Structuring Of Early Design Decisions In Large Infrastructure Tenders – How To Find The Optimal Design Solution?

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STRUCTURING OF EARLY DESIGN DECISIONS IN LARGE INFRASTRUCTURE TENDERS – HOW TO FIND THE OPTIMAL DESIGN?
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ABSTRACT
Decision making in the tender phase of large infrastructural projects is a complex task for contractors as they have to make design decisions with long term effects and based on complex client requirements. Further complexity is added by the constrained environment of a tender and the uncertainty of winning the tender. As the context and the project are unique, there are no standard models for organizing the decision making during a tender. The introduction of Systems Engineering (SE) in the construction industry has led to a more structured way of working, but the application of the methods in the tender phase does not provide a suitable structure for organizing the decision making. As a result contractors struggle with designing an optimal design solution that will convince the client but will also reduce the risks associated with the construction and maintenance of the solution. In this paper we explore the implementation difficulties of SE in a large infrastructural tender. We report our initial findings of this in-depth single case study comprising document studies and open interviews with the tender team. We found that the allocation of design responsibilities between subsystems hampers cooperation for the integration of design and that the used SE approach lacks guidance for organizing a collaborative design process. We make propositions for further research and recommendations based on these initial findings.

KEYWORDS: Infrastructure tenders, Design decisions, Systems engineering

INTRODUCTION
In recent years, contractors have been increasingly in charge of projects including the design, building and maintenance of large infrastructure assets. During the tender phase of these projects they have to deal with complex client requirements including reliability, availability, safety, environmental and financial issues. Contractors have to translate these requirements into a design solution which meets the client’ expectations while at the same time allows the evaluation of risks associated with building and maintaining the proposed infrastructure. An optimal design solution is a design that also convinces the client to award the contract.

Early design decisions with long term effects are taken by the contractor. This makes that the contractors are reconsidering their established design practices and are relying on structured approaches to address the design challenge of these complex projects. Systems Engineering (SE) has emerged as such an approach for the engineering of these complex projects considering all relevant issues that affect the resulting design. It is an approach widely used in other sectors but relatively new in the construction industry. Some contractors have adapted SE in their current design practices but they struggle with practical implementation within the constrained environment of a tender.

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In this paper, we explore the application of SE within the context of a large infrastructural tender. We focus on the issues that arise when using SE as a design method in the context of a tender, and ask the question if the current practice of SE is a suitable method for supporting the decision making to attain an optimal design solution. In the case study analyzed here, the design process is reconstructed and compared with the steps described in general SE-literature to identify the challenges of using SE in a tender.

**THEORETICAL FRAMEWORK**

Systems Engineering (SE) is a systematic way of thinking and a method to manage the problem solving processes in the context of challenging socio-technical questions. The application is recommended for projects with large object complexity and large size where it is difficult to efficiently develop, implement and control a sustainable solution due to the many parties involved (Züst & Troxler, 2006). Consequently, SE can be described as ‘an interdisciplinary engineering management process that evolves and verifies an integrated, life-cycle set of system solutions that satisfy customer’s needs’ (Friedman & Sage, 2004; Mintz, 1994). That is, SE covers a broad set of processes and methods that analyze interactions among requirements, subsystems, constraints and components. Its purpose is to improve the understanding of the system as a whole, and to use this understanding to improve the design decisions throughout the systems life-cycle (Yahiaoui, Harputlugil, & Sahraoui, 2006).

The discipline of systems engineering was developed in the communications industry to meet the networking challenges of the 1950’s. Later on, SE has been applied in the space, defence, and computer industries during the 1960s through the 1990s. Several guidelines for the defence, civilian aerospace and energy industry followed. In the 1980 and 1990s an expansion of SE is seen in various industries dealing with systemic challenges. Similar factors in these industries have lead to the recognition of SE: increased system and product complexity, greater technological capability, more challenging customer requirements, and greater product interoperability with other products and systems (Commercial and Public Interest Working Group, 2000).

Within the Dutch construction industry SE is introduced in 2007 with the publication of an industry wide guiding principle (Werkgroep Leidraad Systems Engineering, 2009). Factors for the construction industry that led to the implementation of SE are the use of integrated contracts, increased complexity due to the involvement of many actors (internal and external), unique projects, changing environment and the fragmentation of traditional phases of construction. The introduction of SE in the construction process has led to changes in working methods for both the client organization and the contractors.

