as described in ISO 15288 is leading. The Technical processes, forming the focal point of this study, can be defined as the actions that lead to determining the wishes of the client and translating them into a product. They therefore contribute specifically to the realization of a system, contrary to the other life cycle processes that support the development of a system. Furthermore, the technical processes allow reproduction of the product, ensure the required service level in use and maintenance is reached and are used to dispose the product at the end of its lifecycle (ISO/IEC-IEEE, 2015).

2.3 Bottlenecks for the application of technical SE processes in the construction of non-residential buildings

According to existing literature, there are a number of bottlenecks that can result in the application of the technical processes of SE not being experienced as fully successful, often related to inefficiency, ineffectiveness, lack of clarity and absence. Due to the complexity of the construction industry it is difficult to cover the entire field of research when defining the bottlenecks. Therefore, a division must be made into several categories that together ensure all problems and causes in the entire field of research are included (Scavarda, Bouzdine-Chameeva, Goldstein, Hays, & Hill, 2006). The Ishikawa, or fishbone, diagram, used for defining the research problem of this study, is known for mapping comprehensive problems and presents its causes in a structured way. For this diagram, the 4M-model is a widely used foundation, allowing potential causes of problems to be identified and grouped. This model distinguishes four categories, being Man, Material, Method and Machine, which will be leading in this literature review. For each category the six bottlenecks that are most persistent, relevant for the SE application in the construction of non-residential buildings and possibly causing dissatisfaction, will be included in this literature review. These bottlenecks will form the starting point for identifying the potential problems and related causes occurring at the general contractor.

2.3.1 Man-related bottlenecks

Human factors are important for SE success and the most frequently mentioned influence on dissatisfaction or problems regarding SE application, hence change or improvement should start with people (SEBoK Editorial Board, 2019). Moreover, the effectiveness of SE depends to a large extent on the persons carrying out or involved in the process (Walden et al., 2015). Human factors that play a role in SE application can be divided in individuals and teams. Individuals each have a role within an organization or project, which involves different tasks. Whether the individual is competent in fulfilling the assigned tasks depends on his or her knowledge, skills and abilities (KSA's). Within the team context, each role comes with certain responsibilities and authorities, which should be in line for a successful application of SE processes (CMMI Product Team, 2010; Estefan, 2008; Fraser & Hvolby, 2010; ISO/IEC-IEEE, 2015; SEBoK Editorial Board, 2019; Walden et al., 2015). These aspects will be used to explore the human-related bottlenecks in SE application in the construction sector, while often referring to the domain of business ontology as the main literary source on the influence of human factors (Ghaleb, El-Sharief, & El-Sebaie, 2017; Staccini et al., 2005, 2007; Uschold et al., 1998).

The first common man-related bottleneck in the application of SE is the lack of explicit description and timely determination of roles, that simultaneously fit the organization or the project. Moreover, these roles are often not assigned to the right people or not understood by those people (de Graaf et al., 2016; de Graaf et al., 2017; ISO/IEC-IEEE, 2013, 2015; SEBoK Editorial Board, 2019; Sheard, 1996, 2000; van den Houdt et al., 2013)

The second bottleneck derived from literature is a lack of knowledge, both in task-specific and sector-wide sense, required to perform a SE task and yet a lack of interest, willingness and time to acquire and share knowledge (de Graaf et al., 2017; de Graaf & Loonen, 2018; Harris, 2008; SEBoK Editorial Board, 2019; van den Houdt et al., 2013; Walden et al., 2015).

Furthermore, literature indicates a lack of the right and sufficiently high skills for performing SE tasks, due to lack of experience, education, training, expertise, communication skills, management skills and variation of skills within a team, as the third bottleneck (Bullard et al., 2008; de Graaf et al., 2016; de Graaf et al., 2017; de Graaf & Loonen, 2018; Makkinga et al., 2018; Redmond & Alshawi, 2017; SEBoK Editorial Board, 2019; van den Houdt et al., 2013; Walden et al., 2015)

The fourth bottleneck can then be referred to as a lack of appropriate and sufficient abilities regarding communication, collaboration, management support, interaction with the customer and social skills (Bullard et al., 2008; de Graaf et al., 2016; de Graaf et al., 2017; de Graaf & Loonen, 2018; Elliott et al., 2012; Hardman & Colombi, 2012; Makkinga et al., 2018; SEBoK Editorial Board, 2019; van den Houdt et al., 2013; Walden et al., 2015)

The next man-related bottleneck according to literature is a lack of on-time, clear and explicit description, allocation and communication of responsibilities. Thereby, these responsibilities do not always fit the person in question and are not always understood by them (CMMI Product Team, 2010; de Graaf et al., 2016; Elliott et al., 2012; ISO/IEC-IEEE, 2012, 2015; Makkinga et al., 2018;

SEBoK Editorial Board, 2019; van den Houdt et al., 2013; Walden et al., 2015).

Finally, literature indicates a lack of timely determination and description of authorities and of these authorities being appropriate, sufficient, understood and accepted, while matching the project and a person's role, tasks and responsibilities, as a common bottleneck (CMMI Product Team, 2010; ISO/IEC-IEEE, 2012, 2015; SEBoK Editorial Board, 2019; van den Houdt et al., 2013; Walden et al., 2015).

2.3.2 Material-related bottlenecks

Material is the next category of factors possibly playing a role in the success or failure of SE application and can include physical material as well as data and information, such as requirements, wishes and opinions.

The first material-related bottleneck based on literature can be described as uncertainty regarding the content and meaning of information and data, such as stakeholder requirements, as this can cause confusion and misunderstanding (Walden et al., 2015; Ward et al., 2018).

Furthermore, incompleteness of information and data during the entire SE process appeared to be a common source for problems with SE application and dissatisfaction on both the client's and contractor's side, since it can lead to rework and a non-complying end product (SEBoK Editorial Board, 2019; Walden et al., 2015; Ward et al., 2018).

The insufficient monitoring and documentation of changes during the SE process is indicated as the third common material-related bottleneck, as changes are often directly implemented into the design instead of documented elsewhere or altered in the requirements (de Graaf et al., 2016; de Graaf et al., 2017).

Another bottleneck entails the insufficient traceability of the used, consulted or produced material, which is in conflict with the main SE principles and often occurs in the field of design decisions (de Graaf et al., 2016; de Graaf et al., 2017; ISO/IEC-IEEE, 2012; Ugurlu et al., 2016).

Poor accessibility of information and data, which should actually be easy and available at all times for the involved parties and should have the correct form for it to be usable, is the fifth bottleneck derived from literature (INCOSE, 2014; ISO/IEC-IEEE, 2012; SEBoK Editorial Board, 2019; Ugurlu et al., 2016).

The last material-related bottleneck involves the insecurity of information and data due to their digital storage and sharing and the openness of communication, risking the expose of sensitive information to stakeholders or competitors. Therefore measures must be taken at the start of each project to guarantee the security of information and data and thus prevent dissatisfaction with the SE application (INCOSE, 2014; SEBoK Editorial Board, 2019).

2.3.3 Method-related bottlenecks

A variety of methods can be used for the application of systems engineering and its technical processes, hence methods are a much discussed part of SE literature and a determining factor for success. In the context of this research, methods include guidelines, standards, rules, procedures, strategies, manuals, models and restrictions that may be defined legally, locally, scientifically or internally (Estefan, 2008; Staccini et al., 2005).

The first method-related bottleneck derived from literature is the failure to apply SE methods in time within many organisations, causing irreversible design decisions being made in the initial stages. Timely and explicit application of SE and mainly verification and validation is therefore highly recommended (de Graaf et al., 2017; Hardman & Colombi, 2012; Redmond & Alshawi, 2017).

Secondly, a lack of clarity on the used methods, such as standards and procedures, is often mentioned as a reason for non-optimal SE application and as a source of dissatisfaction. Describing the methods to be used in a clear and structured way, which is currently often lacking, clarifies for the stakeholders what to expect and increases the chance of technical SE processes being applied successfully with little dissatisfaction (de Graaf et al., 2016; de Graaf et al., 2017; Makkinga et al., 2018).

The assumption that no functional and domain knowledge and no integration with organizational processes is required for the application of SE methods, is indicated as the next common bottleneck (ISO/IEC-IEEE, 2012, 2015; SEBoK Editorial Board, 2019).

