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Challenges of using systems engineering for design decisions in large infrastructure tenders

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Decision-making in the tender phase of large, multidisciplinary, integral infrastructural projects is a complex task for contractors. They have to make decisions in design, construction, maintenance and regularly financing that will have long-term effects based on complex client requirements. The constrained environment of a tender, such as limitations of time and budget, and the unique context of every tender add more complexity. Therefore, no standard models are available for structuring the decision-making process in public tender procedures. Introducing systems engineering (SE) in the construction industry has led to more structured, process-based working methods. Dealing with uncertainty in design information due to the low level of concrete specifications is for the contractors' decision-making process still a significant challenge. As a result, contractors struggle with designing a solution that will not only persuade the client, but will also deliver the optimum value and reduce the risks associated with building and maintaining the proposed solution. In this paper, we explore challenges of using SE and the multi-criteria analysis techniques in a large infrastructure tender to support the decision-making. We report our initial findings of this in-depth single case study involving document studies and open interviews with the tender team. We found that the decision-making is not always done systematically and transparently, and can benefit from explicitly dealing with design uncertainty to create early understanding of the system. Besides, we found that assigning design responsibilities between subsystems lacks guidance for organizing a collaborative decision-making process. We make proposals for further research and recommendations based on these initial findings.

Keywords: Design decisions, infrastructure tenders, systems engineering.

Introduction

In recent years, contractors have increasingly been in charge of the design, building and maintenance of large infrastructure projects through integrated contracts. Using integrated contracts results in a design responsibility shift from the client to the contractor, and the contractor becomes responsible for a larger part of the project life cycle. Although integrated contracts create opportunities for life-cycle-oriented design optimizations, contractors need to anticipate the long-term effects of design decisions during the tender phase which places large information needs on tender teams (Evbuomwan and Anumba, 1998). However, due to the competitive nature of the tender phase with its time, resource and budget constraints, tender teams are often forced to take design decisions without completely knowing the entire infrastructure requirements, its environment of operation, future design decisions and emergent infrastructure behaviour (Aughenbaugh and Paredis, 2004). When submitting the bid a hard decision gate with a fixed price is reached. At this point about 70% of the life-cycle costs are defined even though design uncertainties can be still large (Sanders and Klein, 2012; Walden *et al.*, 2015). Translating the client's reliability, availability, safety, environmental and financial requirements into a design solution that maximizes the probability of

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winning the contract but also allows the evaluation of the risks associated with building and maintaining the proposed infrastructure represents a challenging task for many contractors.

In order to deal with the increased complexity in infrastructure design processes, the greater technological opportunities, the multifaceted client requirements and the greater interoperability with other infrastructure systems, contractors have started to adopt systems engineering (SE) as a guiding design principle and approach (SEATC, 2000). SE takes designers through a series of processes which support analysing the interactions between requirements, subsystems and organizations. The origins of SE can be traced back to the 1930s (Walden *et al.*, 2015). The first significant development was made by the US Department of Defence in the 1950s and since then researchers and practitioners from various disciplines and fields (e.g. aerospace, space, manufacturing and software) have further developed and contributed to the approach (Brill, 1998). Despite the widespread use and successful application of SE for complex projects and design tasks in various industries, previous research has shown that the contextual setting of industries, organizations or projects can lead to SE implementation barriers (Elliott *et al.*, 2012). These barriers are focused on the project phase, not on the tender phase of projects. The impact of the tender context on the applicability of SE in infrastructure projects has not been previously studied, while SE has been implemented widely in the construction industry.

In this paper we argue that the tender phase of large, integrated infrastructure projects poses challenges for contractors in applying SE for design decisions support due to time and resource constraints inherent to tenders. By using the insights gained during the tender phase of an infrastructure project in the Netherlands we explore the challenges that arise when contractors use SE in the context of an infrastructure tender and define the impact of these challenges on design decisions. In the following we give a short overview of SE as an engineering management process and we address its application in the context of public tendering. We then explain our research design followed by the results of our case study. The challenges of SE in an infrastructure tender for the design decisions are discussed. We conclude with some practical recommendations and outlook for further research.

Conceptual background

SE overview

SE can be defined as 'an interdisciplinary engineering management process that evolves and verifies an integrated, life-cycle set of system solutions that satisfy customer's needs' (Defense Acquisition University Press, 2001; Friedman and Sage, 2004). SE covers a broad set of processes and methods that systematically analyses interactions among requirements, subsystems, constraints and components. It is seen as being particularly useful for the management of problem-solving processes in the context of challenging socio-technical questions and large projects with object complexity, where it is difficult to efficiently develop, implement and control a sustainable solution due to the many stakeholders involved (Züst and Troxler, 2006). Various authors have analysed the value of SE, highlighting the positive impact on costs, quality, time and risk (Locatelli *et al.*, 2014).