The uncertainties related to success and restricted time requirements in the conceptual design phase of a tender highlight the importance of SE. However, at the same time it shows various difficulties within the context of a tender:

- Complex tenders involve many engineers and managers who have to work as a team and who spend a lot of time discussing the different opinions and deal with the interface problems that arise between the various responsible subsystem-engineers (Bernold & AbouRizk, 2010).
- Conceptual design decisions have an long term effect on the systems performance (Kam & Fischer, 2004; Sanders & Klein, 2012). Within the extremely constrained environment of a tender, this decision-making is not always done rationally and
requires many interactions to correct for mistakes and to verify the complex decision making process (Suh, 2006).

- The required design information in tenders has grown tremendously due to the shift to more complex requirements. During the tender, team members with many different skills have to collaborate in order to come up with a detailed design to win the tender and to allow the evaluation of construction and maintenance risks.

The growth of this complexity asks for a structured way of collaboration to make optimal design decisions on an integrated level at the different project stages (Chapman, 1998). Collaboration per se does not guarantee that optimal design decisions will be made as the quality of the collaboration is affected by two elements: the system (1) and the process (2) used to promote collaboration (Suh, 2006).

The system (1) involves the organization of the project and its participants to ensure the availability of all information and knowledge needed. Using the concept of SE, we can identify six phases that represent the systems engineering lifecycle (Friedman & Sage, 2004):

1. **Requirements Definition and Management;** This phase can be described as the problem definition. It is necessary to understand what is given and what is not given or inconsistent. (Kossiakoff & Sweet, 2003)

2. **Systems Architecting and Conceptual Design;** Defining the structure and models used to develop and present a system architecture (Kossiakoff & Sweet, 2003). The systems design is divided into subsystems to reduce object complexity in designing an optimal solution. Each team-member has responsibilities towards one or more of these subsystems.

3. **Detailed System and Subsystem Design and Implementation;** Functional decomposition and design traceability that results in design specifications for the system being engineered. (Friedman & Sage, 2004)

4. **Systems and Interface Integration;** Systems integration and interfaces at each subsystems supports the system functionality. The integration of elements, including architecting the subsystems, can only be successful if it is part of the decomposition of a system (Bontempi, Gkoumas, & Arangio, 2008; Sage & Lynch, 1998).

5. **Validation and Verification;** This phase is used to check that the system meets the requirements and specifications, and that it fulfils its purpose.

6. **Systems Deployment and Post Deployment;** This phase is not part of the tender as it is concerned with the testing during construction or maintenance to recommend possible changes in the system or reengineering.

The process (2) outlines the way of collaborating to reinforce the strengths of all participants, minimize confusion and deal with possible disagreements. Having such a structure is essential to be able to make the appropriate decisions (Suh, 2006). Depending on how the project is organized, the outcome of the collaboration will be different since the design process can have many possible solutions. This is also suggested by Sage and Armstrong (2000), they argue that team composition has a strong effect on the effectiveness of the SE process.

**RESEARCH DESIGN**

A single case study is selected to investigate how the project team makes design decisions using the concept of SE in a large tender. A case study is used as research method as this is an explorative study to discover the implementation problems of SE. This specific tender
is chosen for its object complexity, its integrated focus, and the collaboration between several disciplines.

The tender was let by a port authority and included a main traffic junction as part of a infrastructural scheme. For this tender an integrated contract (Engineering & Construct) with Systems Engineering was used. A referential design was part of the contract and served as a feasibility study for the port authority. The referential design could be optimized if the tenderers considered this necessary.

The tender itself was not a large project in terms of size but all interviewees concurred that the tender was complex due to the physical surroundings and involved stakeholders, but not so much due to technical challenges. The physical site had many interfaces with stakeholders and the phasing of construction had to minimize delays for surrounding parcels. Two contractors collaborated as one main tenderer and both had sufficient experience with this type of contract, including Systems Engineering. To that end and the tight schedule, an Integral Design Manager facilitated concurrent engineering between three design managers (including Civil Design Manager, Road Design Manager, and Rail Design Manager). Part of the project team worked from one location, while other parts of the design were designed on different locations. A two-day-kick-off-meeting was initiated to familiarize the project team with the referential design and possible optimizations. This kick-off meeting ended with a client-meeting to discuss the possible design optimizations.