The fourth bottleneck according to literature is the lack of adaptation of methods and models to a specific sector, organization, project or lifecycle phase and of the application of various methods concurrently. Methods should support the SE activities, not replace them (de Graaf et al., 2016; de Graaf et al., 2017; Elliott et al., 2012; ISO/IEC-IEEE, 2012, 2015; Redmond & Alshawi, 2017; SEBoK Editorial Board, 2019; Ugurlu et al., 2016).

Furthermore, a lack of the use and clear display of concurrency, iteration and recursion in the applied methods and models is a common bottleneck. These characteristics could reduce dissatisfaction and problems regarding the application of technical SE processes, as they allow for a more effective communication between contractor and client and a more accurate representation of the client's needs in the end product, resulting in a higher satisfaction of all parties. Moreover, the continuous sharing of information between processes, levels of detail, phases and stakeholders reduces failure (de Graaf et al., 2017; ISO/IEC-IEEE, 2012; SEBoK Editorial Board, 2019; Walden et al., 2015).

The final common method-related bottleneck is a lack of proper methods that contain the right components and have a sufficient degree of maturity. Methods need to have the ability to cope with the growing complexity and the increasing demand for innovation, productivity, speed, quality and safety, as well as with the customer-driven market in which access to information for multiple stakeholders is increasingly expected in projects (Hardman & Colombi, 2012; INCOSE, 2014; SEBoK Editorial Board, 2019).

2.3.4 Machine-related bottlenecks

The last factors that can influence a successful SE application are categorized as machine-related. Machines include physical machines, but also technologies, techniques and resources, or tools. The latter is most frequently mentioned in literature on dissatisfaction and bottlenecks in the application of technical SE processes and will therefore be discussed most extensively. For large-scale and complex systems with a long project duration and many stakeholders, the use of tools to support the SE application is required and will enhance the task efficiency, which in the case of SE usually comes down to computer- or software-based tools (Estefan, 2008; ISO/IEC-IEEE, 2012).

The first common bottleneck in this category is that software tools prevail the SE process, leaving less space for technologies and people to be included in the final solution. It is therefore important to properly map the obstacles and opportunities that arise from software tools for all aspects of a system's lifespan (SEBoK Editorial Board, 2019).

Another frequently occurring bottleneck is that there is too much confidence in the operation of tools, while too little attention is paid to the knowledge needed for the application of SE processes and to how they should actually be applied in practice. A tool should support, but not replace, the activities performed during the SE process (ISO/IEC-IEEE, 2012; SEBoK Editorial Board, 2019).

The third machine-related bottleneck can be described as a lack of application of the right tools, suitable to the situation, organization and project, for which should be borne in mind that no single tool can meets all of these aspects. When applying technical SE processes, tools for requirement management, verification and validation are of special importance. The use of the right tools fosters communication, cooperation and the efficiency and effectiveness of processes, resulting in less risk and failure costs and dissatisfaction (Chami & Bruel, 2018; Elliott et al., 2012; Redmond & Alshawi, 2017; SEBoK Editorial Board, 2019; Ugurlu et al., 2016).

A lack of availability and accessibility of the required tools is the next common bottleneck according to literature. All stakeholders who are allowed or need to use a particular tool, according to the project agreements, should have access to it. Frustration and dissatisfaction regarding the application of technical SE processes can be caused by a lack of availability to a sufficient number of people at the same time and a lack of easy and quick accessibility (ISO/IEC-IEEE, 2012; SEBoK Editorial Board, 2019).

The fifth bottleneck derived from literature is a lack of available tools that are mature enough to keep up with the market needs and the technological development of other tools, despite growing maturity and constant evolvement of tools. Tools must be capable of dealing with the pressure of competition, the growing complexity in the civil sector and the rising demand for innovation, productivity, speed, quality and safety (INCOSE, 2014; SEBoK Editorial Board, 2019).

Finally, an interoperability issue between the various tools used, appeared to be a common bottleneck, as it is the main cause of dissatisfaction with the application of the technical SE processes in the construction sector. Interoperability can be described as the ability of one tool to exchange information with another tool and then use that information. To prevent interoperability issues, open cooperation and clear agreements on the semantics, on which tools to use and on how to arrange the interfaces, are needed (Chami & Bruel, 2018; ISO/IEC-IEEE, 2012; SEBoK Editorial Board, 2019; Walden et al., 2015).

Table 1. Bottlenecks from literature including their literary source

Category	Bottlenecks from literature	Source
Man	1.1 A lack of explicit description and timely determination of roles, that simultaneously fit the organization or the project, and a lack of assigning these roles to the right people, who also understand their role.	[6;7;18;19;23;25;26;31]
	1.2 A lack of knowledge, both in task-specific and sector-wide sense, required to perform a SE task and yet a lack of interest, willingness and time to acquire and share knowledge.	[5;7;15;23;31;33]
	1.3 A lack of the right and sufficiently high skills for performing SE tasks, due to lack of experience, education, training, expertise, communication skills, management skills and variation of skills within a team.	[2;5;6;7;20;21;23;31;33]
	1.4 A lack of appropriate and sufficient abilities regarding communication, collaboration, management support, interaction with the customer and social skills.	[2;5;6;7;8;14;20;23;31;33]
	1.5 A lack of on time, clear and explicit description, allocation and communication of responsibilities that simultaneously fit with and are understood by the person in question.	[4;6;8;17;19;20;23;31;33]
	1.6 A lack of timely determination and description of authorities and of these authorities being appropriate, sufficient, understood and accepted, while matching the project and a person's role, tasks and responsibilities.	[4;17;19;23;31;33]
Material	2.1 Uncertainty regarding the content and meaning of information and data, such as stakeholder requirements.	[33;34]
	2.2 Incompleteness of information and data during the entire SE process, on both the input and output side.	[23;33;34]
	2.3 Insufficient monitoring and documentation of changes during the SE process	[6;7]
	2.4 Insufficient traceability of the used, consulted or produced material.	[6;7;17;29]
	2.5 Poor accessibility of information and data.	[16;17;23;29]
	2.6 Insecurity of information and data due to their digital storage and sharing and the openness of communication.	[16;23]
Method	3.1 The failure to apply SE methods in time.	[7;14;21]
	3.2 A lack of clarity on the methods used.	[6;7;20]
	3.3 Assuming no functional and domain knowledge and no integration with organizational processes is required for the application of SE methods.	[17;19;23]
	3.4 The lack of adaptation of methods and models to a specific sector, organization, project or lifecycle phase and of the application of various methods and models concurrently.	[6;7;8;17;19;21;23;29]
	3.5 A lack of the use and clear display of concurrency, iteration and recursion in the applied methods and models.	[7;17;23;33]
	3.6 A lack of proper methods that contain the right components and have a sufficient degree of maturity.	[14;16;23]
Machine	4.1 Software tools prevail the SE process, leaving less space for technologies and people to be included in the final solution.	[23]
	4.2 Too much confidence in the operation of tools, while too little attention is paid to the knowledge needed for the application of SE processes and to how they should actually be applied in practice.	[17;23]
	4.3 A lack of application of the right tools, suitable to the situation, organization and project.	[3;8;21;23;29]
	4.4 A lack of availability and accessibility of the required tools.	[17;23]
	4.5 A lack of available tools that are mature enough to meet the market needs and technological development of other tools.	[16;23]
	4.6 An interoperability issue between the various tools used.	[3;17;23;33]

3. Methodology

To assess the SE application at the general contractor, a single case study method is applied. Case studies are used to get a clear picture of a problem and to find out the real situation by looking at it from different angles (Yin, 2009). This qualitative research methodology is widely adopted for complex problems in the construction industry and enables the understanding of context-specific events in the 'real world' such as gaining a general insight into what is happening in an organisation and why. It is an eligible methodology for a research with a small group of respondents and a large or unknown number of research variables, which is the case in this study (Golafshani, 2003; Sekaran & Bougie, 2016). Here, the general contractor is the case that has been studied and the following sections discuss the method used for that, consisting of data collection, data analysis and internal and external validation.

3.1 Data collection

The data for this case study is collected through a limited number of interviews that will be analysed in depth. These interviews attempt to identify the problems and associated causes regarding dissatisfaction about the application of technical SE processes and to inventory potential solutions to these problems according to the respondents.