The purpose of applying SE is to improve understanding of the system as a whole, and to use this understanding to improve the decision-making throughout a system's life cycle (Yahiaoui *et al.*, 2006). Decisions that have to be taken relate to the following main life-cycle phases of SE (Friedman and Sage, 2004):

(1) Requirements definition and management phase: the phase in which a coherent and traceable specification and translation of requirements, from top-level specification to all lower levels of the system being engineered, is established.
(2) System architecting and conceptual design phase: the phase in which the system baseline architecture is established early in the project.
(3) Detailed system and subsystem design phase: the phase in which a logical and orderly design process is established through functional decompositions and design traceability. Originating with the system functional architecture and resulting in design specifications for the system being engineered.
(4) Systems and interface integration phase: the phase in which the total system functionality throughout its life cycle is established by system integration and interfaces at each of the subsystems and component levels.
(5) Validation and verification phase: the phase in which every requirement which requires validations and verification shall have a test and every test shall have a requirement.
(6) System deployment and post deployment: Supporting and recommending possible changes in the system design or support through reengineering.

The connection between these life-cycle phases are described in literature, using various life-cycle models such as the Waterfall, Spiral or V-model (Royce, 1970; Boehm, 1988; Forsberg and Mooz, 1992). The V-model, as shown in Figure 1, is the most commonly used model as it accurately represents the system's evolution from the perspective of decomposition and integration activities (e.g. design and built) (Aughenbaugh and Paredis, 2004; Forsberg *et al.*, 2005). The numbers in Figure 1 correspond with the life-cycle phases described above. The left side of the 'V' represents the system's decomposition and the right side represents the subsystems' integration. Figure 2 shows that at each level of the V-model, an iteration takes place between function analysis, requirements analysis and synthesis (Defense Acquisition University Press, 2001). This systematic working method supports the design decision-making process. At each level of the V-model, design decisions influence how the system will fulfil its functions and how the levels of design freedom are reduced. The iterative process continues by defining underlying functions and requirements for the development of the system.

In this iterative design process, engineers have to find the most appropriate solution by examining many potential alternatives using comprehensive technical knowledge and judgement. Design engineers and managers work in multidisciplinary teams (Shen *et al.*, 2010) and are spending much time discussing various opinions and dealing with interface problems that arise between various responsible subsystem engineers (Bernold and AbouRizk, 2010). For example, functional requirements might restrict the design of interacting subsystems. Under these conditions, the decomposition of a subsystem requires many interactions to correct mistakes that are made early and to be able to verify the complex decision-making process (Suh, 2006). This requires trade-offs between performance, cost and schedule, as it is impossible to optimize all three simultaneously and forms one of the basic principles of SE (Kossiakoff *et al.*, 2011). For example, the functional requirement indicating the minimum driving-comfort-level restricts the radius of a bend in a road beneath a cross-over. A possible change in the alignment of the road as a result of a design change in the cross-over conflicts with the functional requirement. Engineers of various subsystems have to solve this design problem. Trade-off management supports this decisions-making process, solving conflicts and satisfying stakeholders needs, requirements and constraints (Locatelli and Mancini, 2012). In the early stages of a project, it is useful to examine alternatives and establish the system configuration; in later stages it is useful to examine lower-level system elements and decide on component configuration.

In other words, SE is a multidisciplinary approach aimed at enabling the realization of successful systems in complex environments (Walden *et al.*, 2015). In order to do so, customers' needs and required functionality are defined early in the development cycles, followed by design synthesis and system validation while considering the complete problem. This is achieved by iterating between function analysis, requirement analysis and synthesis at each stage of the design.

The context of tendering large-scale construction projects

The realization of construction projects start with the definition of the customers' needs and required functionality by the client, mostly complemented with a preliminary design. So, the client starts the SE approach at the upper left side of the V-model (Figure 1) and with the first iterations between the life-cycle stages. After this moment, if the project is procured publicly, the public procurement of the project starts. In the construction industry these public tenders are characterized by:

(1) competitive contracting (Ballesteros-Pérez *et al.*, 2012)
(2) unclear information (Laryea and Hughes, 2008)
(3) limited time
(4) limited resources

Competitive contracting means that the contractor needs to come up with a solution that is more valuable (price–quality ratio) to the client than solutions submitted by other bidders, and at the same time is viable from a business perspective. The process of finding the most valuable proposal requires linking the attribution of design decisions, at each level of the V-model, to the performance of the whole system. A classification for these attributes, ordered by increasing complexity, is given by Aughenbaugh and Paredis (2004):

(1) Systems composition (or compliance) attributes: these attributes depend on the way components are aggregated to the system level using a budget approach, such as mass and distance.
(2) Systems structure attributes: these attributes depend on the way the components are structured in the system, such as cost, construction time and settlement time.
(3) System operation attributes: these attributes depend on the way the components are combined, such as reliability and grounding of equipment.
(4) Complex emergent behaviour attributes: These attributes depend on the way the operational behaviour or value of the system is defined, such as availability, functionality and sustainability.

