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Investigating Systems Engineering Approaches in the Norwegian Construction Industry: A Multi-Case Study

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Abstract. There is an increasing application of Systems Engineering in the Norwegian construction industry. This paper investigates the effects of a Systems Engineering approach on project management performance, prerequisites for success, and which elements contribute to effectiveness from a technical contractor perspective. First, we find a positive perception of Systems Engineering's effect on time, cost, and quality. Second, we provide and rank a list of 12 prerequisites for success. Third, we quantify the perceived importance of five elements of the systems engineering process. Finally, we find a disconnect between what seems to be essential processes and prerequisites and what gets done in practice. To improve Systems Engineering performance, we recommend improving Systems Engineering competence and capabilities, increasing the formality of requirements analysis and documentation, and front-loading the effort and allocation of resources in projects.

Introduction[1]

The construction industry is one of Norway's largest business sectors, generating an annual revenue of 625 billion NOK (Statistics Norway, 2019). We find actors like the client and commissioner, the design/consulting firms, the contractors, and subcontractors within the construction industry. All these actors work together to design and build infrastructure and buildings. While other land-based industries in Norway have had a 30% increase in productivity between 2000 and 2018, the construction industry has had a 10% decrease (Statistics Norway, 2018). There is also a high conflict level in the industry. Some of the reasons for conflict are; delay, cost overruns, and quality problems. Decreasing productivity and these factors may be interrelated.

Systems Engineering Implementation. The Norwegian construction industry has started implementing a tailored version of the Systems Engineering approach adopted from the oil and gas industry, under the name "Systematic Completion," to mitigate these challenges (Beste, 2020; Lynghaug, Kokkula and Muller, 2021). Johansen and Hoel define Systematic Completion as *"an assurance that the project fulfills all functional requirements within the set time-, cost- and quality*

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[1] The first two paragraphs are literal copy of https://gaudisite.nl/SoSE2021_LynghaugEtAlSEinConstruction.pdf previously published by the authors

requirements, planned and verified by a structured process which is managerially driven from design and planning to handover." (Beste, 2020; Johansen and Hoel, 2016 p. 9). More than a definition, this is a set of performance promises.

In addition to the implementation of Systems Engineering methods, the industry uses various contract forms. Design-bid-build has been the dominant regime traditionally. We see a shift towards more integrated contracts like design-build and variants of partnering agreements in the later years. Partnering contracts (when used) often govern the design phase, and projects mostly transition into a design-build regime after the design phase in projects that utilize partnering. See Lynghaug et al. (2021) for further discussion on context.

Bravida. Bravida is a Nordic technical contractor headquartered in Stockholm, Sweden. The company performs contracting work within the disciplines of heating, ventilation, air conditioning, plumbing, electricity, and information- and communication technology infrastructure.

Problem. The effect of Systems Engineering in the Norwegian construction industry is not well documented (Beste, 2020). It is uncertain whether the approach delivers the promised results or not, and there seems to be a lack of a shared understanding of the concept (Lynghaug et al., 2021).

Beste (2020) "*provides a starting point into analyzing the effect of Systematic Completion*" and proposes further studies with more data and an international perspective to complement the research. Furthermore, according to Beste, taking the design team, contractor, or customer's perspective will improve insight. Lynghaug et al. (2021) provide a link between Systematic Completion and Systems Engineering in the construction domain, adding the international perspective. In the present study, we collaborate with Bravida and analyze Systems Engineering in construction from the technical contractor point of view to add one supplementary perspective. Furthermore, we use Systems Engineering as a primary reference perspective and delve deeper into the Systems Engineering processes.

Research Goal. The goal of the research is threefold. First, the research will attempt to determine how successful the application of Systems Engineering is from the technical contractor perspective. Second, we intend to contribute to establishing a shared understanding of Systems Engineering in the Norwegian construction domain. Finally, we aim to provide recommendations on what the industry should focus on in further implementing Systems Engineering and research.

Research Questions. To concretize the research and contribute to documentation and clarification about Systems Engineering in construction, we address the following research questions:

RQ1: How does Systems Engineering affect the technical contractor's project management performance in public healthcare building construction projects?

RQ2: What are the prerequisites to make Systems Engineering work for the technical contractor?

RQ3: What are the elements that contribute to effective Systems Engineering in construction?

Exploring RQ1 indicates whether the Systems Engineering approach contributes to better project management performance for the technical contractor. Project management performance relates to cost, time, and quality (Cooke-Davies, 2002). Answering RQ2, we provide a list of critical prerequisites for the technical contractor's success with the approach. Furthermore, this creates a basis for analysis of the process quality at the technical contractor and comparison with prerequisites essential for the building commissioner. Answering RQ3, we illuminate which Systems Engineering processes typically conducted in the early phase of a construction project contribute to effectiveness.

In the remainder of this paper, we first present the analytical framework consisting of Systems Engineering, Systems Engineering in Construction, and Systematic Completion. Second, we account for our research methodology. Third, we present and discuss findings from our case studies. Concluding the paper, we answer the research question based on our results.

Systems Engineering[2]

Systems Engineering Definition. The International Council on Systems Engineering (INCOSE) defines Systems Engineering as "an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: Operations, Performance, Test, Manufacturing, Cost & Schedule, Training & Support, Disposal. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs." (INCOSE, 2015 p.11).