Data collection started with a review of the contractors’ management system to gain understanding of the design process. Subsequently, open interviews with six key-players of the tender team (including the tender manager, design managers, architect, cost-specialists) were held. These six players together were responsible for making the final decisions, and were involved throughout the whole tender. They were asked to describe the sequence of events from the start of the tender towards the end of the design process. The main topics during the interview were related to the six phases of SE. The issues described by the tender team were used to explore the difficulties of applying SE as an approach to better understand the systems and to make design decisions based on this understanding. The interviews lasted for about one hour, were recorded, and written out into notes for analyzing purposes. The notes were clustered into the six phases of SE. In addition we studied project documentation such as meeting notes and schedules to verify the interview results. Furthermore, the meeting notes were used to investigate how long the design related topics were on the agenda. The interviews were held half a year after the tender ended. All the interviews were taken between December 2012 and February 2013 by the same researcher.

GENERAL FINDINGS

The findings are structured based on the most commonly known phases of systems engineering (Friedman & Sage, 2004) as described in the literature review. Each phase is structured by a description of the findings and a list of problems areas.

Requirements Definition and Management

The project started with a kick-off meeting in which the client requirements were not known by the tender team. Studying the referential design in teams consisting of different specialist resulted in possible optimizations in the referential design. Knowledge of specialist was brought together by a facilitator using creativity techniques in a workshop, a site visit and presentations. Choices and decisions were made on a level of functional requirements as the
detailed design requirements were not yet known by the tender team. At the end of the meeting the tender team made a decision to further investigate two major design optimizations. This decision was based on two days of intensive collaboration which is described by the design manager and architect as: “People automatically discussed their ideas when walking around the posters visualizing the referential design”. “We were integrally thinking, together searching for solutions and value. Everyone was working for the project instead of their own discipline”. The effect of this 2-day kick-off meeting on the team is summarized by the architect as: "At a social-level, we were a team. The differences between the disciplines were not known, I really did not know who worked for which discipline”.

After the kick-off meeting the team started to work on the major design optimizations. During this period the requirements were analyzed but it did not result in a coherent and traceable flow down from top level to lower levels of the systems being engineered. A reason for this situation was that engineers wanted to make a more detailed design before making higher level design decisions. Consequently, the cost specialist was unable to budget the optimizations as many requirements were ‘to be determined’ instead of quantitatively specified.

- The requirements management during the design process did not focus on the flow down from the top level to all lower levels of the system. This caused difficulties for setting up a cost-budget in every stage of the design, which could be used as input for making design decisions.

Systems Architecting and Conceptual design

The systems architecture was based on a traditional decomposition were responsibilities are divided between the involved disciplines (Road work, Rail work and Civil work). Each discipline started with writing a document describing the requirements analysis, the possible risks, interfaces, and optimizations of the conceptual subsystem design. The functions and the interfaces between the subsystems were not fully investigated before deciding on this decomposition. The paneling of the construction made this clear as it also needed a soil-bearing function instead of an architectonical function only. It is described by the tender manager: “The allocation of the scope was unclear. The soil-bearing construction was allocated to the road discipline [as it had no structural function], while it should be allocated to the civil discipline [as it did have a structural function]. As a consequence this object got stuck in the middle.”

- The (perceived) responsibilities for the subsystems were allocated without a clear understanding of the whole system. This resulted in delays of design decisions due to unavailability of information at the responsible discipline.

Detailed System and Subsystem Design and Implementation

The sub-systems elements were allocated in a treelike order. As a result each element was designed within the boundaries known by the responsible discipline. Design information not available within the disciplines consisted of the interfaces with other disciplines (will be discussed in next section) or unavailable technical information. Geotechnical information and information about the subterranean infrastructure are two examples of unavailability of information. This was considered a major risk in the tender but the lack of adequate knowledge to solve this information gap led to confusion about the design parameters. As a consequence
incomplete and delayed information increased the risk evaluation for the construction phase as choices were made with uncertainty about these parameters.