The interviews should be directed in a way that the topics the researcher wants to know about are not overlooked, while still leaving enough room for the context to be discovered and for the respondents to express their opinion, so the true nature and causes of the problem can be traced. That is why a semi-structured interview method is used, which means that the interviews are guided by a set of interview instructions and the list of bottlenecks obtained from the literature review, containing all topics that should be covered. This way, the research can expand in width, but also go in depth and it becomes possible to compare different interviews (Sekaran & Bougie, 2016; Verschuren & Doorewaard, 2015). The interviews are conducted face-to-face, allowing the researcher to ensure the proposed questions are properly understood and to clarify them when necessary. Moreover, it provides for non-verbal communication to be noticed (Sekaran & Bougie, 2016). However, video calling platforms are used for part of the interviews due to COVID-19 regulations.

The research method used to collect data from interviews is the Delphi method. In this method the opinions of experts are measured and subsequently presented to another group of experts. This exchange, comparison and refinement of opinions aims to achieve a certain level of mutual agreement and to define consensus. The complex and project-based nature of the construction industry and the risk of the collected subjective data distorting the picture of reality, make it a challenging industry for conducting research. Hence, such a structured method as the Delphi method, with its systematic and interactive character, is desirable and allows selecting qualified respondents and making the prejudices of both the researcher and the respondents manageable (Hallowell & Gambatese, 2010). The Delphi method ensures that experts in a certain field can communicate anonymously, via the researcher, and in a structured way, so that consensus is defined and agreement is reached on decision-making within an organization. Iteration and controlled feedback are necessary to reduce variation in answers and provide greater accuracy. This, and finding the reason for deviating answers, is accomplished by performing multiple rounds of data collection, with 3 rounds being the ideal number (Brady, 2015; Hallowell & Gambatese, 2010). Therefore this study consists of 3 rounds of data collection, the first being individual interviews about the topics that emerged from the literature review, including feedback provided by the respondents on their answers given in the interview. In the second round a group of other respondents is interviewed individually, using the collected data from the first round as input. The third round aims to reach agreement between the respondents, by presenting them the 'common opinion' as interpreted by the researcher. Whereas the first two rounds are part of this paper, the third round will be conducted by the general contractor itself with the results of this paper, including a visualisation and manual, as the input.

To provide an accurate and transparent representation of the situation and the opinion of respondents, the interviews are conducted individually, preventing peer pressure and influencing each other (Brady, 2015). Furthermore, respondents' bias in judging the opinion of other respondents should be minimized, by presenting the opinions of the first Delphi round anonymously (Hallowell & Gambatese, 2010).

The respondents are selected based on their knowledge of the how and why of SE and associated processes at the general contractor, on their experience with and involvement in the application of technical SE processes, on their eloquence and on having an opinion, positive or negative, about the SE application at the organisation. Moreover a variation in roles, hierarchical position in the organisational structure and workplace is retained. For the first round of interviews, in which is attempted to gain insight into the direction of the problems, experts are selected who are engaged in SE on a daily basis and are therefore most likely aware of the problems faced and able to form an opinion on the topic (Hallowell & Gambatese, 2010).

The eight respondents, which proves to be an effective number for a Delhi study with a limited duration, are presented in table 2 along with their role and the Delphi round they participated in. This study combines the advantages of parallel interviews regarding planning flexibility and the extraction of independent uninfluenced opinions with the advantage of sequential interviews regarding the decrease of variation in opinions, making it easier to form a 'common opinion'. In the first Delphi round three interviews are conducted parallel, sequentially followed by five parallel interviews in the second round. The uncertainty surrounding the exact problem that initiated this study and the assumptions made by the researcher as a result are the reason for starting with three interviews. This amount allows for the direction of the research to be indicated and for the input for the second round of interviews to be sufficient, while simultaneously ensuring the input for the second round is not too extensive or hinders the own opinion of respondents.

Table 2. Overview of the respondents

Respondent nr	Delphi round	Role
1	1	Advisor Systems Engineering
2	1	Advisor Systems Engineering
3	1	Process Manager
4	2	Design Manager
5	2	Design Manager
6	2	Process Manager
7	2	Board Member
8	2	Board Member

Figure 1 depicts the roadmap for the Delphi process of this study, with the information obtained in the research preparation, consisting of the list of bottlenecks according to literature, the interview instructions and the research question, as the input. Based on that, the first Delphi round starts with the three individual interviews, in which the respondents are questioned, completing each of the 4 M's, about the bottlenecks they experience regarding the application of SE at the general contractor and what they consider as its causes or potential improvements. Those interviews are audio recorded and literally transcribed afterwards and processed in a document, summarizing the respondents' opinion per topic. This document is emailed to the respondents for feedback and verification. The revised documents are analysed, merged and categorized according to the researchers interpretation and subsequently emailed to the respondents of the second Delphi round as preparation. During the interviews in the second round the respondents are asked to react on this document and optionally add their own view on the topics. These interviews are summarized, sent out for feedback and analysed as well, whereafter the results of both rounds are combined and presented as six researcher-defined main categories of bottlenecks. In the third Delphi round the common opinion, consisting of bottlenecks and improvement proposals, is identified by comparing the results with each other and to literature and by providing a researcher interpretation. That serves as the answer to the research question of this study. The subsequent steps of the Delphi study, being presenting the common opinion in a group session to try to reach a level of consensus on the common opinion and verifying the answers to the research question, will be performed by the general contractor itself. To help the general contractor in performing these last steps, the researcher provides a poster visualizing the resulting bottlenecks and improvement proposals along with a manual for the group session.

3.2 Data analysis

When using the Delphi method the data is collected through multiple rounds, each round needing the analysed data of the previous round, wherefore the data analysis has to consist of multiple iterative rounds as well. Given the collected data is qualitative, an appropriate way to analyse it is with a thematic analysis. This is done by identifying concepts, categories and theme's from the statements made by respondents and translating the specific results from the individual interviews into less specific, explanatory results classified in theme's (Brady, 2015).

The data analysis of this study is done manually, using the software Excel, and starts with segmenting the verified interview summaries into short fragments of text. Based on the researchers interpretation these fragments are then coded by attaching one or more labels, called concepts, that represent their core subject. To keep track of the relationship between various concepts, it is indicated for each concept whether it is a problem, cause, effect or solution. During the analysis, the naming of concepts is regularly revised by relating them to concepts from other interviews and giving them a similar structure and naming. After the coding, the concepts are categorized by looking for similarities and differences between them in order to delineate themes, which are regularly revised during the course of the analysis as well. Subsequently, the researcher has grouped the themes into subcategories and then into categories, both based on the structure of the literature review and its 4M's, with additions where necessary.

By constant comparison of the coded and categorized data from the different interviews, the