The V-model. Various models and frameworks visualize and guide the Systems Engineering lifecycle. In essence, they convey the message of decomposing the system into comprehensible subsystems and components before integrating them into a complete system (top-down and bottom-up). The V-model depicted in Figure 1 is a widely accepted model. The left leg describes the system design (top-down), and the right leg representing the iterative integration and verification process (Locatelli, Mancini, and Romano, 2014).

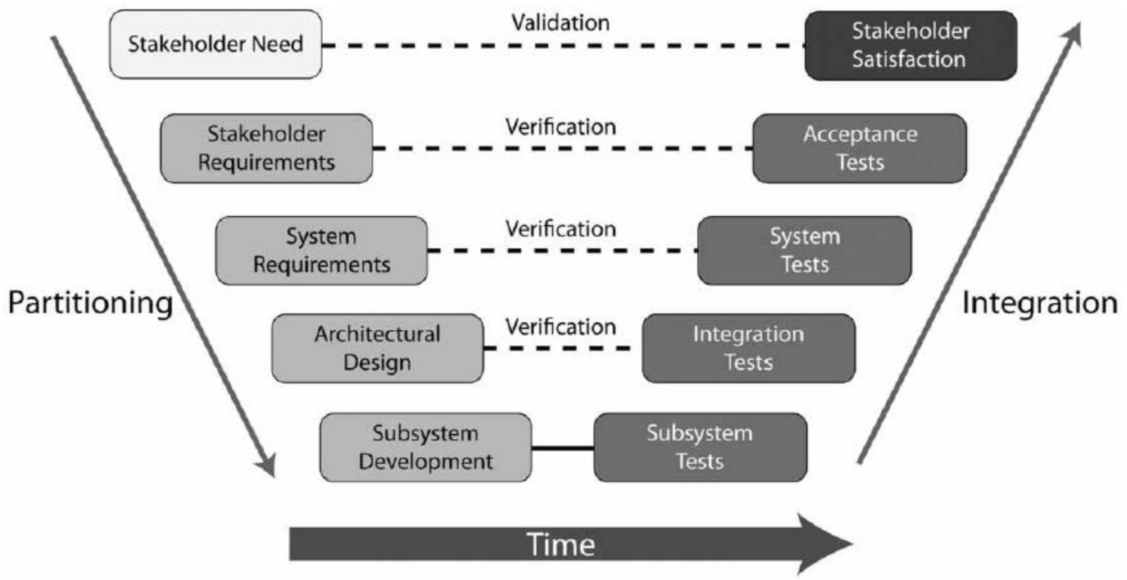

Figure 1. V-model for Sequential Systems Engineering Lifecycle (Emes, Smith, Marjanovic-Halburd, 2012)

While the V-model conveys relative linearity in the process, it is, in fact, much more iterative. The Department of Defense (2001) elaborates on the top-down design process. The process is looping through the steps of requirements analysis, functional analysis, and design synthesis. Methods and techniques summarized as system analysis and control are used to track decisions and requirements, maintain technical baselines, manage interfaces, risks, cost, schedule, technical performance, and verify that requirements are met (Department of Defense, 2001). The output of the process is a de-

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[2] The section, is a condensed version of https://gaudisite.nl/SoSE2021_LynghaugEtAlSEinConstruction.pdf previously published by the authors.

sign/solution and requirements for subsequent stages. Figure 2 depicts the process in one layer. However, depending on the system, it is further decomposed in N number of subsequent layers, shaping the system architecture. Subsequently the process carries on with iterations of bottom-up integration and test, as illustrated with the systems build approach in Figure 3.

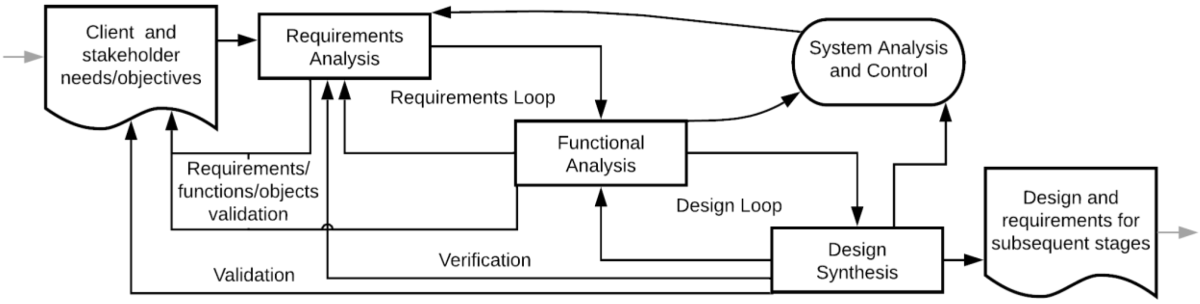

Figure 2. The Systems Engineering Process, adapted from Department of Defense (2001) and de Graaf, Voordijk, and van den Heuvel (2016)