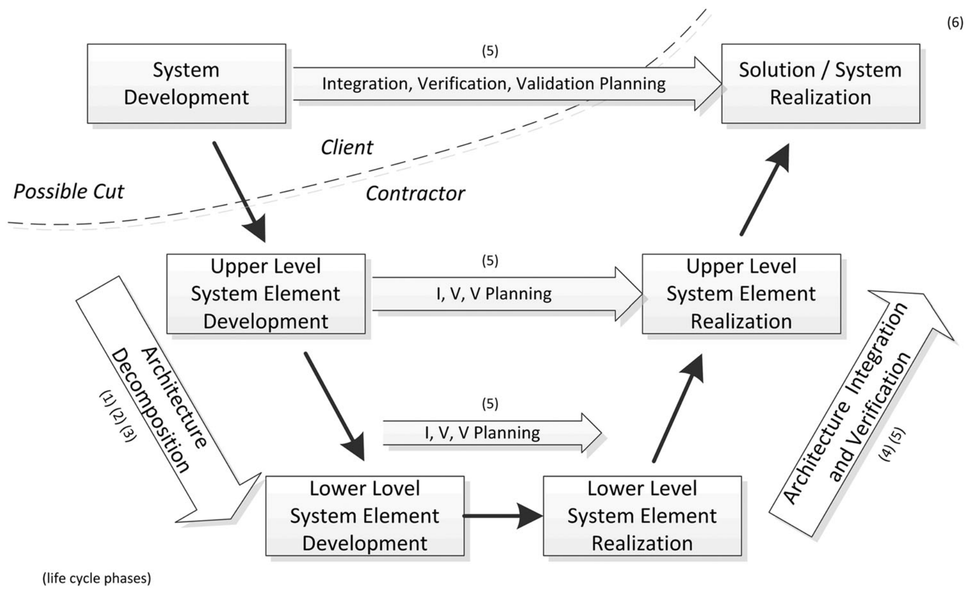

Figure 1 V-model based on: (Forsberg *et al.*, 2005)

In large and complex designs, such as large infrastructure projects, the complex system attributes cannot be known by simply aggregating components to system level. Analysis of detailed areas, for example, elements, is necessary to support the decisions at the system level. During the design phase, decisions about the design are made using trade-offs. Potential alternatives need to be scored requiring a large amount of technical knowledge and judgement. However, the availability of technical knowledge and

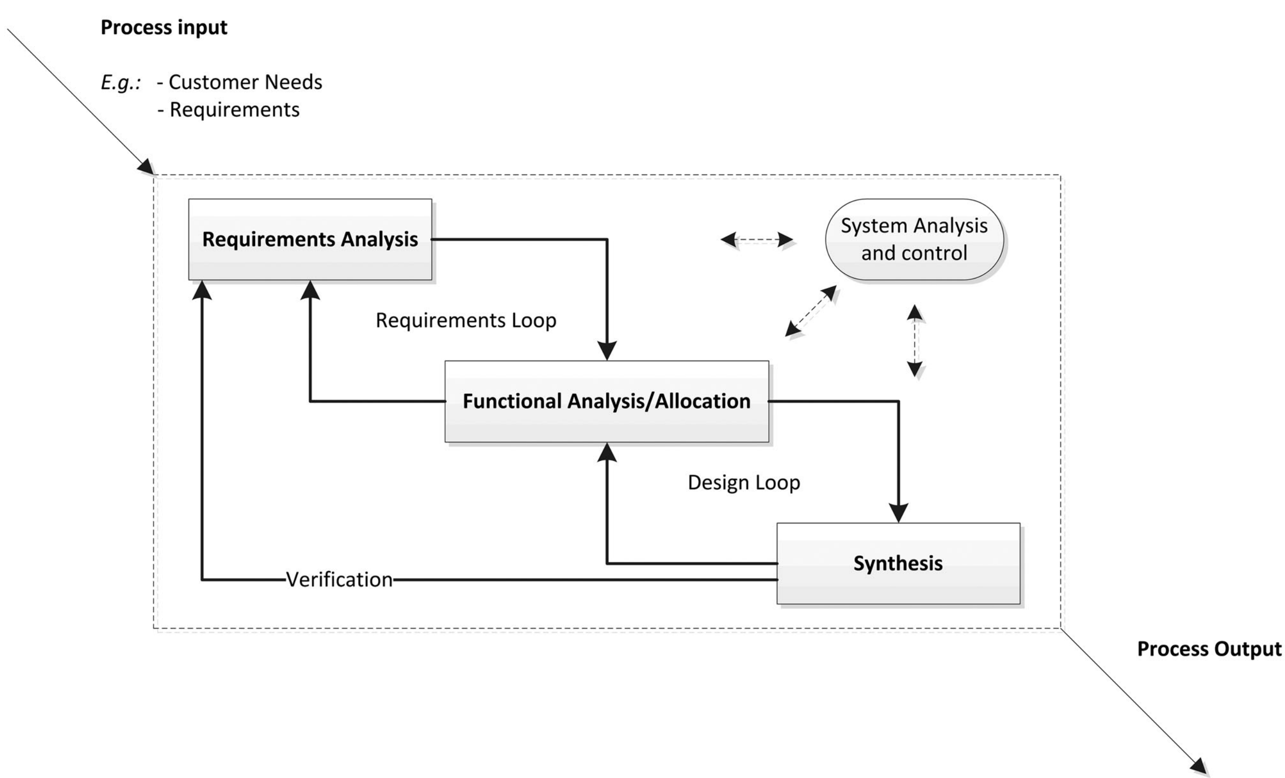

Figure 2 Iteration process based on: (Defense Acquisition University Press, 2001)

judgement is constrained by limited *time* and *resources*, and the tendering process takes place in a changing and dynamic environment which means that *information* is usually both incomplete and unclear (Laryea, 2013).