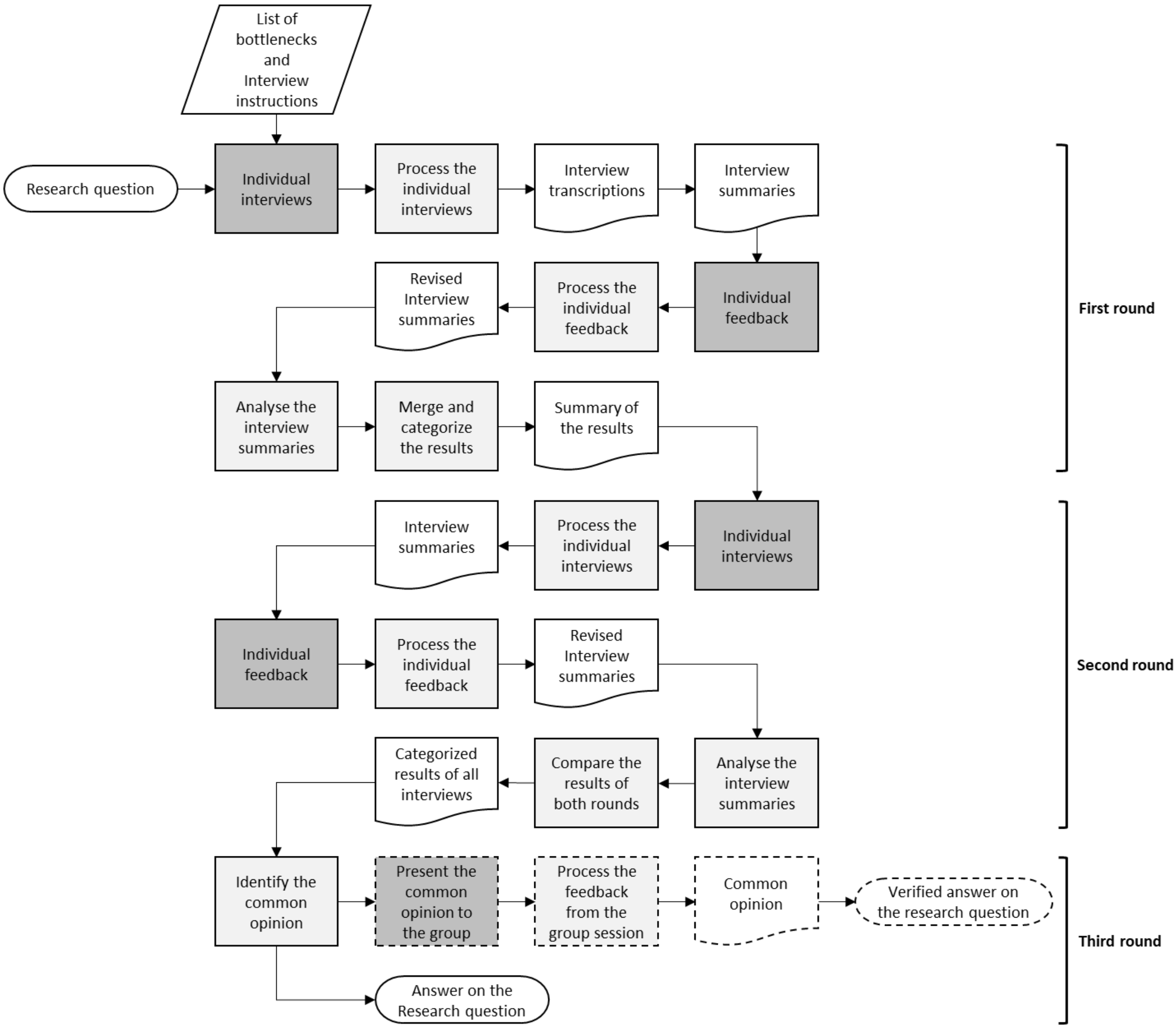

Figure 1. Roadmap of the Delphi study

data from all interviews of the first Delphi round was combined in one sheet, whereby the use of the 4M's as categories appeared not to be ideal, since concepts often belonged to multiple M's. To provide more structure and a clear distinction of main categories of problems, the MECE principle was used. This principle ensures that the main categories are independent and do not overlap (Mutually Exclusive), while they are also complete and collectively include all information from the interviews (Collectively Exhaustive). This way, a number of main categories of bottlenecks are identified from the collected data, taking into account the amount of respondents having a certain opinion, how strong their opinion on the matter was and to what extent they saw this as a real bottleneck. These main categories of bottlenecks were summarized textually in a document, which was then used as input for the interviews of the second Delphi round.

3.3 Internal and external validation

By keeping the research on the actual problem broad in the beginning and by comparing potential solutions with existing literature, internal validity is guaranteed. The interviews are not delimited too much, so that the context and the actual problem can emerge. External validity regarding generalizing the opinions of the respondents to the opinion of the entire organization, is ensured by careful selection of the respondents. Although the problems and solutions researched in his study are quite specific to the general contractors case, they can still be used as an example for other organisation, guaranteeing external validation that way (Golafshani, 2003).

4. Results

In this chapter the results of the research are presented. The statements made by the respondents of the first Delphi round are laid out next to the view of the respondents of the second round on those statements. The representation of the results is divided in six researcher-defined main categories of bottlenecks. These categories deviate from the 4M model used for the category distribution in the literature review, because the categories that emerged from the interviews as logical main categories of bottlenecks do not correspond to the 4M's. Therefore, each bottleneck contains multiple M's and cannot be assigned to one M specifically. Each main category starts with a section describing the bottlenecks followed by a section on the respondents' proposals for improvement on these bottlenecks.

In general, all respondents showed positivity and contentment regarding the SE application at their organisation. When presented the emerged bottlenecks from the first Delphi round, the respondents of the second round explicitly mentioned that the existence of these bottlenecks does not equal a negative SE experience. They indicated the constant development and improvement, their satisfied clients and their leading position compared to other organisations in the sector. Many of the bottlenecks that emerged from the literature review have therefore not turned out to be bottlenecks at the general contractor. Nevertheless, six bottlenecks have emerged from the interviews.

4.1 Partners perform their SE tasks too late

Bottlenecks

The first bottleneck experienced by a respondent of the first round and confirmed by all respondents of the second round, is the late performance of SE tasks – mainly requirement analysis, verification and validation – by some partners. Lack of experience with SE and the Requirements Management Software (RMS) among partners and considering SE tasks an administrative burden are argued to be the main reasons for this. The statement of the same respondent about requirements not being formulated SMART and the design not being adapted when partners perform their SE tasks too late, is neither denied nor confirmed by the other respondents.

Moreover, a SE advisor argues that partners do not always show up at SE training sessions, which is true according to the majority of respondents. However, two respondents note that this is not always the case. The advisors' opinions of partners not seeing the usefulness and necessity of the training sessions and the lack of a contractual obligation to be present as the reasons for their absence, are shared by respondents in the second Delphi round.

Improvement proposals

To ensure that partners do perform SE tasks on time, respondents propose to repeatedly collaborate the same partner organisation and employees within that organisation as done in previous comparable projects or to include the SE experience of partners in the outsourcing choices.

Another solution according to several respondents could be to offer more guidance on and clearer, phased explanation of the SE tasks and what is expected of partners, while focussing on the end goal. Besides, exerting more pressure on partners to perform their SE tasks on time is proposed by one respondent.

Finally, a board member proposes to contractually oblige partners to attend SE training sessions.

4.2 Shortage of management support

Bottlenecks

In the first Delphi round, two respondents discuss the shortage of SE support from some project managers and -directors, while they are the ones who should propagate SE towards the project team, should offer them support in carrying out SE tasks and have the ultimate responsibility over requirements and their timely verification. The majority of respondents from the second round confirm that managers do not always take that responsibility and mention this is the result of the managers having many tasks and little time, wherefore it is not given priority and of some of them having little SE experience. However, there are also two respondents in the second round who argue that the SE support from managers is already reasonably well and that these managers are aware of the urgency of offering SE support.

Besides, an SE advisor in the first round points out that he misses clear choices made by HRM regarding the tasks of SE advisors, wherefore they fall short of time to educate people on SE. Combined with a shortage of people who can perform their SE tasks independently this leads to SE advisors carrying out the actual SE tasks instead of advising on them. Respondents of the second round, however, consider this more of a personal problem instead of an overarching one.

Improvement proposals

The first proposed improvement is to partly relieve the project managers and -directors by shifting the ultimate responsibility for requirements and its timely verification from them to, for instance, the process- and design managers, while they maintain their organisational and controlling role on the progress and quality of the SE process.

Another proposal is to provide project managers and -directors who experience difficulties in offering SE support with extra guidance and explanation and possibly levers for more efficient support, and to make transparent who needs support and on what area.

4.3 Knowledge shortage of on-site employees

Bottlenecks

All respondents discuss the SE knowledge shortage of some employees who mainly work on-site, to which part of them add that especially the older people have insufficient interest in gaining this knowledge and instead want to continue working like they have always done. Therefore, implementing SE improvements on projects is difficult and creates resistance. The majority of respondents from the second Delphi round mention the inadequate connection between theory and practice as a cause for the shortage of SE knowledge. It is argued that process managers and SE advisors, who work in office, do have sufficient SE knowledge, but work as a separate group, developing SE knowledge on their own island, wherefore the SE language they use is not sufficiently recognizable for people working on-site. On that note, one respondent indicates that SE methods and guidelines are unknown or unclear for some employees, whereas others think this is no actual bottleneck and it is sufficient for these employees to know just what they need to perform their SE tasks. Another cause according to all respondents is a lack of SE experience of some employees. Due to large and long-term projects, the SE experience of employees working on one projects for a few years in a row increases slowly compared to in-office employees who concurrently work on multiple projects. Moreover, SE knowledge weakens quickly if not reapplied shortly after the first SE experience or training.

Improvement proposals

A process manager and a board member believe a translation should be made from the theory to the language of practice, so on-site employees will get a better understanding of SE. Since for them it is just important to have knowledge on their SE tasks, but not to know the whole background and that it happened to be called SE, the SE terms could be omitted.

Another proposed improvement is to make transparent who has insufficient SE knowledge and experience, for instance through a dashboard, and to focus on them.

Finally, two respondents propose to concentrate even more on disseminating SE knowledge and providing additional explanation where necessary, preferably shortly before the knowledge needs to be applied. Another respondent, however, argues that the explanation and guidance are already sufficient, but it is up to the employees themselves to be open to SE and get informed.