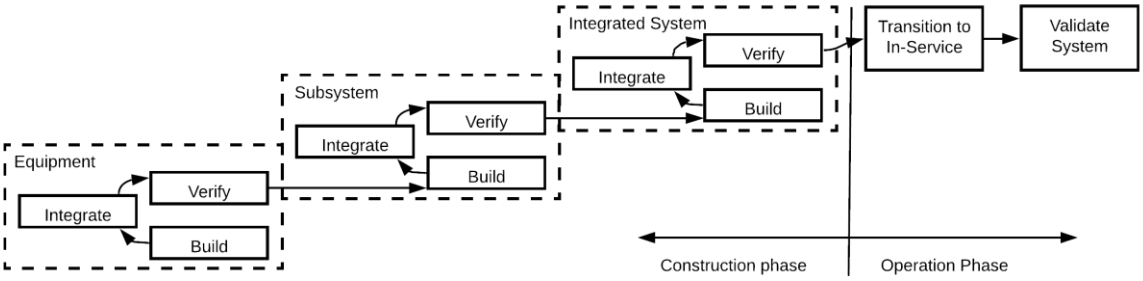

Figure 3. The Systems Build Approach, adapted from Gleckler and O'Neil (2013)

Systems Engineering in Construction

In the past decades, Systems Engineering has gained interest in the construction industry internationally to handle the increasing complexity (de Graaf, Voordijk, and van den Heuvel ,2016, de Graaf, Vromen, and Boes, 2017; de Graaf and Loonen, 2018; Elliott, O'Neil, Roberts, Schmid, and Shannon, 2012; Emes, Smith, and Marjanovic-Halburd, 2012; Makkinga, de Graaf, and Voordijk, 2018; Yoo and Park, 2001). In recent years, the approach also gains traction in the Norwegian construction industry. Johansen and Hoel (2016) and Beste (2020) describe and visualize a concept called Systematic Completion through the V-model, similar to Figure 1. The approach moves through requirements analysis, functional analysis, and design synthesis, similar to the process in Figure 2. In iterations, the process facilitates the development of complete system architecture and design. Subsequently, the system is constructed and verified in a stepwise series of integration and test activities, similar to the system build approach we depict in Figure 3. While moving through these processes, Systematic Completion aims to consider all aspects, similar to the list stated in the INCOSE definition of Systems Engineering. Based on these identical traits, we conclude that Systematic Completion is a tailored version of Systems Engineering and hereafter treat Systematic Completion as Systems Engineering.

Research Method

The research uses an exploratory multi-case study approach with a triangulation of document analysis and interviews. According to Yin, the case study approach is relevant when trying to explain some contemporary circumstances. E.g., how and why some social phenomena work (Yin, 2018 p.9). To avoid the common pitfall with case study research, investigating too many topics, and trying to answer too broad research questions (Baxter and Jack, 2008), we limit the study by context (healthcare building construction) and time (early phase of the projects). To increase our ability to draw generalizable conclusions, we conduct a cross-case analysis from three separate single case studies (Yin, 2018 p.16).

The research moves through three phases; understand, explore, and evaluate, see Figure 4. In preparation for the research, we conducted a literature review, exploring the body of knowledge related to Systems Engineering in the construction domain (see Lynghaug et al. (2021)). In the present study, we perform a document review and nine semi-structured interviews with the technical contractor's key personnel, namely project managers, systems engineers, and project developers. To concretize the results, a survey assessing various statements on a five-point Likert scale follows the interviews. The statements originate from the literature review, the document review, and the interviews. We use academic supervisors for validation in the academic domain and Systems Engineers from the technical contractor and a principal contractor for validation in the industry domain.

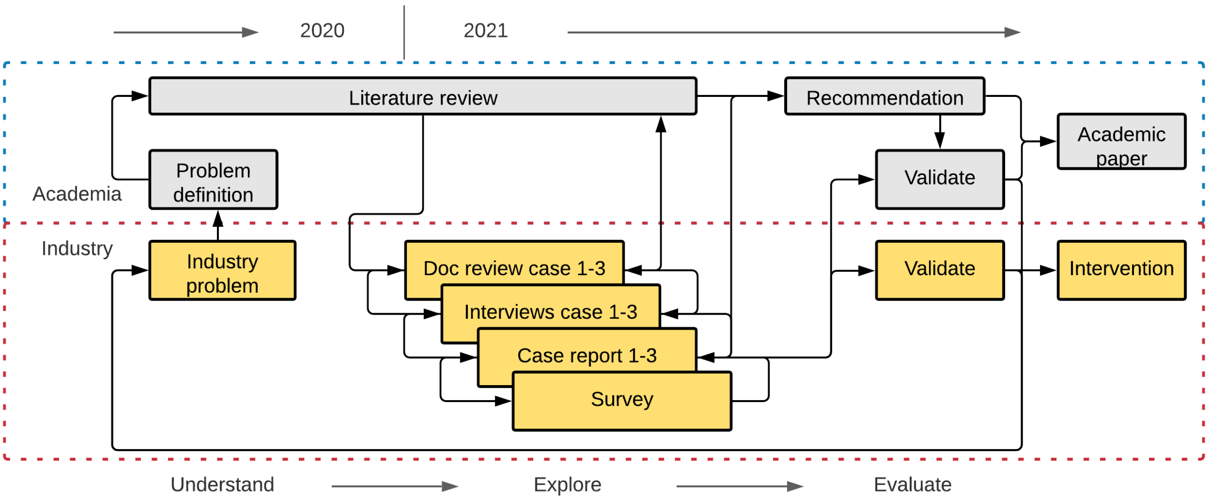

Figure 4. High-level Overview of Research Design

We review three ongoing projects where the contractor is involved with one or more technical disciplines. The main author of this paper works for the technical contractor and is actively engaged in one of the projects we investigate.