The iterative approach of SE can be used to improve the decisions throughout the life cycle (Yahiaoui *et al.*, 2006). Then, the decomposition follows the iteration between functional analysis and physical design as described in SE literature. Once a design decision is made, this results in a more detailed decomposition. However, the design process in public tenders is interrupted at the moment the tender is issued by the client and the bid is summited by the contractor, shown in Figure 1 by the dotted line (Borches, 2010). In other words, the procurement procedures in a public tender constrain the iterative process inherent to SE. The contractor is challenged to make decisions based on incomplete design specifications that finally lead to uncertainties about the return on investment for the contractor. Without the complete system design, the design performance developed by tender teams lack the support of defined, more complex, attributes. Therefore, engineers need to understand the nature of the uncertainty involved, to be able to make and redefine their design decisions. The SE approach as prescribed in literature appears to be limited in its applicability for design decisions in construction tenders and it is this contextual limitation that leads to the main research question addressed in this paper: What challenges do contractors face when using SE to support design decisions in large, integrated infrastructure tenders? By answering this question we intend to contribute to the literature on SE applications in project-based firms and the further development of the SE approach for decision-making in construction projects.

Research design and methods

In order to answer our research question, we conduct a single case study. The rationale for studying a single case is the limited understanding of the contextual impact of construction tenders on the application of SE for design decisions. Furthermore, the application of SE in practice can be best illustrated by using case studies (Friedman and Sage, 2004) and the selected case can be seen as being a typical tender for larger, integrated infrastructure projects (Yin, 2003). We selected the researched tender as it was issued on an integrated project (Engineering and Construct) for which SE was prescribed by a port authority in the Netherlands. The project included a main traffic junction as part of an infrastructure development area. There were many interfaces with stakeholders, and the construction phasing had to minimize delays for the area development. A referential design was part of the tender and served as a feasibility study for the port authority. In total, five organisations located in the Netherlands tendered four months for the contract. In the Dutch construction industry, the introduction of SE resulted in the reconsideration of design practices by large Dutch contractors (BAM, 2008). They rely on SE to address the design challenge of complex projects (Van Ark, 2013). The researched tendering entity was a joint venture between two large Dutch contractors with sufficient experience with this type of contract, including SE. The tender team consisted of a tender manger, integral design manager and cost specialist supported by several engineering specialist and design managers. The team had about nine weeks for the design and another four weeks for finishing the bid. The characteristics of the selected tender represent the described context with limited time, resources, competition and unclear information.

The data collection included participatory observations, interviews and document study (minutes of meetings, schedules, project-reports). The first author was actively involved in the researched organization and the tender as system engineer. There were about 60 days of contact with the team during the 13 weeks of tendering. This gave the researcher full access to all project data to ensure reliability, and allowed the researcher to be present at relevant tender meetings such as weekly team meetings, peer-to-peer desk-meetings and ad-hoc meetings. During the meetings the interactions of the tender team were observed in terms of the design issues discussed and the uncertainties in design decisions addressed. Due to the active participation of the researcher in the meetings, observations could not be directly noted but were recorded as an outcome of reflections of the researchers taking place after the meetings. The possible bias created by the active involvement of the researcher is minimized using data triangulation.

According to Friedman and Sage (2004) the difficulty with SE case studies is to clearly distinguish the SE concepts during the iterative process. Therefore, they developed a framework for case study evaluation of SE concepts, which makes it possible to illustrate related case studies. The entire framework has nine general SE concepts, of which six concepts are considered most relevant to SE as they represent the phases in the SE life cycle: (1) Requirements definition and management, (2) System architecting and conceptual design, (3) Detailed system and subsystem design, (4) Systems and interface integration, (5) Validation and verification, and (6) System deployment and post deployment. We used the six SE life-cycle phases to structure our data collection and analysis to reveal the challenges faced by contractors using SE.

