Rolling out Systems Engineering in the Dutch Civil Construction Industry

Identifying and Managing the Factors leading to Successful Implementation

S.T.A. van den Houdt
Section Systems Engineering
Faculty of Technology, Policy and Management
Delft University of Technology, The Netherlands
S.T.A.vandenHoudt@student.tudelft.nl

Dr. J.L.M. Vrancken
Section Systems Engineering
Faculty of Technology, Policy and Management
Delft University of Technology, The Netherlands
J.Vrancken@tudelft.nl

***Abstract* — Contractors in the Dutch civil construction industry are adopting Systems Engineering (SE) into their work processes, to manage the increasingly complex and multi-disciplinary nature of their projects. The implementation rate of SE is low due to unknown problems caused by multiple factors. Currently, there is no overview of the factors affecting the implementation rate of SE in the Dutch civil construction industry and how these should be managed. Through review of existing literature and case studies on civil construction projects, a list of factors affecting the successful implementation of SE has been formulated and their relative effect on the implementation rate of SE is determined. In this article six key problem areas are identified, which negatively influence the implementation rate of SE. We propose that contractors adopt a single, independent organizational entity in their organization for process and SE management, who implicitly implement SE within the standard working procedures. Towards the client, these procedures depend on the level of SE-maturity of the client. This approach helps contractors to manage the identified problem areas, thereby improving the implementation rate of SE in their organizations.**

Keywords — Systems Engineering; Implementation; Success Factors; Civil Construction Industry; Netherlands

I. Introduction

In the Dutch civil construction industry, the largest public clients initiated a shift from the *solution*-oriented to the problem-oriented approach [1]-[3]. Contractors are no longer solely responsible for the execution of mono-disciplinary projects, but are expected to design, built, finance, maintain and operate increasingly complex, multi-disciplinary projects [4], [5]. This change directly affects the working practices of both the client and the contractor, requiring more transparency, a client focus and an explicit working method safeguarding the traceability of the increasingly functional requirements [6]. Both client and contractor have adopted *Systems Engineering* (SE) as a method to facilitate the realization of these new requirements [7]-[12]. Previous research has confirmed that the application of SE can increase the overall effectiveness of large-scale engineering projects, reducing the overall project schedule, while product quality is increased [13]-[15].

The problem is that the implementation rate of the SE working method among the operating companies and disciplines of contractors is different and various interpretations of SE emerged. Successful implementation of SE can only take place if it becomes clear which factors contribute to the success of this implementation [14]. Currently, it is unclear what the success factors behind the implementation of SE in the civil construction industry are and how these should be managed to improve the application and results of SE within the sector. Also, the approach chosen to manage SE can work in one project but not in another project, because of the unique characteristics of each construction project [16].

In this paper, we aim to identify what the success factors behind the implementation of SE in the civil construction industry are and how these should be managed to improve the implementation rate and results of SE. Through review of literature, an initial list of factors is formulated that are likely to have an impact on the success of the implementation of SE. Next, the practical applicability of these factors in the construction industry is assessed, by applying them in four case studies. In the same case studies the relative effect of the factors on the implementation rate and their scores are determined. Based on a cross-case confrontation of the factor scores, key problem areas are identified, which negatively influence the implementation rate of SE. The key problem areas are linked back to existing management approaches for SE, resulting in recommendations that can improve the implementation of SE within the Dutch civil construction industry.

In this paper, we first establish definitions for SE in general, and as commonly interpreted by the Dutch civil construction industry. On the basis of these definitions, we present an initial list of factors expected to affect the implementation rate of SE. Secondly, we briefly assess the applicability of the factors in practice during the case studies and review the key problem areas. Then, we present proposed improvements to better facilitate the implementation of SE at contractors in the industry. Finally, we present a number of recommendations for future work.

II. LITERATURE REVIEW

SE is based on the principles of the systems approach, synthesis, holism, organismic analogy (organicism), adaptive optimizing, progressive entropy reduction and adaptive satisficing, applied to the actual realization – engineering – of products or projects [17]. There is no unambiguous definition of SE, as it can be defined as a profession, a process or a perspective [13], [18], [19]. Even though the definitions are different, they show a high degree of similarity since the ultimate goal is the same: to create a successful system as a whole solution to some complex problem. In the context of the civil construction industry, the implementation of SE should contribute to the traceability of the requirements, effectiveness of the working process and an increasing suitability.

In the following sub-sections the factors potentially affecting the implementation of SE are described. The factors are categorized in three tables: SE processes, management and organization of SE, and project context of SE. For each factor is indicated whether it is relevant at the level of project (P), organization (O) and/or sector (S).

A. Systems Engineering Processes

ISO/IEC 15288 provides four process groups needed to successfully implement SE [20]:

1. *Organizational project-enabling processes;*
2. *Agreement processes;*
3. *Project processes;*
4. *Technical processes.*

The processes can be applied concurrently, iteratively and recursively to a system through its entire life cycle. The processes should be tailored to satisfy the particular circumstances of the industry where they are applied [13]. Contractors within the civil construction industry seem to focus on the project and technical processes [21], [22]. However, none of the processes may be disregarded during the tailoring of SE since they are all closely related to the achievement of the SE goals, and therefore to the successful implementation of SE [13]. In other industries where SE is applied there seems to be a higher level of trust between client and contractor, resulting in a more cooperative character and long-term relationships, leading to increased standardization and optimization over the boundaries of projects [23], [24].