Data Collection and Analysis

Step 1. For each case, we first review the governing documents of the project related to Systems Engineering. Furthermore, we review documents and databases containing requirements, functional descriptions, interface matrices, integration- and test frameworks and plans. This effort provides the first insight into the implementation of Systems Engineering beyond the formal requirement to use the approach and contributes to shaping the outline of semi-structured interviews.

Step 2. We recruited nine informants from the three projects to participate in interview sessions. Rather than recruiting informants based on whether they are experienced or knowledgeable about Systems Engineering, we recruited them based on their role in a project required to use Systems Engineering. We do this to avoid overly optimistic results by interviewing only "the community." Hence, the range of informants spans from first-time users to personnel with decades of experience with Systems Engineering.

The interviews consisted of a half general and half case-specific set of questions. We mainly asked exploratory "what" questions and open "how" questions. We conducted seven interviews via MS Teams and two interviews face to face. We taped and transcribed all interviews for analysis purposes. Furthermore, we coded the transcripts into eight categories. First, two general categories, "What is Systems Engineering" and "how have you been working with Systems Engineering in this project".

Second, addressing the research questions directly with three codes related to "Project management performance", "Prerequisites", and "Elements contribution". Finally, three categories related to "Knowledge", "Personnel replacement", and "Future development".

Step 3. Based on the findings in interviews, where our informants illuminated and emphasized various aspects of the Systems Engineering process, we compiled a survey to have all informants quantify their perceptions and opinions on a list of statements. In the survey, we asked the informants to rank statements about their competence and knowledge, a list of 12 potential prerequisites to succeed with Systems Engineering, the importance of five elements of the Systems Engineering process, 12 statements about how their project performs on elements and prerequisites, and last we included the same eight statements that Beste (2020) analyzed by survey in her work (performance claims from Johansen and Hoel (2016)). The informants also had the opportunity to select an "I don't know" alternative for all statements and give text comments after every section. We analyzed and compared the results by calculating a Net Promoter score (Reichheld, 2003).

Results and Analysis

Building construction, in general, is getting more complex. There is an ever-increasing amount of technology integrated into new buildings. Healthcare building construction projects are especially complex, both in terms of integrated technology (e.g., rooms for magnetic resonance imaging) and requirements related to safety (e.g., seamless redundant power supply for critical functions or safety related to medical gas installations). We assume such projects to have high potential benefit from the application of Systems Engineering. Therefore, the research analyzes three public construction projects within the healthcare building construction domain where Bravida is working.[3] Table 1 describes the case projects. All three projects use Systems Engineering.

Table 1. Overview of the case study projects

	Project 1	Project 2	Project 3
Description	Project 1 builds a new healthcare facility in Norway. The facility includes hundreds of rooms of various sizes and complexity.	Project 2 builds a new healthcare facility in Norway. The facility includes hundreds of rooms of various sizes and complexity.	Project 3 builds a new healthcare facility in Norway. The facility includes thousands of rooms of various sizes and complexity.
Contractual approach	Partnering contract with a consecutive design-build contract.	Partnering contract with a consecutive design-build contract.	Design-bid-build approach with partnering/optimization before construction starts.
Size / Budget	>=30 000 sqm	<=30 000 sqm	>=100 000 sqm
Bravida scope	Single discipline contract	Interdisciplinary contract	Single discipline contract
Bravida contract worth	>=100 MNOK	>=100 MNOK	>=100 MNOK

Findings in Document Review

Formal Implementation of Systems Engineering. The formal implementation of Systems Engineering in all three projects, to some extent, follows the BA2015 guidebook on Systematic Completion (Johansen and Hoel, 2016), NS6450 (Standards Norway, 2016), and NS3935 (Standards Norway, 2019). Project 1 explicitly requiring a Systematic Completion according to all three documents in the "requirements for Systematic Completion" provided by the commissioner. Project 2 explicitly requiring startup and trial operation according to NS6450 with a few clarifications from the commissioner and the principal contractors governing documents referring to the BA2015 guidebook. Project 3 explicitly requiring the project to execute Systematic Completion according to

[3] The paragraph is a literal copy of section II.-B in Lynghaug, Kokkula and Muller (2021).

NS6450. Documents in all three projects also render content from the guidebook with clarifications about the concept and what deliverables the commissioner expects.

The reader should also be aware that the BA2015 guidebook refers to NS6450, which refers to NS3935. In other words, the reader must consider the three documents as complementary parts of the bigger picture. The standards have a higher degree of formality. However, none of them explicitly describes in detail how to perform the processes. Hence the need for clarifications from the commissioner or principal contractor. In Project 1 and 2, the responsibility for coordination lies with the principal contractor's Systems Engineer. In Project 3, the responsibility lies with the commissioners Systems Engineer and a project manager for technical disciplines. All projects use Systems Engineering in combination with a lean construction approach. In sum, we find a formal top-down integration of a Systems Engineering approach in all projects from the very beginning.

Needs and Requirements. All projects have requirements implemented. Projects 1 and 2 have a functional program describing upper-level needs, capacities, and concepts. Furthermore, the commissioner in these projects has a series of standard requirements specifications they use in all construction projects. The standard requirements specifications go in parallel (and are harmonized) with project-specific technical programs and descriptions. However, functional objectives outrank general requirements if there is a conflict between the standard requirements and the technical programs. In practice, must the contractor consider both documents and ensure documentation and approval of any deviation. In a third layer, the commissioner describes needs and specifies what equipment and quantities the contractors shall install in each room in a room functions program.