Semi-structured interviews with six key players of the tender team (including the tender manager, design managers, architect and cost-specialists) were held about six months after the tender was summited. These six players contributed to the design process throughout the tender and were involved in the final design decision-making. Each interview lasted for about one hour, was recorded and then transcribed. A business model review and day-to-day involvement of the researcher in the project provided the basic input for the interviews. Interviewees were asked to chronologically describe the sequence of events, using the first five life-cycle phases of SE as themes (Friedman and Sage, 2004). The final phase, system deployment and post deployment, was not part of the tender and therefore not addressed. The challenges, such as design issues and uncertainties in design decisions, described in each life-cycle phase by the interviewees were further explored to find the difficulties of applying SE. The interviews were analysed by indexing the statements based on the SE concepts defined by Friedman and Sage (2004) and we used the classification of Aughenbaugh and Paredis (2004) to analyse the discussed designs decisions. The statements were verified using the produced tender documents, for example, the design documents and minutes, and checked with the constructed timeline of the tender (Figure 3). The interview results were checked for inconsistencies with the tender documents and the co-authors and interviewees reviewed the results.

Case description and analysis

Figure 3 shows the timeline of the tender including the relevant activities of the life-cycle stages as described by Friedman and Sage (2004). The Roman numbers within square brackets relate to the relevant activities in Figure 3. In the following we elaborate more on the six SE life-cycle phases and how the tender context influences the design decisions during the phases.

Requirements definition and management

The main challenge for the tender team was to understand the referential design and explore feasible and competitive optimizations within a short period of time. The tender team started with a kick-off meeting [I]. They did not familiarize themselves with the client requirements as a means to enlarge their creativity. The effect of this kick-off meeting on understanding the referential design is described by the design manager and architect as: 'People automatically discussed their ideas when walking around the posters imagining the referential design'. 'We were thinking integrally; together searching for solutions and value. Everyone was working for the project instead of their own discipline'. Bringing together the knowledge of several specialists in a workshop using creativity techniques, a site visit, and presentations had a positive collaboration effect. The architect summarized this effect as: 'At a social-level, we were a team. The differences between the disciplines were not evident, I really did not know who was working for what discipline'. At the end of the second day, the explored optimizations based on functional requirements were discussed in the client meeting [II]. After this client meeting, the team started to elaborate on two major design optimizations. In the next four weeks, the design requirements in the contract, potential risks, interfaces and optimizations of the referential design were analysed. This means that both the requirements loop and the design loop were compared based on the referential design (Figure 2). The results of this analysis were documented in several design reviews [III]. The requirements analysis [IV] was used to verify if the referential design would meet the contractual requirements, as well as what possible risks the design optimizations would create. In these four weeks more detailed design documents, such as specific regulations for working with high-voltage cables [V], were reviewed and consequences for the design were considered by the engineers. The minimum distance between equipment and the high-voltage cable was estimated to decide on a construction method and effective grounding systems. The regulations were not translated into detailed requirements by the engineers due to the limited available time and conceptual design stage. The design decisions (Table 1) were directly drawn on the conceptual drawings. As a result of the limited availability of time and resources, the alignment of the design loop and the requirements loop did not sequentially grow. New or changed information to reduce epistemic uncertainty could not explicitly be studied on possible design consequences. Therefore, the relevant regulations could not be verified without the implicit knowledge of engineers.

System architecting and conceptual design

The system architecture was given by the client and was in line with the referential design. The challenge for the tender team was to understand the system architecture and the corresponding functionalities before allocating design responsibilities. An example of such a situation is the panel design of the construction ramp [VII]: the panelling was designed based on an architectural function by the client. The allocation of the design responsibility was therefore allocated to the road discipline. However, the ramp could benefit from adding a soil-supporting function to the panelling (Table 2). This thinking was described by the tender manager:

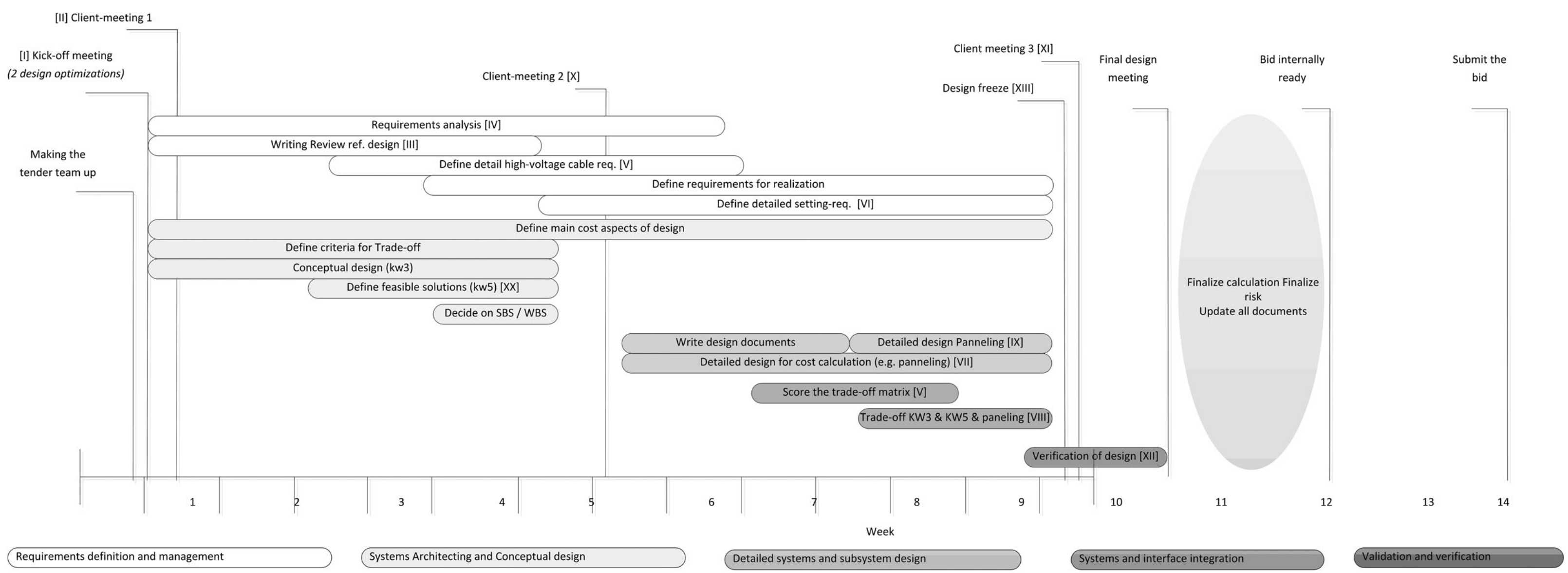

Figure 3 Timeline of tender

Table 1 Attribution of design decisions relevant in the requirement definition and management phase

Phase	Design decision	Attribute	Explantion
Requirement definition and management	Elaborate on two optimizations	System composition	Not explicitly mentioned
		Systems structure	*Costs* and *time* of referential design checked
		System operation	Not explicitly mentioned
		Complex emergent behaviour	*Functionality* was determined based on experience of experts. No attributions were defined
	Check specific regulation documents	System composition	*Distance* between equipment and high-voltage cable was estimated to decide on construction method
		Systems structure	Not explicitly mentioned
		System operation	*Effective grounding* for equipment
		Complex emergent behaviour	Not explicitly mentioned

> The scope allocation was unclear. The soil-supporting construction was allocated to the road discipline [as this had no structural role], while it should be allocated to the civil discipline [as this did have a structural role]. As a result, this object became stuck between two disciplines.

This optimization was found around week 6, when several feasible solutions for the ramp were already defined. Engineers had to redesign their solutions and could make the final decision based on a trade-off [VIII] only at the end of the design. Time to further develop this alternative was not available anymore, which had consequences for the detailed design.

Detailed system and subsystem design

The systems' architecture defines the detailed system and subsystem design, and creates interfaces between subsystems. Each subsystem should be designed within the defined interfaces and required design information from decisions made in other subsystems. An integral design manager facilitated concurrent design between three design-managers (including civil design manager, road design manager and rail design manager) to make sure that milestones were achieved and interfaces were discussed. In weeks 3 and 4 feasible solutions for construction 5 were determined [XX]. Design information not available within the feasible solutions consisted of interdisciplinary interfaces and unavailable technical information. The possible optimization of the panelling was found around week 6. Parameters to determine pre-loading periods of soil [VI] were needed as input for the trade-off between the feasible solutions [VIII]. The cost engineer needed the parameters to calculate the cost of each alternative based on the input given by the design engineers. Missing this information was considered a major risk and resulted in making a trade-off [VIII] with incomplete and delayed information. The cost input (a system structure attribute) for the trade-off [V] could

Table 2 Attribution of design decisions relevant in the system architecting and conceptual design

Phase	Design decision	Attribute	Explantion
System architecting and conceptual design	Adding soil-supporting function to panelling	System composition	Not explicitly mentioned
		Systems structure	*Costs* for subsystems provided by suppliers were not available. A detailed system design was needed
		System operation	*Sustainability* between concrete and synthetic material
			Functionality of panels, architectural or structural
		Complex emergent behaviour	Not explicitly mentioned

therefore not support the design process. The risk evaluation of the solution at the design freeze [XIII] increased and resulted in a less competitive bid.

Engineers have to deal with uncertainty about the information they have and do not have. As is seen in the case, decisions are typically postponed when information is unclear or incomplete (Table 3). Other design decisions were postponed due to uncertainty about information given by possible suppliers. The competitive environment means that specialized subcontractors need to be contracted before the contractor knows the detailed system design, or knows the design at all.

> […] Based on all the information given by suppliers, all advantages and disadvantages for each solution, a risk assessment and a cost calculation, one alternative seemed best according to the trade-off. However, many of the team members expected the other solution.
> […] we did have arguments for each alternative. But we were afraid to make a wrong decision, so we decided not to make a decision.

Besides the absence of information, the allocation of responsibilities was often unclear: 'Different engineers and managers pointed at one another as being the one who should make the final decision based on expertise, responsibility or leadership.' The challenge in the detailed design is to consider the various (detailed) solutions and deal with the absence of information. Within tenders, epistemic uncertainty is always present. A more detailed architecture requires detailed design information, while this might be unavailable.