Within the civil construction industry the main SE processes are translated into a V-model depicted in Fig. 1, which incorporates the life cycle of systems in six phases. Requirement Analysis (RA) and Verification and Validation (V&V) form the two main activities of SE in the civil construction industry [7].

During the RA the client translates its needs into client requirements, so the contractor can design them into the optimal solution for the problem at hand [25], [26]. To gain benefit from SE, a high level of design freedom is desired [27], [28]. This design freedom is largely determined by the level of functionality of the requirements provided by the client. The requirements by the client are often incomplete, inconsistent and ambiguous. Further analysis of the requirements by the contractors is necessary: the 'high-level requirements' have to be made SMART (Specific, Measurable, Acceptable, Realistic and a product of Time) [29]. The decomposed requirements always need to be coupled to the original high-level requirements and harmonized between client and contractor to prevent undesired system results. Central coordination is required to allocate the decomposed requirements to the appropriate parties, considering all life cycle stages of the system [30].

A detailed elaboration of all activities of the RA conducted during civil construction projects can be found in [31].

V&V is the process of checking whether the requirements have been fulfilled and if the result is in line with the needs defined [32]. V&V can be performed at any level and is not only related to the end result of the project [7]. During the V&V activities client and contractor need to closely cooperate and share information, because they both have to agree with the outcome of the V&V activities [33]. The (sector-wide) standardization of V&V procedures can help to support this cooperation, because expectations are clear before the project starts. Standardization establishes principles of integrity, propriety and trustworthiness that establish the confidence to cooperate. Furthermore, this will help employees to optimize the V&V methods over projects [34]. V&V documents constitute legally binding documents, so there must be agreement on the used V&V plans and procedures [22].

Table 1 summarizes the aforementioned factors that potentially affect the implementation of SE based on Systems Engineering processes.

B. Management and Organisation of Systems Engineering

Implementing SE requires the coordination of technical and managerial processes. The management of systems is derived from "regular" management as well as system management [35]-[37]. SE managers play a key role during the implementation and management of SE during the life cycle of civil construction projects. There is no one-size-fits-all way to define the details of what managing SE encompasses, since it depends on project context variables as defined in the next sub-section of this paper. The level of managerial support depends for the most part on the availability, skills, and competencies of the SE managers. SE managers are not to be expected to personally complete all of the SE activities, but will be required to assume a leadership role with the appropriate level of authority to ensure that they are accomplished within project teams.

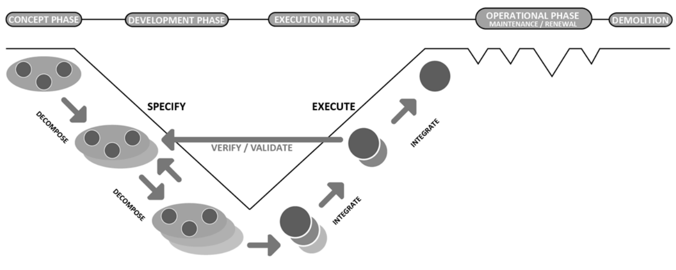

Fig. 1. The V-model and life cycle of a civil construction project.

TABLE I. LIST OF FACTORS POTENTIALLY AFFECTING THE IMPLEMENTATION OF SYSTEMS ENGINEERING BASED ON SE PROCESSES

Category		Factor	P	O	S	Case Scores A	B	C	D	Avg. Score
Systems Engineering Processes	*General*	Consideration of all SE process groups	X	X	X	10	10	0	0	5,00
		Application rate and alignment SE throughout all life cycle phases	X		X	10	10	0	0	5,00
		Level of SE standardization	X	X	X	5	5	5	5	5,00
		Alignment of SE theory with application in practice	X	X	X	5	5	0	5	3,75
	Requirements Analysis	Up-to-date requirements	X			10	10	10	5	8,75
		Harmonization of requirements specification between client and contractor	X		X	10	10	0	0	5,00
		Functionality of requirements	X			5	5	0	0	2,50
		Completeness and level of detail of requirements	X			10	10	10	10	10,00
		SMART formulation of requirements	X			10	10	10	0	7,50
		Consideration of latter life cycle stages during requirement analysis	X			10	10	0	0	5,00
		Linkage of interfaces to requirements	X			5	5	10	5	6,25
	Verification and Validation	Coupling of V&V with requirements	X			10	10	5	5	7,50
		Continuity of V&V during the life cycle of the project	X			10	0	10	0	5,00
		Collaboration of client and contractor during V&V	X	X	X	10	10	0	5	6,25
		Standardization of V&V procedures	X	X	X	10	10	10	5	8,75
		Agreement on V&V plans and procedures	X	X	X	10	10	10	0	7,50

To successfully implement SE within an organization it should be enabled in three layers of the organization [38].