There is little traceable flow down of requirements between the layers, and the relation between the standard requirements and the project-specific requirements makes the picture more complex. Also, the sum of specifications in the room functions program imposes capacity requirements for various systems (e.g., power budget, ventilation capacity, control, etc.). In Project 3, the contractor works according to a technical description with a finished design that specifies equipment, quantities, and tolerances. In addition to the technical requirements in all projects, various documents state requirements for how the contractors shall work. This is consistent with Aslaksen, Brouwer, and Schreinemakers (2008), saying that a substantial part of the Systems Engineering effort in construction is concerned with designing the work. Some of the informants confirm this perspective in the interviews, focusing on construction workflow design when explaining their application of Systems Engineering.

Traceability. In Project 1 and 2, it is difficult to find traceable requirements flow down between the various documents. In Project 2, the delivery description, to some extent, refers to requirements in documents and standards. In Project 3, the technical specification, to some extent, renders functional requirements and acceptance criteria as needed to perform verification. Furthermore, there is no other formal documentation of any requirements analysis in Project 1 and 2, besides the resulting delivery description documents.

Interfaces. We find thoroughly prepared interface matrices and interface documents describing the interfaces between systems and disciplines in all three projects. The matrices and documents clarify who does what, both related to engineering and construction in an interface.

Test Planning. All three projects have started test planning on an upper level in the partnering- and optimization phase. All three projects use a database tool capable of linking and aggregating test plans in a hierarchy of single systems tests, integrated tests, and full-scale testing. The detailed test planning of the technical contractor in the database tool, with corresponding functional descriptions (functional requirements) and acceptance criteria, is still relatively immature at the time of review. Projects 2 and 3 have just started construction and have a checklist scheme for internal verification operational in Dalux. Dalux is the tool the contractor uses to communicate with its skilled workers. Project 1 has not yet started construction and has barely begun developing its checklist scheme.

Findings in Survey and Interviews

In the survey, we asked the informants to rank a series of statements on an ordinal five-point Likert scale spanning from "Strongly agree" to Strongly disagree" and "Not at all important" to "Very important". In the following paragraphs, we present an excerpt of the results (see Table 2, 3, 4, 5, and 6) with Net Promoter scores (NPS) at the right side of every table. For project-specific survey sections, we present the individual projects score together with the total. For non-project-specific sections, we present only the total score across all projects with response distribution.

Step 1. In the interviews, we find varying levels of experience and competence in Systems Engineering among the informants. We expect this, as some informants are first-time users, while others have completed several projects following a Systems Engineering approach. As Lynghaug et al. (2021) find evidence in the literature that competence and knowledge are enablers of successful Systems Engineering implementation, we attempt to quantify the competence and knowledge among informants, as this may explain any process quality differences between the projects. We present the results with a Net Promoter score in Table 2. The results confirm the varying levels of competence and knowledge. We find that Project 3 performs somewhat better on the self-assessment of competence and knowledge. Furthermore, the informants in Project 3 seem to be on a higher level in Bloom's taxonomy, while some informants in Project 1 and 2 struggle to understand how to perform Systems Engineering in practice. This result is in keeping with interview findings.

Table 2. NPS Scores for Competence and Knowledge

	Total NPS	Project 1	Project 2	Project 3
I have a clear understanding of how to perform Systems Engineering	-2/9	-3/3	-1/4	1/2
I have a clear understanding of what Systems Engineering is	3/9	1/3	1/4	1/2
I am well acquainted with the BA2015 guidebook for Systematic Completion	-5/9	-3/3	-2/4	0/2
I am well acquainted with NS6450	-1/9	-1/3	0/4	0/2
I am well acquainted with NS3935	-4/9	-3/3	0/4	-1/2
I have participated in skills development initiatives related to Systems Engineering	-2/9	0/3	-2/4	0/2

Step 2. In the interviews, we ask the informants to reflect on what prerequisites must be in place for the technical contractor to succeed with a Systems Engineering approach. As the informants proposed various prerequisites, we decided to test a list of 12 prerequisites that three or more informants support in the interviews. We present the results with a Net Promoter score and response distribution in Table 3. We remove the "I do not know" responses before calculating Net Promoter scores. We find that all the listed prerequisites receive a high positive Net Promoter Score.

Step 3. Furthermore, we ask the informants to assess the importance of five processes to achieve effective Systems Engineering. We present the results with a Net Promoter score and response distribution in Table 4. We find that all the tested processes earn a high positive Net Promoter Score.

Step 4. Having established what prerequisites for success and what Systems Engineering processes the informants consider important, we ask the informants to rate the performance of their project in a new series of statements. In particular, this series of statements assesses processes, outputs, and performance related to requirements (enablers of subsequent verification). We present the results in Table 5 with Net Promoter scores for the individual projects.