Systems and interface integration

Integration of all subsystems was difficult as the level of detail between the subsystems was not aligned. Engineers optimized subsystems without paying attention to the interfaces with other disciplines as communication about the design process was not aligned (Table 4). This resulted in discussions about details while major design decisions remained to be made (e.g. panelling of construction [IX]). An example given by the architect:

> during the tender we were looking in AutoCAD to check about some minor centimetre scale work, while we would have known that it was impossible if we had only looked at the site. […] if we had asked this earlier in the design process, then we would have said 'no' right away as we would have seen the bigger picture.

Allocating responsibilities based on the subsystems caused engineers to invest in components at the expense of the whole system, as explained by a design manager: 'Design choices were mostly made internally [within a discipline] which causes a risk that the product does not represent the integrated nature of the project. At crucial moments, you do not know what is happening.' For example, measures can be introduced to use resources optimally in one object, or to optimize one aspect, without assessing the impact on the overall performance of the system. This is highly likely to result in suboptimal designs.

The challenge for integrating subsystems is to focus on the attribution of each design decision throughout the design process. Each engineer is responsible for a subsystem and needs to be aware of its attribution to the whole system. However, this case suggests that this overview is not used or supportive for defining attributes. As a result, epistemic uncertainty is translated into a higher risk profile when submitting the tender, and reduces the chance of winning the contract.

Validation and verification

The design verification was carried out by the contractor before submitting the bid-documents [XII]. Critical design information was implicitly stored in drawings rather than being expressed in requirements, as explained in the 'Requirements definition and management' section. As a result, the design verification became complicated as criteria for test success and failure were not matching with the level of detail in the requirements (Table 5). According to one design manager: 'The design was more detailed than the requirements. […] I daresay that a decomposition of the requirements would have triggered the client expressing other wishes compared with our design. […] That we have insufficiently analysed, insufficiently proven'. The client also stated that they would use the verification to confirm if the contractor provided a solution according to requirements. The challenge for verification in the tendering process is to find a design level for verification of the defined requirements. During the tendering process, several client meetings took place [II, X, XI] to discuss the proposed design solutions by the contractor. However, the client is not allowed to give statements on how they value the optimizations.

Discussion

The use of SE means that an iteration should take place between function analysis, requirements analysis and synthesis, starting from the decomposition towards

Table 3 Attribution of design decisions relevant in the detailed system and subsystem design

Phase	Design decision	Attribute	Explantion
Detailed system and subsystem design	Solution for construction 5	System composition	Not explicitly mentioned
		Systems structure	Pre-loading *time* of soil were not available.
			Decision made without clear impact on *costs*. This makes it impossible to determine the reduction of costs
		System operation	*Interfaces* with other disciples not aligned with level of detail in design.
			Settlement of other objects could not be determined
		Complex emergent behaviour	Solution had impact on other solutions. *Reliability* of design required a more detailed design. Translated into a higher risk profile
	Solution for construction 3	System composition	*Cost* is not known exactly, only based on assumptions
		Systems structure	Pre-loading *time* of soil was not available
		System operation	*Settlement* of alternatives not known.
			Accessibility of construction site during construction
		Complex emergent behaviour	Not explicitly mentioned

integrating the subsystems. In a case with uncoupled subsystems, clear information and available technical knowledge, the decomposition and integration process of a system design needs iteration to find a life-cycle set of system solutions that satisfies customer needs. In practice, this iteration between functional analysis, requirements analysis and synthesis is interrupted when issuing a tender. The contractor takes over when the client issues a tender. A second interruption takes place when submitting a bid. In delivering an integrated infrastructure project, the winning tender design becomes the starting point for the remaining part of the V-model. Between these interruptions, the design managers have to break up the issued tender design into coupled subsystems to deal with the design complexity and to develop a bid design without being able to reduce all uncertainties related to subsystems integration. The design managers are supported by a set of general SE processes and methods, such as trade-off matrices, stakeholder analysis, software tools, decomposition strategies of the system and many other processes and methods (Walden *et al.*, 2015). These general processes and methods rely on the iterative character of SE, which is interrupted in tenders. The investigated case supports our argument that applying SE in the context of a tender for a large, integrated infrastructure project creates challenges for contractors. We could reveal two main challenges:

(1) Making early design decisions

The exploration of design optimizations starts at the beginning of a tender, when the design is not fully specified. Limited time and resources make it necessary to quickly choose between feasible optimizations using expert judgement and experience. The case shows that

Table 4 Attribution of design decisions relevant in the systems and interface integration phase

Phase	Design decision	Attribute	Explantion
Systems and interface integration	Level of detail was not determined	System composition	Not explicitly mentioned
		Systems structure	Not explicitly mentioned
		System operation	Measures introduced to use resources optimally in one object, or optimize one aspect, without assessing the impact on the overall performance of the system
		Complex emergent behaviour	*Risk profile* when submitting the tender

Table 5 Attribution of design decisions relevant in the validation and verification phase

Phase	Design decision	Attribute	Explantion
Validation and verification	Unable to verify requirements as information only available in drawings	System composition	Not explicitly mentioned
		Systems structure	*Costs* determined based on drawings and reports. No attributes available for costs.
			Verification became complicated as criteria for test success and failure were not matching with the level of detail in the requirements
		System operation	Not explicitly mentioned
		Complex emergent behaviour	Not explicitly mentioned

the early decision-making is not always done systematically and transparently, and results in the inability to verify the proposed solution.