Higher management. The higher management should establish a vision which incorporates how the organization wants to apply SE and which must be understood by all. Ultimate success in the implementation of SE is highly dependent on managerial support from the top down [35]-[37], [39]. The organizational and process structure of the company where SE is implemented should provide for:

- Clarity of roles and responsibilities coupled to SE activities;
- Having the proper leadership that understands and believes in SE and the benefits that can be realized as a result of its implementation;
- The establishment of a good communications capability throughout the entire organization, with the customer, and among suppliers;
- Incorporating an effective feedback and control capability that will permit periodic evaluation and allows continuous process improvement.

Project teams. Within projects, the project management serves the same role as higher management in an organization: they should support and provide resources to implement SE. SE managers should have sufficient authority over project teams, meaning that the advice of the manager is binding to project management [38].

Individuals. Before individuals will start to work with SE they have to perceive the potential benefits and these should be entitled to them. Furthermore, the appropriate tools, level of training and documentation should be provided to them. Together with their prior experiences with SE these will determine the overall skill and competencies of the project employees [38], [40], [41].

SE and SE management is part of traditional project organizations. This means that SE has to be carefully aligned with project management; process management; risk management; configuration/knowledge management and other supporting processes [42], [43]. SE coordination of an interdisciplinary organization during the whole life cycle of the project is essential, because all of the key participants in the systems development process not only need to know their own responsibilities, but also their interface with one another [38].

Table 2 provides the list of factors that potentially affect the implementation of SE based on the management and organizational literature. The factors are categorized according to the management building blocks for organizational change and the category ‘interfaces’ in [44].

C. Project Context of Systems Engineering

The project context variables are argued to have a strong impact on the success of the implementation of SE [6], [27], [35]. To analyze the impact of the project context variables and their underlying factors have been identified. Limiting the set of project context variables was necessary, because the environment of a system is limitless. The main identified project context factors are:

- Project arrangements [45];
- Project team [29], [30], [46];
- Working environment [47], [48];
- Resource availability [22], [30];
- Client [6], [49];
- Contractual arrangements [7];
- Stakeholders [50];
- Project task [47], [51];
- Industry standards and legislation [20].

Table 3 provides the list of factors that potentially affect the implementation of SE based on the project context variables as found in literature. The factors are categorized in *project* and *environment* factors. A detailed elaboration on the factors can be found in [31].

TABLE II. LIST OF MANAGEMENT AND ORGANISATIONAL FACTORS POTENTIALLY AFFECTING THE IMPLEMENTATION OF SYSTEMS ENGINEERING

	Category	Factor	P	O	S	Case Scores				Avg. Score
						A	*B*	*C*	*D*	
Management and organization of SE	*Strategy*	Availability and clarity of mission, vision and objective regarding SE	X	X	X	5	5	5	0	3,75
		Support from higher management		X		5	0	5	5	3,75
		Level of agreement and understanding regarding SE	X	X	X	10	0	5	5	5,00
	Structure	Clarity of roles and responsibilities coupled to SE	X	X	X	5	5	5	5	5,00
		Balance between PM, SE and process management	X	X		5	5	0	5	3,75
		Cooperation among supporting processes	X	X		10	10	-	-	10,00
		Representation of supporting processes in the project management team	X			5	5	-	-	5,00
		Coordination of interdisciplinary organization	X	X		5	0	5	5	3,75
	Culture	Support from project management team	X			10	0	0	5	3,75
		Level of support for SE from individual project employees	X			5	5	5	5	5,00
		Acknowledgement of the learning process by project employees	X			?	?	?	?	?
	People	Availability of SE manager	X	X		10	10	5	5	7,50
		Skills and competencies of SE managers	X	X	X	10	10	5	10	8,75
		Level of authority of SE in manager in project	X	X	X	5	0	0	0	1,25
		SE skills and competencies of project employees	X	X	X	5	5	5	0	3,75
		Individual prior experience with SE		X	X	?	?	?	?	?
	Resources	Resources available for the application of SE within the project	X			10	5	0	5	5,00
		Resources available for the development of SE		X	X	?	?	?	?	?
		Level of managerial support provided by SE manager	X	X		10	10	5	5	7,50
		Availability and quality of SE tools and methods in the organization		X		10	10	10	10	10,00
		Availability and quality of SE training and documentation	X	X	X	5	5	5	5	5,00
		Availability of KM tools (e.g. Relatics®)	X	X	X	10	10	10	10	10,00
		Alignment of KM tools between disciplines, projects and other stakeholders	X	X	X	5	5	5	5	5,00
		Awareness and usability of the knowledge management tools	X	X	X	10	5	5	5	6,25
	Results	Actual benefits of applying SE	X	X	X	?	?	?	?	?
		Perceivable benefits of applying SE	X	X	X	10	0	?	10	6,67
		Level of evaluation and feedback from SE in projects	X	X	X	5	5	0	5	3,75
	Interfaces	Continuous identification of interfaces	X			10	10	5	0	6,25
		Up-to-date formulation of interfaces in accessible environment	X			10	10	10	5	8,75
		Regular and scheduled interface meetings including all stakeholders	X			5	5	5	0	3,75

TABLE III. LIST OF PROJECT CONTEXT FACTORS POTENTIALLY AFFECTING THE IMPLEMENTATION OF SYSTEMS ENGINEERING

	Category	Factor	P	O	S	Case Scores				Avg. Score
						A	*B*	*C*	*D*	
Project context	*Project*	Level of freedom in project arrangements	X			10	0	5	0	3,75
		Project team composition	X			10	5	5	5	6,25
		Job happiness and internal pressure	X	X		5	?	?	5	5,00
		Project task (size / complexity)	X			10	10	10	10	10,00
		Contract arrangements	X		X	10	5	0	0	3,75
	Environment	Overall SE skills and competencies of client (experience and expertise)	X		X	10	5	0	5	5,00
		Overall SE skills and expertise of subcontractors / suppliers	X		X	0	0	?	0	0,00
		Applicable industry standards and legislation	X		X	5	0	0	0	1,25
		Relationship with client (trust)	X	X	X	10	0	5	0	3,75

III. CASE STUDIES

In order to determine the relevancy of the factors in the Dutch civil construction industry, they have been applied in case studies.