Table 3. Ranked List of Prerequisites to Succeed with Systems Engineering

	1 - Strongly disagree	2 - Disagree	3 - Neutral	4 - Agree	5 - Strongly agree	NPS	Rank
It is important to have well defined interfaces	0	0	0	0	8	8/8	1
It is important to have enough and unambiguous documentation	0	0	0	0	8	8/8	1
It is important to have a shared understanding of Systems Engineering and how we should perform it	0	0	0	1	8	8/9	2
It is important that the commissioner is capable of making decisions continuously and timely	0	0	0	1	7	7/8	3
It is important to have an interdisciplinary perspective	0	0	0	1	7	7/8	3
It is important to have traceability of requirements through various phases and decision-making processes	0	0	0	1	7	7/8	3
It is important to have buildable design documents before construction startup	0	0	0	1	7	7/8	3
It is important to allocate enough time and resources to perform Systems Engineering	0	0	0	2	7	7/9	4
It is important to involve all actors in the project on an early stage	0	0	1	0	7	6/8	5
Systems Engineering requires more effort (hours) in the early stage of a project	0	0	0	3	6	6/9	6
It is important to limit replacement of project personnel	0	0	0	4	5	5/9	7
It is important to have the design/engineering team involved in the project throughout to handover	0	0	1	2	5	4/8	8

Table 4. Process Importance for Effective Systems Engineering

	1 - Not at all important	2 - Less important	3 - Neutral	4 - Important	5 - Very important	NPS	Rank
Requirements analysis	0	0	0	2	7	7/9	1
Functional analysis	0	0	0	3	6	6/9	2
Design synthesis and development of design documents	0	0	0	4	5	5/9	3
Integration and test planning	0	0	0	4	5	5/9	3
User involvement and need specification	0	0	0	5	4	4/9	4

Table 5. In my project, we have [Performance Statement]

	Total NPS	Project 1	Project 2	Project 3
Performed a thorough requirements analysis	2/9	1/3	-1/4	2/2
Unambiguous system requirements	1/9	1/3	-1/4	1/2
Well organized requirements documentation	0/9	0/3	-1/4	1/2
Traceability from requirements to design	2/9	1/3	-1/4	2/2
Traceability from requirements to test plans and procedures	-1/9	0/3	-2/4	1/2
Experienced challenges related to ambiguous requirements or lack of documentation	0/9	1/3	0/4	-1/2
Experienced challenges related to changing requirements	2/9	2/3	0/4	0/2
Developed unambiguous functional descriptions (or received these from the commissioner)	-2/9	-1/3	-1/4	0/2
Designed according to the requirements	0/9	1/3	0/4	-1/2
Started test planning in the partnering phase	1/9	2/3	0/4	-1/2
A commissioner that delivers decisions continuously and timely	-6/9	-1/3	-4/4	-1/2
Allocated enough man-hours to perform a good Systems Engineering	-1/8	0/2	-2/4	1/2

Requirements and Functional Descriptions. According to the survey result (see Table 4), requirements analysis and functional analysis are the most critical processes for effective Systems Engineering. Simultaneously, we find that unambiguous documentation and traceability of requirements are both top-three prerequisites for success with Systems Engineering (see Table 3).

We find varying levels of requirements analysis, documentation of the analysis, and traceability of requirements in the three case projects. In Project 3, this is a minor part, as the technical contractor has limited responsibility for engineering. Most of the work goes according to a finished specification i.e., the effort focuses on choosing the products that fulfill the specification (see Beasley, Pickard, and Nolan (2017) for further discussion on requirements vs. specification). In Project 1 and 2, requirements analysis requires substantial effort as the contractor enters the projects in an earlier stage and subsequently also takes over responsibility for engineering when entering the design-build contract. Looking at the results in Table 5, we find consistent results for Project 2 and 3. Project 2 has poor performance on requirements, documentation, and traceability, while the project also experiences challenges related to ambiguous requirements and lack of documentation. Project 3 has straight opposite results. Project 1, however, has good self-assessed performance on requirements, documentation, and traceability but also experiences challenges with ambiguous requirements and lack of documentation. However, looking at the response distribution for Project 1, we find that the informants disagree internally.

The results indicate that there may have been a thorough requirements analysis but that documentation has some improvement potential, which we also see in the document review. I.e., an informant entering the project later will have difficulties finding evidence of a detailed requirements analysis and all changes to the specification. One informant explains this in part through the tight cooperation in the partnering phase and states in the interview that *"We worked tightly with the other contractors in the partnering phase and optimized the project with a holistic focus in collaboration through series of meetings. In retrospect, I see that the documentation of the processes could have been better."*

We argue that a complete requirements traceability would require a tremendous effort that would most likely not survive a cost-benefit assessment. Finding a reasonable level of requirements documentation and traceability will reduce challenges related to ambiguous requirements and lack of documentation and contribute to increased legal clarity related to changing requirements. As both Projects 1 and 2, and partly Project 3, have experienced challenges related to ambiguity and changing requirements, we recommend that the technical contractor increases the effort related to requirements documentation and traceability. Presenting any generalizable quantified risk associated with poor requirements analysis and ambiguous documentation is impossible. Every project is unique, and the magnitude of effects will vary according to what requirement is under consideration. We will, however, present a few examples from the projects that should motivate contractors to increase the formality and accuracy of requirements analysis and documentation.

Example 1. In Project 1, we can trace a case related to a part of the low voltage systems delivery scope to two conflicting documents with differing scopes. The increased scope imposes a financial risk at approximately 0.1% of the project budget, which may result in a loss for the contractor. We argue that this is a case of ambiguous requirements that the contractor should have clarified before signing the contract. Even though an "ambiguity argument" may flip the dispute in the technical contractor's favor, the contractor must eliminate such risk during requirements analysis.