4.4 Employees perform the verifications too late

Bottlenecks

All respondents indicate that the verification is often performed too late in the projects' process by the responsible employees, which costs more time and energy than if performed on time. People not considering performing verifications a priority, not liking it and not seeing its usefulness, are believed to be the causes by all respondents, as are considering performing verifications an administrative burden and filling in the RMS a necessary evil to comply with the contractual agreement and get paid by the client. Moreover, the respondents all agree on verifications being time consuming and busy employees being assigned to perform verifications as an extra task, while it does not match their role.

Another discussed cause is the lack of clarity for some employees about the ultimate goal of SE, its benefits for the general contractor and themselves and the importance of performing SE tasks on time.

A delayed design of SE and the RMS due to a delay of clarity on contractual agreements is mentioned by two respondents as a cause for employees not being able to start the verifications in time. Another respondent, however, argues that this is just a former problem.

According to an SE advisor it occurs that, as a result of postponed verification, other non-authorised employees take over this task and fall short of time to perform their own tasks, which is confirmed by all respondents of the second Delphi round. This SE advisor also believes that too little attention is currently paid to the match between someone's abilities and responsibilities while assembling teams. However, two respondents refute this opinion by pointing out that responsibilities are currently in the right place and a lack of the right abilities is too easily used as an excuse for not performing verifications.

Moreover, the majority of respondents discussed that the client's demand to verify all requirements - a 100% score - costs a lot of money, time and energy, especially the last few percent's, while it is not useful and even almost impossible to verify all requirements.

Finally, the ever-changing representation of SE in the general contractors' Quality Management System (QMS) and this representation being fragmented across primary and secondary project-supporting processes, creates uncertainty among employees and is by the majority of respondents argued to be a cause of the late performance of verifications. Besides, the term 'supporting' makes the employees assume that someone will actually come to support them in performing their verifications, wherefore they postpone starting on it by themselves.

<u>Improvement proposals</u>

To encourage employees to actually perform the verifications they are responsible for themselves, two board members propose they should be called to account more explicitly and should be given additional explanation by project managers, when postponing their verifications.

A proposed improvement aiming to prevent employees from taking over each other's verification tasks is to only grant verification rights in the RMS to the people responsible for it, and provide others with a read-only permission. Even though people could still exchange their login details, taking over verifications is hampered.

For a better match between abilities and responsibilities, a respondent of the first Delphi round proposes to work with colour coding more often. The respondents of the second round, however, see this as an unnecessary proposal with no added value.

The majority of respondents believe that verifying less requirements and instead make risk-based, use-case driven and spot-checked decisions on which requirements to verify, would be an improvement. Another proposed way to verify less requirements is by only verifying the main requirements, i.e. larger groups of requirements, instead of every single sub-requirement or characteristic separately. The characteristics will then still be verified as part of the main requirement, but do not need a separate checkmark anymore, which means less administration.

Four respondents argue that clarifying the ultimate goal of SE more frequently and thoroughly and enthusing people about SE and timely performance of verification, will be an improvement. One of them also proposes to continue to inventory practical problem areas intensively, so employees can be provided tips on how to verify in a smarter and more efficient way.

The final improvement proposal of this section is made on the fragmented representation of SE in the QMS and entails a decentralized assigning of the SE tasks to the various primary processes, presenting them as an actual yet shallow design step, with a link to a central page explaining all the SE tasks. This way an clear overview is maintained, understanding the verification tasks becomes easier to employees and content changes only have to be made on the central page.

4.5 Uncertainty about validation

<u>Bottlenecks</u>

The validation of requirements in the design together with the client is, although desired, currently not performed according to one of the respondents, as the current forms of contracts do not always allow the general contractor to know the use of a building, making validating impossible. On the contrary, the majority of respondents state that the validation actually is performed, although not explicitly enough and with varying ways of documenting its results. They also mention that the client is often not willing to completely document the validation out of fear of shifting the responsibility towards themselves and uses the validation as an excuse to correct his own mistakes.

<u>Improvement proposals</u>

To improve the bottleneck of uncertainty about validation, a respondent, in whose eyes the validation is not performed, proposes that the general contractor should clearly declare its wish to validate and should indicate how they want that to be arranged contractually. Another respondent says the client should be stimulated to dare to record the validation results.

4.6 Difficulties with the use and operation of the Requirements Management Software

Bottlenecks

With regard to the use of the RMS the respondents indicated a number of bottlenecks. Firstly, the majority of them discusses that the RMS is not intuitive which, combined with a lack of clear and complete manuals, leads to fields in the RMS regularly being filled in incorrectly. The complex design of the RMS is argued to be a cause of the use being difficult to understand, especially for the ones who never used it before. Moreover, the RMS design differs per project, since it is usually determined by the client's requirement structure, making it necessary for employees to be constantly updated.

The majority respondents agree on the RMS not always operating properly, particularly in large projects with many documents when the software becomes slow and frequent clicking is needed for one thing to appear, which frustrates the already busy employees.

The next bottleneck that is indicated by the majority of respondents concerns the RMS not doing a great job in keeping together associated requirements. When the extracted sub-requirements from one main requirement or theme are loaded into the RMS separately, the cohesion gets lost and these sub-requirements will be verified by various professional disciplines and without the context of the main requirement, allowing sub-requirements to be verified while they are not verifiable yet in terms of its context.

Finally, the majority of respondents indicate that a link between the RMS and BIM is desirable, but not yet in place. They believe the organisation not investing in it, the existing systems for this link not meeting the wishes, the fear of being too far ahead of partners and clients and a lack of the necessary uniformity in language are the reasons for that. According to them, linking the requirements and supporting documents of the RMS to BIM would provide the opportunity to detect deviations between them. Two respondents, however, do not like such a development and think that the individual tools must first be further improved before such a link can be applied and that it should be applied in a slow pace for it to stay manageable.

Improvement proposals

One of the respondents states that filling in the RMS should be made more intuitive. Another proposes the use of colours to make the RMS more transparent and easier to use, but the majority of respondents from the second round do not see the added value of this. Two respondents indicate a less complex design of the RMS, to make it easier to use, as an improvement, in which those who have to work with the RMS in practice should have a bigger say in the design, instead of just the separate group of SE advisors and process managers.

The two process managers propose the use of one standard design or certain design standards for the RMS together with the client, which should bring the requirements structure and RMS design of the general contractor and its clients closer together.

To ensure that all associated sub-requirements stick together and to their main requirement, three respondents believe it would be good to stay closer to the original Requirement Breakdown Structure of the client. This will make the RMS more transparent and will reduce the experience of verification as an administrative burden and the incorrect completion of fields in the RMS.

The majority of respondents agree on the establishment of a link between the RMS and BIM, for which the software already exists, being a valuable improvement in terms of documenting verifications in BIM and entering into validation with the client using this, allowing to demonstrate whether the clients' complaints are justified. Moreover, the link reduces the experience of verification as an administrative burden, as the BIM model will serve as a document of proof for the verification and changes will only need to be adjusted in one place. A few respondents, however, believe that the link should be introduced gradually and manageably, as a sudden introduction would be too fierce and too fast for the employees to handle. They also argue that there are still too many challenges in optimizing the operation of the individual software, fearing an even more complex, less workable and slower system, which is more error-prone. Besides, they do not see the added value of a link compared to two separate systems.

5. Discussion

In this section, the researcher's interpretation of the results is discussed, combined with a comparison to literature, in order to provide the general contractor with a suitable advise.

In 2006, the general contractor started to implement SE almost from scratch and the steps that have been taken since, show the focus on SE and the recognition of its importance. The fact that the respondents can indicate the bottlenecks of the SE application at the general contractor fairly clearly, proves the advanced SE development already made and the significant current level of SE, which is confirmed by the researcher's experience and the organisation's documents. Besides, the general contractor bases its SE method on some of the most widely used and valuable SE documents and standards and possesses quite a bit of in house, and even certified, SE knowledge.

The discussion will be presented per main category together with the associated bottlenecks and improvement proposals, similarly to the results section. Although this research mainly focuses on the bottlenecks, the general experience of the SE application appeared to have quite some positive aspects as well. The bottlenecks and improvement proposals that proved to be relevant and valid in the discussion, are adapted or supplemented by the researcher where necessary and graphically presented as a poster in Appendix 1, which can be used for the third Delphi round.