The case studies are conducted at the Royal BAM Group. BAM is a major European construction company with 26,600 employees and revenues of 7,9 billion euros. Each year BAM carries out hundreds of civil construction projects with a great variety in size and complexity in more than 30 countries [52].

A. Approach

Firstly, four representative projects for the case studies are selected, based on a set of fixed and variable project selection criteria described in [31].

Secondly, the occurrence of each factor, as identified in the previous section, in the selected projects is derived, by conducting semi-structured interviews and reviewing project documentation. These interviews are conducted with a variety of SE users and experts. Previously undocumented factors that are also relevant are added to the analysis.

The implementation rate of SE is determined by assigning a relative score to each factor, based on the interview results and project documentation. During the cross-case confrontation, the scores from the four cases are used to calculate an average score, as depicted in the last column of Table 1 through 3. A 10-point scale is used, where a 10 represents the best outcome. A low factor score within a single case means that on average this factor negatively influences the implementation rate of SE and needs attention in the project. A low average score indicates that the factor indicates a repetitive problem and needs attention in the organization or sector as a whole.

A detailed elaboration on the case results, factor scores, and cross-case confrontation can be found in [31].

B. *Previously undocumented Factors*

During the case studies the following previously undocumented factors were identified, which have an effect on the implementation of SE:

Time pressure and parallel planning. Due to increased time pressure in the tender and development phase – originating from the contract from the client – the majority of the processes needs to be conducted in parallel, to be completed on time. Although the SE theory acknowledges the existence of iterative feedback loops, there is little theory on how to deal with the informational needs during the parallel processes [13], [32]. Currently, the inability to manage these parallel interfaces seems to be a major reason for miscommunication. An example is the start of the design, before the RA is completed or the start of the execution before the design is completed.

Level of interdisciplinary knowledge. Designers and engineers from the different operating companies and disciplines have specific technical knowledge. During the development phase of multi-disciplinary projects there is a high level of incomprehension or ignorance of the interfaces between disciplines. A cause for this ignorance seems to be the lack of understanding of each other's technical proficiency and capabilities.

Physical distance. In the design phase, teams of engineers are formed based on their specific technical background. Not in all situations the engineers work on-site. If there is a dedicated project location, the engineers cluster together in rooms according to their technical background. An engineering team with another technical background convenes in another room and so on. Their communication is mostly formal, during planned meetings or official documents. Informal communication during their daily tasks can benefit the integral design.

C. *Key Problem Areas*

Based on the cross-case confrontation, the following six key problem areas were identified:

Uncertainty originating from the client. Experience and expertise regarding SE differs among the clients. As a result, the choice of clients to choose a contract type, which requires the implementation of SE, differs as well. Further project arrangements – mostly set by the client – determine the manner in which some SE processes are desired and can be altered by the contractor. This variety in clients' background and wishes introduces uncertainty for the contractor. There are three reasons why a client is unable to provide a complete set of requirements that still offers enough design freedom for the contractor:

- The client is unfamiliar with functional specification, resulting in an incomplete or over-complete list of requirements. The prior expertise and experience of the clients play a major role.
- The client believes to know what he or she wants. This desire is translated into detailed requirements, offering less solution freedom.
- A relatively large amount of binding documents (f.i. laws and regulations) are applicable to the requirements, restricting the solution freedom.

The relationship with the client in terms of trust and mutual understanding plays a key role to successfully implement SE. This also applies to the relationship between contractor and subcontractor and/or supplier. For example the harmonization of requirements between client and contractors is much easier, if a good relationship exists between client and contractor.

Neither responsibility, nor authority for standardization. The cross-case confrontation showed that the V&V processes taking place within projects are different, due to a lack of standardization, both within the sector and within the organization. Contractors are standardizing supporting processes, but lack the capacity to successfully implement these within their projects. Within the examined contractor, the operating companies and their employees in the various disciplines are not obliged to work according to the standards.

SE managers have limited authority to set processes for SE and thus improve standardization over projects, because they are often not involved. Lack of support from higher and project management; changing roles and responsibilities (no clarity); and the low awareness of the importance of SE are responsible for the lack of adoption by individuals.

Standardization is made more difficult due to the involvement of subcontractors and suppliers. Due to the short period of involvement in projects, these external parties have only limited time and incentive to follow standardized procedures as desired by the contractor. As a result, the overall level of agreement and understanding regarding SE may decrease. A team approach with mutual understanding is essential to successfully implement SE. An SE manager should take a leadership role in facilitating this standardization, but currently lacks the proper recognition and authority.