Example 2. In Project 2, there was a case related to the expansion of the projects high voltage systems. The expansion is a consequence of an increasing power budget. Moreover, the rising capacity needs lead to a further increase of interfacing systems' capacity requirements, which again offset the interface to third party systems. The relocation of the interface forces the contractor to re-engineer parts of the projects high voltage system and increase the scope of work substantially. The expanded scope poses a financial risk at approximately 1.1% of the project budget. The risk is traceable to one ambiguous requirement that the contractor should have clarified during requirements analysis.

Example 3. In Project 1, there has been some confusion related to the requirements for another part of the low voltage systems. As the contractor did not have the necessary domain-specific expertise in the project as the delivery description was due, the contractor accepted an offer from the consulting firm to help build the delivery description. In the hectic conclusion of the partnering phase, the contractor failed to recognize the effects of a single requirement imposing delivery of a far more expensive solution than the one specified in the contractor's cost calculation. The misinterpretation and lack of clarification of one single requirement later result in an extra cost/loss for the contractor equal to 0.05% of the project budget.

Furthermore, we find that project 1 and 2 has not yet completed developing (or received) unambiguous functional descriptions. A functional description is, in practice, the hindsight version of functional requirements, as they are the basis for verification in the projects' test regime but seem to be ready relatively late. Informants in each of the two projects argue in the interviews that *"In my opinion, these things should be finished earlier"* and *"How do you know what to build if you don't have well-defined functional descriptions (requirements)? In my opinion, things should come in a different order (functional description before entering a design-build contract).".*

Resource Allocation. We find that allocating enough resources is an essential prerequisite and that successful Systems Engineering requires more effort in the earlier stages. Furthermore, it is crucial to limit personnel replacement (see Table 3). Project 3 performs well on allocating resources (see Table 5), and we find in the interviews that both informants have participated in the project from startup. Project 2 has a poor performance on resource allocation (see Table 5), and we find in the interviews that there has been a frequent replacement of project personnel. One informant states in the interview that *"I am sure that we will achieve high quality, but I am uncertain if we have calculated enough hours for Systems Engineering"*. We also find that Project 2 struggles with challenges related to requirements analysis, as we discuss above. Project 1 performs mediocre on allocating resources (see Table 5), with one informant responding "I do not know". Two out of three informants state in the interviews that the project should have allocated more resources to the partnering phase to (among others) perform better requirements and functional analysis. We also find that the project experiences challenges with ambiguous requirements and lacking documentation. We can trace the challenges back to the requirements analysis and a resource shortage in the partnering phase.

Project Management Performance. None of the case projects are completed at the time of our research. Hence, it is not possible to prove the positive promised effects on project management performance numerically. Furthermore, the Norwegian construction industry has introduced many concepts in the later years (e.g., more integrated contracts and lean construction approaches). The introduction of several new concepts in the same period makes it difficult to measure the impact of the particular method. In the interviews, we find that all informants generally have a positive attitude towards Systems Engineering and its effect when we apply the approach fully. However, one informant with many years of experience states that *"I have never seen that happen"*. We also find a lack of shared understanding of what Systems Engineering is and how to perform it. The lack of shared understanding may also affect the quality of the implementation. All informants are confident that their project will deliver on time and quality. The confidence related to cost is somewhat lower.

To provide a basis for comparison related to project management performance, we tested the same statements as Beste (2020) did with personnel from the commissioner side at Statsbygg. We find that all statements except "Buildings with better indoor climate" receive a positive Net Promoter Score (see Table 6). Regarding lifecycle cost, the original wording is "more accurate" life cycle cost. We find the term ambiguous. Therefore, we redefined the statement in our survey after a discussion with Beste.

Improving Systems Engineering Performance

We find some pain points for the technical contractor related to the performance of Systems Engineering performance and provide three recommendations for improvement initiatives that we will discuss in the following sections. First, we recommend systematically improving Systems Engineering competence among key personnel. Second, we recommend increasing the formality of the requirements analysis process and documentation. Finally, we recommend front-loading the workload and allocate more resources in the early phases of projects.

Table 6. Systems Engineering Contributes to [BA2015 Performance Statement]

	1 - Strongly disagree	2 - Disagree	3 - Neutral	4 - Agree	5 - Strongly agree	NPS
Early detection of errors (both in design/engineering and construction), avoiding costly rectifications and warranty claims	0	0	0	4	5	5/9
Higher quality on buildings and installations	0	0	0	3	6	6/9
Lower life cycle cost (authors interpretation)	0	1	2	2	3	0/8
Buildings with better indoor climate	0	0	4	2	1	-3/7
Better involvement and training of operations personnel	0	0	1	4	4	3/9
Good documentation	0	0	0	1	8	8/9
Less stress and lower conflict level	0	0	2	4	3	1/9
Satisfied users of the building	0	0	1	4	3	2/8

Improve Systems Engineering Competence. The research reveals that the level of Systems Engineering competence varies a lot among the informants. We argue that competence affects the quality of the Systems Engineering processes. We also find support in the literature that knowledge and skills affect the extent to which Systems Engineering is applied (de Graaf et al., 2017). Furthermore, our findings indicate that the performance of Systems Engineering processes increases and the challenges related to deficiencies decrease when the personnel's capabilities increase. There is, however, some uncertainty associated with this conclusion as Project 3 uses a contractual approach that removes a lot of the responsibility for engineering from the technical contractor.