5.1 Partners perform their SE tasks too late

Bottlenecks

The late performance of SE tasks – mainly requirement analysis, verification and validation – by some partners is seen as a relevant bottleneck by both the respondents and the researcher. This is in line with a previous research which states that "contractors experience problems such as the verification and/or validation not being executed by the supplier, not being complete, or not being executed at the desired level of detail" (Makkinga et al., 2018). Similarly, the lack of experience with SE and the RMS among partners and considering SE tasks an administrative burden are relevant as the causes, since it is confirmed by all respondents and the researcher's insight. Literature also recognizes these causes as important factors in the non-optimal application of SE (de Graaf et al., 2016; de Graaf et al., 2017; van den Houdt et al., 2013). However, the statement of one of the respondents of the first round that the requirements would not be formulated SMART and the design would not be adapted when requirements are missing, is not given attention to by the other respondents and not recognized by the researcher and is therefore not considered of an important value for this study.

Nearly all respondents see the failure of some partners to show up for SE training sessions as a bottleneck and so does the researcher. The opinion of two respondents that this is not always the case, is already incorporated into the description saying 'some' respondents fail to show up. Therefore it can be assumed that this bottleneck is relevant and those respondents have been lucky to coincidentally cooperate with partners who were present.

Improvement proposals

The proposal to include the SE experience of partners in the outsourcing choice is considered suitable by the researcher, as in literature experience with SE is considered essential for a smooth process and good cooperation regarding SE tasks, ultimately leading to less mistakes, overwork and costs (de Graaf et al., 2016; de Graaf et al., 2017; Makkinga et al., 2018; van den Houdt et al., 2013). The researcher prefers monitoring SE experience on beforehand over solving problems, arising from cooperating with less experienced partners, after they happened. For the same reason, repeatedly working with the same (employees within) partner organisations could be suitable, however, according to the researcher, the general contractor can only negotiate that with partners, but not enforce it.

The researcher believes that the proposal to offer more guidance on and clearer explanation of SE tasks, is not a relevant improvement, since these things are already offered by the contractor and continuing what is already being done cannot really be called an improvement. Moreover, offering more and clearer guidance and explanation entails extra time and energy, while the lack of time is already a main cause of the SE bottlenecks. According to the researcher, the proposal to exert more pressure on partners will not contribute to the partners' intrinsic motivation to perform tasks, and may actually lead to more resistance and a greater threshold to get started (SEBoK Editorial Board, 2019). However, a step by step, phased explanation is considered suitable, as it ensures that the information remains manageable for partners and the number of tasks seems smaller, wherefore it is more likely they start performing them early.

To contractually oblige partners to attend SE training sessions is not a solution to the actual problem in the eyes of the researcher, since with this proposal the cause of the bottleneck, being partners not seeing the usefulness and necessity of training sessions, remains. Mandatory presence does not evoke intrinsic motivation to learn something from the session and people will be easily distracted. A better improvement would therefore be to motivate partners for attending training sessions and to show them the benefits they could get from it in advance by presenting them the positive experiences of other partners trough a motivational video.

5.2 Shortage of management support

Bottlenecks

The shortage in SE support from some project managers and -directors is considered a relevant bottleneck by the researcher, as management plays an important role in motivating employees. Moreover, literature shows the importance of management support for a smooth and stable SE process in which tasks are well understood and performed on time by the team members and that a lack thereof likely leads to non-optimal SE application in the civil sector (Bullard et al., 2008; de Graaf et al., 2017; de Graaf & Loonen, 2018;

SEBoK Editorial Board, 2019; Walden et al., 2015). Similarly the causes, being managers having many tasks and little time, wherefore offering SE support does not get priority and some of them having little SE experience, is concurring to the researchers insight and to literature (SEBoK Editorial Board, 2019; van den Houdt et al., 2013). Since a few respondents indicate they experience the management support as positive, the researcher deduced that SE support can differ greatly per project and management on these projects. With the general contractor mainly involved in long-term projects and employees spending a number of years on just one project, it is likely that just one particular project is decisive for the employees' image of management support, although there might be other projects where a shortage of management support is an actual bottleneck. The exact source of the experience of a lack of SE support should therefore be further investigated.

The proposed lack of clear choices made by HRM regarding the tasks of SE advisors, is interpreted by the researcher, as it is by other respondents, as a personal displeasure about time shortage, which has already been indicated as the cause of several bottlenecks, but is not relevant for the overarching picture outlined in this study as a separate part of this bottleneck.

Improvement proposals

The respondents' proposal to shift the ultimate responsibility for requirements and its timely verification is not supported by the researcher. In general, the employees of the general contractor are all busy and therefore shifting this responsibility would only imply shifting the problem instead of solving it. Besides, more fragmentation of SE responsibilities would create a lack of clarity and people would no longer know who to address when SE tasks are not performed. In addition, several respondents indicated that the responsibilities are currently in the right place.

The proposal to offer extra guidance and explanation is mostly, like one of the proposals in the previous paragraph, continuing in the same direction and therefore no actual improvement. However, with some additions, this proposal could be an improvement. The researcher believes this proposal should focus on making transparent which managers have difficulties with offering SE support through, for instance, employee surveys on their satisfaction with the SE support of a particular manager, in which should be specified exactly in what area support might lack. The results can then show the managers in which area they need help, so they will be intrinsically motivated to search for it (SEBoK Editorial Board, 2019). According to the researcher another improvement would be to assign managers who have difficulties with offering SE support to a project together with at least one manager who does not experience those difficulties to allow mutual learning. Given the protracted projects of the general contractor, this will be al long-term improvement, which is challenging to apply in practice, as SE support is not the only factor that must be taken into account when assigning managers to a project.

5.3 Knowledge shortage of on-site employees

Bottlenecks

The knowledge shortage of some on-site employees is recognized as a bottleneck by the researcher and corresponds to the high influence of knowledge on SE application according to literature, which also applies to mainly older people having insufficient interest in gaining SE knowledge and the difficult implementation of SE improvements on-site (de Graaf et al., 2017; de Graaf & Loonen, 2018; Harris, 2008; SEBoK Editorial Board, 2019; van den Houdt et al., 2013; Walden et al., 2015).

The study of Elliot et al. (2012) shows the importance of simple language instead of technical jargon for good communication and collaboration with the client. Furthermore, literature indicates a lack of knowledge and attention for the practical application of SE processes (ISO/IEC-IEEE, 2012; SEBoK Editorial Board, 2019). Taking this into account, the researcher confirms the proposed bottleneck of an insufficient connection between theory and practice.

SE experience and knowledge go hand in hand, as knowledge is developed through experience and a lack of experience is a common cause of non-optimal SE application according to literature (de Graaf et al., 2016; de Graaf et al., 2017; SEBoK Editorial Board, 2019; van den Houdt et al., 2013), wherefore the researcher considers it an accurate main cause of the SE knowledge shortage.

Regarding the SE methods and guidelines that are unknown or unclear for some employees according to one respondent, the researcher joins the other respondents in their opinion of this being an irrelevant bottleneck for this study and it being sufficient for these employees to know the purpose of SE and how to perform their tasks within the SE process.

Improvement proposals

The proposal to make a translation between the theory and the language of practice is a good one in the eyes of the researcher, yet still to general. To specify this proposal, the researcher suggests to involve on-site employees who have to apply SE in practice in SE development and making this translation to more recognizable terms. This way, SE will become more accessible to them and their interest in gaining SE knowledge will increase. Elliot et al. (2012) suggests as well to "use plain language in SE documents which may be read by nonpractitioners" in order to overcome difficulties in the explanation of SE and the development SE knowledge.

The proposed improvement to make transparent who has insufficient SE knowledge and experience, for instance through a dashboard, and to focus on them, can be useful according to the researcher, since knowing the weak spots in an organisation is key to improvement. To visualise this through a dashboard, the researcher suggest to ask employees a few standard questions at the start of each project to gauge their SE knowledge and experience and to anticipate to the outcome.

The respondents' proposal to concentrate even more on disseminating SE knowledge and providing additional explanation again suggests continuing what is already being done and is therefore not considered an actual improvement by the researcher, which is supported by the respondent arguing the explanation and guidance is already sufficient. Besides, additional explanation will not address the source of this bottleneck and SE experience and knowledge will naturally increase in time over practice, as it is applied more and more at the organisation.