Limited knowledge sharing and updating within the organization. Within the organization the sharing and updating of SE knowledge seems limited for a number of reasons:

- Supporting processes are unbundled and scattered throughout the operating companies and disciplines. Besides SE, several other supporting processes specialists are organized on the level of operating companies and not on the organizational level;
- SE managers have only limited time available for knowledge gathering and updating, due to relative high work load on projects;
- The amount of time an SE manager designates to analysis of evaluations and feedback is relatively low, because this time is not externally billable.
- The usability of the knowledge center in which all SE processes can be found, is low and outdated, negatively influencing the adoption by individual employees.

In situations where no member from a central department for SE or process management is involved in a project, the control and feedback remains within the operating company and is not shared.

SE expertise not involved. The cross-case confrontation showed that the available SE expertise is not used to its full extent. As a result, SE is not implemented or applied incorrectly, without the awareness of project employees that they are wrong. The main reasons for the lack of involvement of SE expertise are:

- No awareness that SE knowledge is present within the contractor's organization;
- Deliberately not chosen by the project management team. No resources are available to deploy an SE expert within the project or the project management team does not support the involvement of SE.
- No SE expertise capacity available within the contractor's SE department or other parts of the contractor's organization.

In the situation were there is no SE expert assigned from a dedicated department, new problems arise. An employee from the operating companies or an external consultant is approached to facilitate the implementation of SE. The level of managerial support provided by these employees varies and knowledge gained by these employees is not easily transferred back to the rest of the organization.

Another reason for not involving an SE expert within a project is that the project employees are not aware of their wrongful application of SE. Their awareness is limited due to the fact that there are no checks and balances for employees to compare their work with. Providing practical examples with clear check and balances helps to increase this awareness [38], [41], [53].

Due to high time pressure in the initial phases of the project, SE and other supporting processes are likely to be disregarded by the project management team, due to the focus on technical processes.

Poor management of interfaces within the SE life cycle. In all researched projects the identification and management of interfaces proved to be very important. Even small mono-disciplinary projects proved to contain multiple internal (engineer versus executer) and external interfaces (contractor versus client/supplier). Currently, a lack of coordination of these interfaces negatively influences the implementation of SE. The reason for the poor interface management does seem to originate from a lack of regular and scheduled interface meetings. In several cases the project employees responsible for the interface management did not put enough effort facilitating these. In some cases it seemed that the employees responsible for integral functions, did not possess the right (personal) skills to do so. In other cases a lack of a dedicated process manager, included in the project management team, seemed to be the reason.

Currently, most of the project teams consist of mono-disciplinary experts working on a specific project element in a particular life cycle stage. This obstructs the integrated character of SE and overcome the interfaces that occur during the projects. Furthermore, the project size and/or complexity do not seem to have an influence on the decision if SE should be applied or not: the extent in which SE processes are conducted should be tailored to the project. In (larger) projects, were SE is explicitly required by the contractual arrangements; interfaces are continuously identified, formulated into an up-to-date environment and coupled to the requirements. However, in the other (smaller) projects these advantages are not utilized, but can improve the management of the interfaces.

The analysis of the cases showed that the development and execution phases within the building process are completely different activities and cultures. Despite the fact that interfaces are often identified and documented, they are disregarded during the transition from one phase to another. The mutual understanding and awareness seems to play a key role here. Internally, the designers and engineers do not seem to feel responsible for the proper execution of the project, while the executers do not feel responsible for the design of the project. An increased level of interdisciplinary knowledge and early involvement of all stakeholders can positively influence the level of mutual understanding, which is necessary to successfully implement SE.

SE is considered as a separate process, besides other supporting processes, such as project management and risk management. SE should be considered as an integral part of these processes [13], [25], [54]. Because contractors are currently implementing, adopting and learning SE as an organization, they have chosen to separate SE from the other supporting processes. This explicit separation seems to have a negative effect on the implementation of SE, because it emphasizes the different way of working, causing resistance among employees.

Insufficient perceivable benefits. The cross-case confrontation confirmed that the majority of the project employees do not perceive enough benefits from the application of SE. Further research should be conducted to better understand which benefits the individual project employees perceive. By increasing the level of support from the project team management for all supporting processes; the level of support provided by the SE manager; the proper alignment of the supporting processes; and the practical usability of the majority of SE tools, the level of perceivable benefits can be increased.

One of the main assumptions of this research is that a successful implementation of SE within civil construction projects will increase quality and decrease failure costs. At this moment this assumption cannot be quantitatively substantiated. We assume that contractors are adopting SE, simply because it is required by its clients. However, for higher management and project management the potential financial benefits that are the result of SE implementation still seems to be a main reason to support SE or not.

The identification of the key problem areas shows that the factors are widely overlapping with all supporting processes in construction projects. SE is not only concerned with the technical process. These findings are in line with [13], which states that SE should be considered as a systematic way of working, independent of the underlying activities. Here a discrepancy between existing literature and the interpretation by the contractor seems to arise. The contractor treats SE as a separate supporting process and expertise, which resides on the same level as other supporting processes. The theory suggests that SE should be treated as a certain expertise; while at the same time it is a umbrella method over all other supporting processes.

IV. Proposed Improvements

Considering the identified key problem areas and existing literature, the following proposed improvements provide contractors with approaches to better manage the implementation of SE within their projects.