The design loop and requirements loop were not aligned for supporting the decision-making in the requirements management and definition phase. In the system architecting and conceptual design phase, the contractor needed extra time to interpret the conceptual design which resulted in a delay to find optimizations needed for a competitive design. The contractor needed to iterate in the design process; however there was not sufficient time to do so. Decisions were postponed as a result of interdisciplinary interfaces and unavailability of technical information. This is in line with a study of Laryea and Hughes (2008) concluding that the success of tenders depends largely on the skill, experience and judgements of the available engineers.

The early decision-making could benefit from defining attributes to the overall system level when a decision is made as proposed by Aughenbaugh and Paredis (2004). This study shows that attributions of potential alternatives to system level are not explicitly defined when making design decisions (Tables 1–5). The attributions of the decisions in the studied tender were mostly system composition or systems structure attributes. The more complex attributes require a better understanding of the system design. This makes it impossible for design managers to explicitly define the design performance in a tender, since the whole system cannot be fully specified. Trade-off studies are used to decide on alternatives by applying weighting criteria based on requirements, cost and schedule without having the relevant detail information or indicating the aleatory or epistemic uncertainty. The choice of an alternative, without knowing the involved uncertainty, makes it impossible for design managers to develop the economically most optimal design. That is, SE supports only a coherent and consistent design as the solution fits within the given design space by the client. SE does not support the search for the most economically optimal solution in a tender, which is essential for contractors.

(2) Creating understanding of design uncertainties

Engineers make early decisions based on limited information within a limited time frame, and a point-of-no-return is created after a tender is submitted. This implies that engineers have to make their decisions right the first time. Decomposition of the system based on the systems functionality is provided by using SE. However, as the case study suggests, the allocation of responsibilities can hamper the system integration. Unclear and unavailable information within the responsible discipline and inconsistencies in the level of design detail are identified as causes. Detailed information (e.g. soil parameters) was needed as input for the trade-offs in the detailed system and subsystem design phase. As this information was not available a decision was made which increased the risk evaluation for other subsystems. Dealing with this kind of uncertainty is not incorporated in the current design processes using SE in public tenders. A way to address missing or unclear information is to compare its impact on the design alternatives, to use a margin of uncertainty in the trade-offs. Explicitly comparing the uncertainty in (missing) design parameters can help in improving the systems understanding. A survey about an MRI (Magnetic Resonance Imaging) development organization by Borches (2010) shows that the lack of a systems overview is a barrier for creating an optimal design. The results of that survey cannot simply be transferred to the construction industry but it does show that an early systems overview is required to support the attribution of each decision to system level.

According to Suh (2009), allocating responsibilities makes collaboration essential for sound decision-making, and for dealing with possible disagreement. The mixed results of using system decomposition and processes to promote effective interaction and collaboration in the investigated case, and the absence of a decision-making framework to decide on alternatives (Bate, 2008), show that collaboration and design-decision support are not yet properly addressed in applying the SE approach for construction industry tenders. As a result, the client will not fully benefit from an integrated design and the contractor is insufficiently able to find a solution that will convince the client the best solution is on offer.

Conclusions

In this paper we have explored the use of SE by a contractor in the constrained environment of a public tender. Contractors have implemented SE to address the complexity of large, integrated infrastructure projects and gained experience with SE by structuring their design processes accordingly. Now, the challenge is to develop approaches for the integration of subsystems during the tendering stage, in order to create early understanding of the impact of design choices. The focus on systems integration can lead to more optimal designs as it is the integration that reveals the value subsystems add to the final design. The attribution of decisions to system level can support the contractor in creating a better understanding of the system. SE provides this understanding when both detailed design information and sufficient time is available to iterate in the design process. For tenders, this is often not the case as detailed information is rarely provided and time is limited due to the hard decision gate when submitting the tender. This leads to a situation in which contractors can submit a suboptimal design solution.

The interruption of the design process in the tender context suggests that the current implementation of SE lacks support for dealing with uncertainty in design decision. Being able to identify the uncertainty and incorporate this in the early decision-making is a challenge for contractors. This creates a need for tailoring SE to the context of construction tenders. We recommend to develop a decision-making tool, indicating the uncertainty of information at different system levels, to support the design decision-making process. Complex client requirements, including reliability, availability, safety, environmental and financial considerations, should be incorporated into the decision-making tool, to achieve cost, schedule and risk performance. We further recommend developing guidelines and coping strategies for the identification of reliability levels that support the exploration of feasible and competitive design solutions in a tender. At last, we recommend to carry out more case studies of public tenders to further explore the design challenges in large tenders as the presented case is limited due to its explorative character.

Disclosure

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