5.4 Employees perform the verifications too late

Bottlenecks

The bottleneck of employees performing their verifications too late is confirmed by both the researcher and literature (de Graaf et al., 2017; Hardman & Colombi, 2012; Redmond & Alshawi, 2017). Also the indicated causes, namely verifications not getting priority and being considered not useful and an administrative burden, as well as them being time consuming and assigned as an extra task, while the ultimate goal and benefits of timely performance are still unclear to some employees, are relevant and accurate according to the researcher's insight and literature (ISO/IEC-IEEE, 2015; SEBoK Editorial Board, 2019; Makkinga et al., 2018; van den Houdt et al., 2013). Moreover, both the researcher and existing literature confirm the delayed design of SE and the RMS due to a delay of clarity on contractual agreements as a plausible cause (ISO/IEC-IEEE, 2012; SEBoK Editorial Board, 2019; Walden et al., 2015; Ward et al., 2018).

Taking over each other's verification tasks, as indicated by the respondents as a result of postponed verifications, is a true story in the eyes of the researcher. This is in keeping with existing literature, which shows that the acceptance of SE by individuals is impeded if responsibilities are not taken or shifted (ISO/IEC-IEEE, 2012, 2015; van den Houdt et al., 2013).

The by one respondent mentioned bottleneck about insufficient attention for the match between someone's abilities and verification responsibilities is not confirmed by any other respondent and even denied by two. The opinion of those two respondents on responsibilities being in the right place is shared by the researcher and the aforementioned causes are rather expected to be determining for postponed verification, wherefore this bottleneck is considered irrelevant for this study.

Similarly to the majority of respondents, the researcher recognize the client's demand to verify all requirements as a relevant bottleneck and does not perceive a 100% score as an added value for the final quality of a project, but rather as an obstacle with regard to the current time shortage or employees.

The bottleneck of the ever-changing and fragmented representation of SE in the general contractor's QMS leading to uncertainty among employees, is recognized by the researcher from own experience and document analysis. Literature states that changing and unclear information leads to confusion, dissatisfaction and an impediment on the efficiency of the SE process. Similarly, employees assuming the term 'supporting' implies they will be helped with performing verifications can be confirmed by the researcher and literature (Walden et al., 2015; Ward et al., 2018).

Improvement proposals

The proposal of calling people who postpone their verifications to account more explicitly and giving additional explanation, is not considered a relevant and actual improvement by the researcher, since this is already done.

The proposed improvement of limiting the verification right in the RMS to the responsible employees only, is expected to be useful in the eyes of the researcher, although it addresses one of the symptoms rather than the actual causes of this bottleneck.

Using colour coding for a better match between abilities and responsibilities is indicated as an unnecessary proposal with no added value by both the researcher and other respondents. Besides, it has also just been shown that the bottleneck for which this would be an improvement is not seen as a relevant bottleneck, making this improvement superfluous.

The various proposed ways of verifying fewer requirements are considered to be practical and easily applicable by most respondents and the researcher. However, these require intensive consultation with the client.

Clarifying the ultimate goal of SE more frequently and thoroughly and enthusing people about SE and timely performance of verifications, which is proposed as an improvement by some respondents, is by the researcher again seen as continuing what is already been done. The proposal to continue to inventory practical problem areas intensively, however, is considered a good one in the eyes of the researcher, although quite obvious and not innovative.

The last improvement proposed by the majority of the respondents, being a decentralized assigning of SE tasks to the various primary processes with a link to a central explanation page, is by the researcher considered as a very relevant and practically applicable improvement that provides more clarity and a better findability of the verification process, making it more attractive to perform verifications immediately (de Graaf et al., 2016; ISO/IEC-IEEE, 2012; Ugurlu et al., 2016).

5.5 Uncertainty about validation

Bottlenecks

Just one respondent argues that validation is currently not performed, whereas the others argue it is, although not explicitly enough and with varying ways of documenting its results. Considering this, the researcher assumes the latter is correct and concurrently forms the reason for the one respondent believing validation is not performed. However, the only thing that can be surely concluded is that there is a level of uncertainty about whether or not the validation takes place. The researcher believes that the respondents' statement about the client often not willing to completely document the validation out of fear of shifting the responsibility towards themselves and using the validation as an excuse to correct his own mistakes, is plausible. Besides, existing literature shows that a lack of clarity and traceability of information could lead to misunderstandings, dissatisfaction and errors and does not benefit the cooperation between client and contractor, which makes this a relevant bottleneck (de Graaf et al., 2016; de Graaf et al., 2017; ISO/IEC-IEEE, 2012; Makkinga et al., 2018; Ugurlu et al., 2016).

Improvement proposals

Since the proposal about the general contractor declaring the client its wish to validate including the way they want to contractually arrange that assumes that the validation is currently not performed, the researcher believes that, instead of declaring this, the general contractor should enter into a conversation with the client on how to arrange and document the validation. The proposal to ensure that the client dares to record the validation then becomes superfluous, as they can prevent their fears and propose solutions through the conversation.

The researcher believes that, in order to tackle the problem of validation uncertainty at its source, the general contractor should refine its validation protocols and manuals, collect them in one accessible spot and communicate them to the employees. It is important for the general contractor to invest in clarifying the uncertainties about validation. This improvement is in line with the study of de Graaf et al. (2016), which aims to "limit failure costs by improving clarity, traceability, and demonstrability of the processes of the firm" and states that clear procedures should be established in order to do so.

5.6 Difficulties with the use and operation of the Requirements Management Software

Bottlenecks

The by the majority of respondents indicated bottleneck of the RMS not being intuitive which, combined with a lack of clear and complete manuals, leads to the RMS being filled in incorrectly, is a plausible and relevant bottleneck according to the researcher, given that all these respondents have experienced the use of the RMS not being intuitive. The same applies to the RMS' complex and project-varying design and slow operation, which is likely to cause irritation, misunderstanding and dissatisfaction in the eyes of the researcher. This is in keeping with existing literature, which states that easy and fast access to and operation of tools play an important role in preventing dissatisfaction and frustrations about the application of SE processes (ISO/IEC-IEEE, 2012; SEBoK Editorial Board, 2019).

The bottleneck of the RMS not doing a great job in keeping together associated requirements is considered plausible and relevant. Not only in the eyes of the researcher and the majority of respondents, but also compared to literature, which states that software tools, and in this case their operation, often prevail the SE process without properly taking into account the practicality for people who have to work with it (SEBoK Editorial Board, 2019). Employees do actually need the context for proper verification.

The link between the RMS and BIM is an interesting technological development according to the researcher. Despite two of the respondents not being enthusiastic about this link, the researcher believes that their conservative ideas are not conductive for the development of the general contractor itself, nor for the already conservative construction industry in general. Other industries, such as the infrastructure industry, should be taken as an example for the way of coping with technological developments.

Improvement proposals

The first proposal to make filling in the RMS more intuitive and easier in use is supported by the researcher, however, it should be further specified to make it an actual improvement. Using colours for that is considered of no added value by both the researcher and the majority of respondents. On the other hand, involving people who have to work with the RMS in the decisions on its design as proposed, is a meaningful and practically applicable way to specify this improvement according to the researcher.

The proposal of using a standard RMS design together with the client, which is increasingly applied in the infrastructure industry as well, could be a useful improvement in the eyes of the researcher. Standardization provides more clarity and fewer errors, although the researcher expects it to be difficult to get all clients to agree on one standard design and therefore proposes to initiate a conversation with the client and work on the standardization of individual elements in the design as a first step. This is in keeping with the study of van den Houdt et al. (2013), which states that "standardization establishes principles of integrity, propriety and trustworthiness that establish the confidence to cooperate", while emphasizing the importance of reaching agreement with the client on the proposed standardisation.

Ensuring the sub-requirements stick together and to the associated main requirement by staying closer to the original Requirement Breakdown Structure of the client is expected to be a useful improvement by the researcher, although the general contractor should bore in mind that the standard RMS design is not compromised.

The final improvement proposed by respondents, being the introduction of a link between the RMS and BIM, is considered to be a good improvement and an interesting technological progress by the researcher. Besides, this improvement will address the interoperability issue between various tools, which is indicated in the literature review, as the link will facilitate the exchange and use of information between the different tools, reducing a major source of dissatisfaction in the construction industry (Chami & Bruel, 2018; ISO/IEC-IEEE, 2012; SEBoK Editorial Board, 2019; Walden et al., 2015). A gradual and manageable introduction of this link, proposed by the resistant respondents, would in the eyes of the researcher imply that, since the employees are often assigned to one large project for a couple of years, the link can only be used partially at the start of a new project. However, the advantages of the link are reached if there is clarity about whether or not to use it and if the general contractor shows confidence in the link by making full use of it for the entire project. To test such a link and prove the benefits it could first be tried in a pilot project and resistant employees could be convinced by giving examples of the benefits and making sure the link works well from the start.