One single, authoritative organization for process and SE management. We propose that contractors adopt a single, independent organizational entity in their organization for process and SE management. This organization is responsible for the implementation of SE and has been granted the authority to implement and standardize all SE related processes, enabling successful implementation of SE. By bundling all supporting processes in one organization, the knowledge of all these experts is bundled as well. The separate and independent character of the organization ensures that project employees do not negatively relate the supporting processes to one of the operating companies. Furthermore, due to the bundling of resources (f.i. SE specialists) from the whole organization, better resource allocation and specialization is possible. This results in an increased availability and quality of SE experts.

Removing the financial barriers for operating companies to stimulate an increased involvement of SE experts or process managers within their projects, is crucial for successful implementation. This can be realized by splitting the operational costs of the independent organization evenly across the participating operating companies.

Continuous feedback in a knowledge center and sharing of knowledge. During the case studies we found that the lack of time and people in projects, often results in low priority for the overhead of knowledge activities. The conclusion that can be drawn is that inter-project learning cannot be effective without effective inter-project learning activities. By creating one single organization for process management the sharing of knowledge across disciplines is stimulated, because employees are part of the same team and work according to the same rules and values. Furthermore, due to the coverage of the operational costs more time can be dedicated to knowledge gathering and sharing.

The central knowledge center can be used to improve SE trainings; provide practical examples based on best practices; and continuously share the latest information coupled to the updating of (project management) documentation.

Introduce SE implicitly, rather than explicitly. SE has acquired a negative image with part of higher management and individual project employees of the examined contractor. As a result, the further implementation of SE as an explicit concept has become unnecessarily difficult. At the same time [20] and [13] showed that SE comprises several processes and activities that are not specifically named as SE. By adopting SE activities in task descriptions of employees, without explicitly formulating them as part of SE, the initial resistance is circumvented. Applying this approach slowly changes the standard way of working and thinking of designers, engineers, planners and executers. A clear role and responsibility for each project employee provides clarity, which positively ensures awareness and can positively influence their support.

Implement what is useful. Although the various initiatives within the civil sector stimulate to standardize the SE processes, the contractor should anticipate a certain level of uncertainty from the client. Depending on – for example – the *level of functionality* of the requirements and the type of contract, the level of useful SE activities conducted may change accordingly. By coupling SE activities to task descriptions, as mentioned in the previous proposed improvement, multiple scenarios can be embedded within the organization adapting to these context variables. Additionally, if the client does not explicitly require SE, the SE activities contributing to the internal goals of the contractor can still be executed. In this scenario the SE activities are implicitly incorporated in the task description of project employees.

Further research should be conducted on which SE activities should be done depending on which context variables. Again, the centralized organization for process support can align the level of SE activities between the operating companies involved.

Right people, in the right place. Besides SE managers, integral design leaders, integral preparations managers and project managers fulfill an important role in the facilitation and support for implementing SE. Only those employees who are in support of SE and understand its application – alongside their technical experience and expertise – may function as manager on an integral function. This ensures support within the project management for supporting processes, thus increasing the support from individual project employees. Furthermore, only those project management employees, who fully understand the concept of systems thinking during the entire life cycle of a project, can properly manage their interfaces. The central organization for supporting processes should focus on uniform training of all project management team members to establish this support and understanding.

Stimulate the learning process. Due to the combined effect of the six key problem areas, the implementation of SE within the sector is an incremental and time-consuming process. SE depends on the joint effort of multiple stakeholders, including client, contractor and suppliers. Although contractors can stimulate the further implementation of SE in this industry, they cannot force the implementation and therefore should accept the learning process.

Within the larger multi-disciplinary projects, the process manager is responsible to create acceptance, feasibility and support. By actively involving project employees in discussions, where the individual issues of employees are broadened to multiple issue discussions, the learning process is stimulated. The process manager should be flexible and be open for change, as the feedback from the construction process remains leading for the improvement of the supporting processes.

Building long-term relationships with external parties can help to increase the level of standardization within the sector. The proposed organizational entity serves as a central point within the contractor from which communication and the relationships with external parties can be unambiguously managed. Contractors should try to engage in discussions on SE within the sector and create trade-offs if needed for unanticipated change.

V. Conclusions and Future Work

In this paper, we established a list of factors affecting the successful implementation of SE, based on a review of literature and practice (Section II). We presented three previously undocumented factors, which prove to have an effect on the implementation of SE in civil construction projects in the Netherlands (Section III.B). To gain preliminary insight into the key problem areas of the implementation of SE in civil construction projects, we performed four case studies with varying selection and scoring methods concerning the identified factors (Section III.A). Based on the key problem areas six proposed improvements are delineated, which provide insight for contractors to better facilitate and manage the implementation of SE (Section IV).

This research offers a more specific strategy for SE implementation than has been considered in related literature. We showed that within BAM – and possibly more contractors active within the civil construction industry – SE is closely interwoven with all other management aspects and should be treated as such, by implicitly adopting SE in the work processes. To do so, this research proposed an organizational model for further integration and representation of project (management) teams of civil construction projects.