- The available client-requirements were assigned to specific subsystems without further specification of the requirements. Engineers designed according to these requirements. As a result many requirements were implicitly available in drawing, rather than explicitly available in requirements.

**Systems and Interface integration**

Integration of all subsystems seemed difficult as the level of detail between the subsystems was not aligned, which led to difficulties in the decision-making process. Much discussion about some minor details can be seen in the tender while some major design decisions still had to be made (e.g. paneling of construction). An example given by the architect: "*during the tender we were looking in AutoCAD to check about some minor centimeter work, while we could know that it was impossible if we only looked at the site. [...] if we had asked this earlier in the design process than we would have said 'no' right away as they would see the bigger picture (context)*".

This component focus approach caused people to invest in components at the expense of the whole system as is explained by a design manager: "*Design choices were mostly made internally [within a discipline] which causes a risk that the product is not representing the integrality of the project. On the crucial moments you do not know what is happening.*" For example, measures are introduced to use resources optimally in one object, or to optimize one aspect, without assessing the impact on the performance of the system. This can result in suboptimal designs.

- The structure for collaboration and communication was not formally arranged. The design managers did collaborate based on their identified interfaces. However, the interfaces are discussed on a high level of abstraction as interfaces of elements were not identified by the engineers.
- The communication failed because information was not available within the team but had to be given by engineers outside the team.
- Although a systems engineer or integrated design manager can facilitate the SE process, the main input of the SE process depends on the contribution of all team members together.
- The level of detail between the possible solutions led to discussions about details instead of functionality at the systems architecture level.

**Validation and Verification**

Critical design information was stored in drawings rather than in requirements which is needed for verification. Decisions about how to decompose the requirements were postponed as it was thought that these were too detailed for that moment. This made verification of the design difficult as criteria for test success and failure were difficult to determine on such a high requirements level. According to a design manager: "*The design was more detailed than the requirements. [...] I dare to say that a decomposition of the requirements would have triggered us that the client had other wishes compared to our design. [...] That we have insufficiently*"
analyzed, insufficiently proven”. The client also noted that they would use the verification to validate if the contractor provided a solution according to her wishes.

- The design effort is mostly found in the drawings which make the verification and validation of the design criteria difficult. As a result it is difficult to make design choices explicit and traceable.

This case study suggests that for this tender it was beneficial to make early design decisions based on collaboration in the requirement analysis phase. In this phase a system and process (Suh, 2006) was available to organize collaboration between the participants to assure that all the information and knowledge was available on a functional level. Collaboration was reinforced by combining the strengths of all participants during the two-day kick-off meeting. This resulted in a decision to focus on two major design optimizations. After the optimization decision was made, the subsystems were automatically allocated in a traditional way. This systems decomposition into subsystems is supported by a set of processes and methods in the concept of SE. However, the allocation of responsibilities hampered the system integration due to unavailability of information at the responsible discipline and due to differences in the level of design detail.

DISCUSSION

This study is useful for creating grounds upon which more focus can be determined about the influence of SE on the decision-making process in a tender. The challenge for the contractor is to create early understanding of the system to develop the integration of systems, and to make optimal design decisions. The use of SE can provide this understanding when all information and time is available. As this is not the case in a tender, the use of SE makes it necessary to make early decisions based on limited information within a limited timeframe. As a result, the contractors use a traditional decomposition of the design to come up with a design solution. This decomposition does not include the integration of complex client requirements, including reliability, availability, safety, environmental and financials issues into the engineering effort, to meet cost, schedule and risk performance.

Furthermore, the allocation of responsibilities based on the subsystems makes collaboration essential to be able to make appropriate decisions (Suh, 2009), and to deal with possible disagreements. The mixed results of using systems and processes to promote effective interaction and collaboration, and the absence of a decision-making framework (Bate, 2008), show that interaction and collaboration is not yet properly addressed in the SE approach for the construction industry.

Although this study is based on a single case it seems that the current practice of SE in the construction industry needs more focus on systems integration including the allocation of responsibilities to get a better understanding of the whole system. The focus on systems integration will lead to more optimal designs as it is the integration that adds value to the subsystems, and will support the contractor in creating understanding of the system. In future work, we aim to develop a framework that integrates the requirements into a decision-making model that supports the early decision making process.
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