For the indicated bottleneck on the lack of clear and complete manuals for the RMS, the researcher proposes to improve the completeness, findability and ease of use of current manuals and possibly add some video tutorials on the RMS, which is often more appealing to users than verbatim manuals.

6. Conclusion

In this study, the bottlenecks and associated causes and consequences that play a role in the application of technical SE processes at the general contractor have been identified. For these bottlenecks improvements are proposed that seem to be suitable, to provide the general contractor with an advice on the development and improvement of its SE application. This study used existing scientific literature on the application of technical SE processes in the construction industry, the opinion of interviewed employees of the general contractor serving as the case for this study and the insight of the researcher. Finally, a poster is designed to visualize and present all findings.

It can be concluded from this study that the dissatisfaction among SE experts of the general contractor regarding the application of technical SE processes, which gave rise to the study, is limited and that positivity predominates in the eyes of the employees when it comes to SE application. Nevertheless, the nature of the dissatisfaction has been revealed, hence resolving the uncertainty on the topic. Partners performing their SE tasks too late, shortage of management support, knowledge shortage of on-site employees, employees performing the verification too late, uncertainty about validation and difficulties with the use and operation of the RMS are the main bottlenecks deducted from this study. The mapped and elaborated bottlenecks will support the general contractor in its goal of continuous improvement. Moreover, this early detection of bottlenecks allows for early problem-solving and hence prevents the things currently experienced as bottlenecks from growing into major sources of dissatisfaction. This applies not only to the studied general contractor, but also to other organisations from within and outside the construction sector who can use the lessons-learned from this study to analyse the presence of the bottlenecks at their own organisation, prevent them from occurring or apply the improvement proposals if they already have.

7. Limitations and future research

This research has two main limitations. First, this study is limited to the subjective opinion of eight respondents, which is not a complete representation of whether or not there is dissatisfaction regarding the SE application among employees, since the respondents mainly consider the topic from their own point of view. When selecting the respondents, the researcher did however take into account a variation in functions, workplace and hierarchical position in the organization. Besides, The pool of respondents is limited to the general contractors' employees only, while a number of indicated bottlenecks concern partners and clients, which makes their opinion on these bottlenecks interesting as well. On top of that, some of the improvement proposals associated with these bottlenecks require the assistance of and cooperation with them, which cannot be controlled only facilitated by the general contractor. In a follow-up study, a larger group of respondents could therefore be selected, including people from the partners' and clients' side.

Second, this research, using the Delphi method for data collection, is limited to the first two rounds of this method due to lack of time. The third round, which is important for reaching a higher level of consensus between respondents, will have to take place beyond this study and could be conducted by an employee of the general contractor using the manual and poster produced by the researcher. The implementation of the proposed improvements is beyond the scope of this study as well and therefore further research could focus on assessing these improvement proposals.

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Appendix


Application of Systems Engineering
Partners perform their SE tasks too late
BOTTLENECKS
▪ Some partners perform SE tasks (requirement analysis, verification and validation) too late.
▪ Partners have a lack of experience with SE and the RMS.
▪ Partners consider SE tasks an administrative burden.
▪ Partners do not always show up at SE training sessions.
▪ Not all partners see the usefulness and necessity of attending training sessions.
▪ Presence at SE training sessions is not contractually obligated for partners.
IMPROVEMENT PROPOSALS
▪ Repeatedly working with the same (employees within) partner organisations.
▪ Include the SE experience of partners in the outsourcing choice.
▪ Clear and dosed explanation of SE tasks with focus on the end goal.
▪ Motivate partners for SE tasks and training sessions by presenting them the positive experiences of other partners (e.g. through a short video). (R)
Shortage of management support
BOTTLENECKS
▪ Shortage of SE support from some project managers and – directors when performing SE tasks.
▪ Project managers and -directors do not always take their responsibility in propagating SE towards the project team.
▪ Mainly project managers and – directors with a lack of SE experience fall short in offering support.
▪ SE does not always get priority due to a lack of time.
IMPROVEMENT PROPOSALS
▪ Make transparent which managers have difficulties with offering SE support and in what area (e.g. through employee surveys), so these managers know that they have to ask for help. (R)
▪ Assign managers who have difficulties with offering SE support to a project together with at least one manager who does not experience those difficulties to allow mutual learning. (R)
Knowledge shortage of on-site employees
BOTTLENECKS
▪ SE knowledge shortage of some employees who mainly work on-site.
▪ Insufficient interest of older people in gaining SE knowledge.
▪ Difficulties with the implementation of SE improvements at projects.
▪ Inadequate connection between theory and practice.
▪ A lack of SE experience as the main cause.
▪ Employees work on one project for a few years in a row, wherefore experience is built op slowly.
▪ SE knowledge weakens quickly if not reapplied shortly after the first SE experience or training.
IMPROVEMENT PROPOSALS
▪ Make a translation from the theory to the language of practice by involving on-site employees who have to apply SE in practice in SE development and the translation to more recognizable terms. (R)
▪ Make transparent who has insufficient SE knowledge and experience, through a questionnaire at the start of each project (R) and an online dashboard, and focus on these people.
Employees perform the verification too late
BOTTLENECKS
▪ Verifications are often performed too late in the process by the responsible employees.
▪ Verifications do not get priority and people do not like it or see its usefulness.
▪ Performing verifications is considered an 'administrative burden' and is time consuming, while people are already busy.
▪ People often get performing verifications as an 'extra task'.
▪ A delayed design of SE and the RMS due to a delay of clarity on contractual agreements, resulting in late performance of verifications.
▪ Other non-authorised employees take over the verification task and fall short of time to perform their own tasks.
▪ The client demands the verification of all requirements, which takes time, money and energy, but is not useful or possible.
▪ Lack of clarity for some employees about the ultimate goal of SE, its benefits and the importance of its timely performance.
▪ An ever-changing and fragmented representation of SE in the general contractors' QMS leading to uncertainty.
▪ Employees assuming the term 'supporting' implies they will be helped with performing verifications.
IMPROVEMENT PROPOSALS
▪ Only grant verification rights in the RMS to the people responsible for it (and provide others with a read-only permission) to prevent the over-taking of verification tasks.
▪ Verify less requirements by making risk-based, use-case driven and spot-checked decisions in which requirements to verify or by only verifying the main requirement instead of all sub-requirements separately.
▪ Clarifying the ultimate goal of SE more frequently and thoroughly and enthuse people about SE and timely performance of verification.
▪ Inventory practical problem areas intensively and respond to that.
▪ Assign the SE tasks decentralized to the various primary processes in the QMS, presenting them as an actual yet shallow design step, with a link to a central explanation page.
Uncertainty about validation
BOTTLENECKS
▪ Uncertainty about whether or not the validation with the client takes place.
▪ The validation is not performed explicitly enough.
▪ The validation results are documented in various ways.
▪ The client is often not willing to completely document the validation out of fear of shifting the responsibility towards themselves.
▪ The client sometimes uses the validation as an excuse to correct his own mistakes.
IMPROVEMENT PROPOSALS
▪ Enter into a conversation with the client on how to arrange and document the validation. (R)
▪ Refine the validation protocols and manuals, collect them in one accessible spot and communicate them to the employees. (R)
Difficulties with the use and operation of the RMS
BOTTLENECKS
▪ The RMS is not intuitive which, combined with a lack of clear and complete manuals, leads to fields being filled in incorrectly.
▪ The RMS' complex and project-varying design makes its use difficult to understand and leads to employees constantly needing to be updated.
▪ In large projects with many documents, the operation of the RMS is slow and frequent clicking is needed for one thing to appear.
▪ The RMS not doing a great job in keeping together associated requirements. When the extracted sub-requirements from one main requirement or theme are loaded into the RMS separately, the cohesion gets lost and these sub-requirements will be verified by various professional disciplines and without their context.
▪ A link between the RMS and BIM is desirable and would provide opportunities for the general contractor, but is not yet in place.
IMPROVEMENT PROPOSALS
▪ Improve the completeness, findability and ease of use of current manuals for the RMS and add video tutorials. (R)
▪ Make filling in the RMS more intuitive and easier in use by involving those who have to work with the RMS in the decisions on its (less complex) design.
▪ Work on the use of one standard design of (elements in (R)) the RMS together with the client.
▪ Ensuring the sub-requirements stick together and to the associated main requirement by staying closer to the original Requirement Breakdown Structure of the client.
▪ Introduce a link between the RMS and BIM, so the BIM model can serve as a document of proof for the verification and changes will only need to be adjusted in one place.