The following limitations should be kept in mind while interpreting the results presented in this paper. Only four case studies at a single contractor were conducted. As a result, the identification of the factors and key problem areas cannot be generally representative for contractors in the civil construction industry. Future research should focus on a larger group of civil construction projects. The proposed approach should be applied to case studies in a variety of organizations in the industry, to statistically assess the relevance of the factors and proposed improvements to increase the implementation rate of SE.

Secondly, the proposed improvements are partly based on the organizational context of the contractor were the case studies were conducted. This means, for other contractors to use the proposed improvements, they should be compared with the organizational context in which they are embedded, and where necessary, adapted.

The most significant claim is that the list of factors as presented enables to measure the implementation rate of SE. However, for the following factors this effect could not be determined, based on the available data:

- Acknowledgement of the learning process by project employees;
- Individual prior experience;
- Resources available for the development of SE;
- Actual benefits of applying SE.

In the current approach, the scores of the factors are based on qualitative data, derived from interviews and project documentation. Future research should focus on the quantification of the factors, so the reliability and comparability of the case studies are increased. This enables the development of industry-wide best practices. In future research all life cycle stages of the SE process should be assessed, not only requirement analysis and V&V.

Acknowledgment

The authors wishes to thank all involved BAM employees for their devoted time and openness during the conducted interviews. A special expression of appreciation is given to A. Verbraeck, J.L.M. Vrancken, W.W. Veeneman, and P. de Greef for their valuable reviews and suggestions made to improve the contents and clarity of this article.

References

[1] I. Koenen, "Vaker systems engineering bij RWS en ProRail," *Cobouw*, 07-Dec-2010. [Online]. Available: http://cobouw.nl/nieuws/algemeen/2008/06/14/Vaker-systems-engineering-bij-RWS-en-ProRail. [Accessed: 18-Feb-2013].

[2] M. Damen and J. V. Geijlswijk, "ProRail en Rijkswaterstaat zetten in op Systems Engineering," *CAD Magazine*, vol. 18, no. 7, Emmeloord, 25-Jul-2007.

[3] Rijkswaterstaat, "Systeemgerichte Contractbeheersing Anno 2011," Rijkswaterstaat, Utrecht, Oct. 2011.

[4] Cobouw Redactie, "Systems Engineering en aanbesteden in de gww," *Cobouw*, 26-Oct-2005. [Online]. Available: http://cobouw.nl/nieuws/algemeen/2005/10/26/Systems-Engineering-en-aanbesteden-in-de-gww. [Accessed: 18-Feb-2013].

[5] J. Koning, "Durf te kiezen," *Cobouw*, 14-Feb-2008. [Online]. Available: http://cobouw.nl/nieuws/algemeen/2008/02/14/Durf-te-kiezen. [Accessed: 18-Feb-2013].

[6] S. Emmitt, *Managing Interdisciplinary Projects*. Oxon: Spon Press, 2010.

[7] Werkgroep Leidraad Systems Engineering, "Leidraad voor Systems Engineering binnen de GWW-sector," Werkgroep Leidraad Systems Engineering, 2009.

[8] J. A. Gelderloos, "Applicability of an integral design approach based on steering by aspect systems in the construction industry," Delft University of Technology, Amsterdam, 2010, unpublished.

[9] N. Verboom, "Implementatie van Systeemgericht Contractbeheersing binnen Rijkswaterstaat," Delft University of Technology, Delft, 2007, unpublished.

[10] V. P. van der Meijden, "Lessons Learned, toetsen van vraagspecificaties eisendeel," Rijkswaterstaat, Oct. 2009, unpublished.

[11] J. Donkers, "Requirements Management within Grontmij Randstad Techniek," Delft University of Technology, 2011, unpublished.

[12] C. J. van Leeuwen, "Systems Engineering," Delft University of Technology, Leiden, 2009, unpublished.

[13] INCOSE, *Systems Engineering Handbook*, 3rd ed. San Diego: INCOSE, 2012.

[14] E. C. Honour, "Understanding the value of systems engineering," *Proceedings of the INCOSE International Symposium*, pp. 1–16, 2004.

[15] E. Beerda, "ProRail stuk goedkoper uit," *Cobouw*, 17-Apr-2010. [Online]. Available: http://cobouw.nl/nieuws/algemeen/2010/04/17/ProRail-stuk+goedkoper-uit-met-d-c-contract.xml. [Accessed: 17-Feb-2013].

[16] H. Maylor, *Project Management*. Pearson, 2010, pp. 1–441.

[17] D. Hitchins, "What are the general principles applicable to systems?," *INCOSE Insight*, vol. 12, no. 4, pp. 59–63, Dec. 2009.

[18] S. Ramo, "Systems Engineering Manual," Federal Aviation Administration USA, Washington, 2006.
[19] H. Eisner, *Essentials of Project and Systems Engineering Management*, 3rd ed. Washington: John Wiley and Sons Ltd, 2008.
[20] NEN-ISO/IEC 15288, "Systems and software engineering - System life cycle processes," Delft, 2008.
[21] Volker Infra, "Systems Engineering in Projecten van VolkerInfra," Koninklijke Volker Wessels Stevin, Vianen, Nov. 2009.
[22] Koninklijke BAM Groep nv, "SE-wijzer," Koninklijke BAM Groep nv, Bunnik, Jun. 2008.
[23] S. Fernie, S. Weller, S. D. Green, R. Newcombe, and M. Williams, "Learning across business sectors: context, embeddedness and conceptual chasms," vol. 2, pp. 557–565, 2001.
[24] R. Graham, "Managing the project management process in Aerospace and Construction: a comparative approach," *International Journal of Project Management*, vol. 17, no. 1, pp. 39–45, 1999.
[25] E. W. Aslaksen, "Systems Engineering and the Construction Industry," *Requirements and Construction*, pp. 1–4, Jan. 2005.
[26] K. Pohl, "The three dimensions of requirements engineering: a framework and its applications," *Information systems*, vol. 19, no. 3, pp. 243–258, 1994.
[27] A. P. Sage, *Handbook of Systems Engineering and Management*. New York: Wiley, 1999.
[28] D. Hitchins, *Systems Engineering*. Chichester: John Wiley and Sons Ltd, 2007.
[29] N. J. Slegers, R. T. Kadish, G. E. Payton, J. Thomas, M. D. Griffin, and D. Dumbacher, "Learning from failure in systems engineering: A panel discussion," *Systems Engineering*, vol. 15, no. 1, pp. 74–82, Jul. 2011.
[30] L. E. Bernold and S. M. AbouRizk, *Managing performance in construction*. Wiley Online Library, 2010.
[31] S.T.A. van den Houdt, "Identifying and Managing the Success Factors behind the Implementation of Systems Engineering," Delft University of Technology, Delft, 2013.
[32] B. S. Blanchard, *System Engineering Management*. John Wiley & Sons, 2012.
[33] B. Elliot, "INCOSE UK Chapter Working Group on Applying Systems Engineering to In Service Systems," INCOSE, London, Oct. 2008.
[34] S. Arnold, "Where is Standarisation Guiding Us?," presented at the INCOSE UK Chapter Spring Conference, Swindon, 2007.
[35] A. Kossiakoff and W. N. Sweet, *Systems engineering: principles and practice*. Wiley Online Library, 2002.
[36] R. I. Faulconbridge and M. J. Ryan, *Managing Complex Technical Projects*. Boston: Artech House, 2005, pp. 1–26.
[37] A. Sharon, O. L. de Weck, and D. Dori, "Project management vs. systems engineering management: A practitioners' view on integrating the project and product domains," *Systems Engineering*, 2011.
[38] A. Pyster, D. Olwell, N. Hutchison, S. Enck, J. Anthony, and D. Henry, *Guide to the Systems Engineering Body of Knowledge (SEBoK) version 1.0*. New Jersey: The Trustees of the Stevens Institute of Technology, 2012, pp. 1–852.
[39] J. Kotter, "Leading Change: Why Transformation Efforts Fail," *Harvard Business Review*, 1995.
[40] A. Squires, "Investigating the Relationship between Online Pedagogy and Student Perceived Learning of Systems Engineering Competencies," Stevens Insitute of Technology, Hoboken, NJ, USA, 2011.
[41] H. L. Davidz and J. N. Martin, "Defining a strategy for development of systems capability in the workforce," *Systems Engineering*, vol. 14, no. 2, pp. 141–153, Apr. 2011.
[42] H. Eisner, *Essentials of Project and Systems Engineering Management*, 2nd ed. Wiley, 2002.
[43] A. P. Sage, *Systems Management for Information Technology and Software Engineering*. New York: Wiley, 1995.
[44] M. A. Nieuwenhuis, *The Art of Management*. the-art.nl, 2003.
[45] A. Hamilton, *Handbook of Project Management Procedures*. London: Thomas Telford, 2004.
[46] A. P. Sage and L. Armstrong, *Introduction to Systems Engineering*. London: Wiley, 2000.
[47] M. Bosch-Rekveldt, Y. Jongkind, H. Mooi, H. Bakker, and A. Verbraeck, "Grasping project complexity in large engineering projects: The TOE (Technical, Organizational and Environmental) framework," *International Journal of Project Management*, vol. 29, no. 6, pp. 728–739, Aug. 2011.
[48] L. S. Pheng and Q. T. Chuan, "Environmental factors and work performance of project managers in the construction industry," *International Journal of Project Management*, vol. 24, no. 1, pp. 24–37, Jan. 2006.
[49] J. K. Pinto, D. P. Slevin, and B. English, "Trust in projects: An empirical assessment of owner/contractor relationships," *International Journal of Project Management*, vol. 27, no. 6, pp. 638–648, Aug. 2009.
[50] S. Olander and A. Landin, "Evaluation of stakeholder influence in the implementation of construction projects," *International Journal of Project Management*, vol. 23, pp. 321–328, 2005.
[51] R. Evaristo and P.C. van Fenema, "A typology of project management: emergence and evolution of new forms," *International Journal of Project Management*, no. 17, pp. 275–281, 1999.
[52] Koninklijke BAM Groep nv, "Jaarrapport 2011," Koninklijke BAM Groep nv, 2012.
[53] K. Lasfer and A. Pyster, "The Growth of Systems Engineering Graduate Programs in the United States," presented at the Conference on Systems Engineering Research, Los Angeles, CA, USA, 2011.
[54] P. de Boer, "Systems engineering in infrastructure: An approach for better results," *Journal of Public Works & Infrastructure*, 2008.