Moreover, we find that only 4 out of 9 informants have participated in skills development initiatives related to Systems Engineering. Furthermore, among the four informants who have participated in skills development initiatives, only two informants state that they clearly understand how to perform Systems Engineering. This finding indicates that there is a need to rethink these skills development initiatives. We discussed different approaches with the informants and have started preparing a three-step initiative, including introductory seminars, case workshops, and supervised application of the approach in projects. In other words, gradual elevating in Bloom's taxonomy (See Krathwohl (2002)).

Formalize Requirements Analysis and Improve Documentation. Findings in document review, interviews, and survey reveal poor performance with requirements analysis and documentation that impose substantial financial risk for the technical contractor. We argue that the functional analysis and development of functional descriptions should be an integral part of an iterative process, as Figure 2 depicts. Moreover, the technical contractor should finish the functional analysis in the partnering phase to eliminate risk before entering a fixed price agreement for the execution phase. Furthermore, the contractor should ensure a reasonable level of traceability. Through participation in cross-regional projects simultaneously as performing the research, we find that other departments have tools and processes for a more formal requirements analysis and tracing through a requirements breakdown structure. Finally, the examples provided above make it evident that it should be a high priority for the technical contractor to unambiguously clarify all requirements. We assume improved capabilities will lead to improved process quality for requirements and functional analysis.

Our findings related to poor requirements quality have implications also for other actors like the commissioner. There is rich literature considering challenges with requirements. We find support for effects on risk and cost from challenges with requirements management (Wheatcraft, 2011). Furthermore, we learn from other industries that the quality of requirements seems to have an inverse correlation with the effort needed to gain acceptance for verification procedures (Bahill and Carson 2011, as cited in Carson, 2015). Also, program failure directly links to the quality and clarity of requirements (Hoehne PMP and Russell EISE, 2018). Finally, risk related to ambiguity also applies to the commissioner. Hence, we argue that all actors will benefit from improving requirements quality.

Moreover, a natural next step in developing the various Systems databases the projects use could be integrating and testing functionality for requirements management. To avoid reinventing the wheel, we suggest looking for inspiration from other industries (E.g., see Damien Wee and Muller (2016) evaluating the effectiveness of a requirements Management System). Furthermore, the literature discusses various tools to ensure requirements quality, like natural language processing (Vaz, 2018).

Front-Load Workload and Resource Allocation. The research reveals that resource shortage in the early phases of a project affects the technical contractor's challenges with requirements analysis. The informants agree that Systems Engineering requires more resources in the early stage. However, especially in Project 1, we find that resource shortage in the early phase affects the process quality leading to substantial financial risk for the contractor. In Project 2, the frequent personnel replacement might have some of the same effects. Furthermore, we find that in a large contract such as Project 1, the various sub-disciplines require substantial expertise.

Comparing the cost of one extra senior engineer over one year with risks surfacing as we describe in example 1, related to only one ambiguous requirement, we argue that front-loading related to resource allocation will benefit contractors. Furthermore, we assume such front-loading will decrease the need for "firefighting" later in the project. Finally, we assume that increased spending in the early phase will result in savings later in the project in general. This assumption is in keeping with Emes et al. (2012) principle five. The results of Beste (2020) also support this assumption. A front-loading of the contractors' workload will also have implications for the commissioner regarding the need for earlier decisions (see Table 5).

Conclusion

This research provides an insight into how the construction industry applies Systems Engineering methods in healthcare construction projects seen from a technical contractor point of view. We find that the projects incorporate all the assessed elements to some extent but that the quality of the processes has some improvement potential. This finding is as expected, as there is still a learning process going on with implementing the approach.

RQ1. How Does Systems Engineering Affect the Technical Contractor's Project Management Performance in Public Healthcare Building Construction Projects? None of the case projects are completed at the time of our research. Hence, it is not possible to prove the positive promised effects. Furthermore, drawing such a conclusion would require a comparison with similar projects that do not use Systems Engineering. Our informants perceive that a Systems Engineering approach contributes positively to project management performance when properly applied. We find indications that Systems Engineering process quality affects project management performance. Moreover, competence seems to affect Systems Engineering process quality together with resource allocation.

RQ2. What are the Prerequisites to Make Systems Engineering Work for the Technical Contractor? We test a list of 12 prerequisites for the technical contractor to succeed with Systems Engineering. All prerequisites receive high Net Promoter scores (see Table 3 for complete list). The top-three ranking prerequisites are (rank in brackets):

- Well-defined interfaces (1)
- Enough and unambiguous documentation (1)
- A shared understanding of Systems Engineering and how to perform it (2)

- A commissioner that is capable of making decisions continuously and timely (3)
- Interdisciplinary perspective (3)
- Traceability of requirements through various phases and decision-making processes (3)
- Buildable design documents before construction startup (3)

RQ3. What are the Elements that Contribute to Effective Systems Engineering in Construction? We test a list of five elements in the Systems Engineering process. All elements receive high Net Promoter scores as essential for effective Systems Engineering for the technical contractor (see Table 4). The order of importance according to the informants' perception is (rank in brackets):

- Requirements Analysis (1)
- Functional Analysis (2)
- Design Synthesis (3)
- Integration and test planning (3)
- User involvement and need specification (4)

Limitations

The present study only provides indications based on the opinion of our informants. Moreover, the random choice of informants based on their role in a project rather than merits with Systems Engineering safeguards for overly optimistic results one might get by talking to the "community". On the other hand, it raises a reliability issue as an inexperienced first-time user might not have the necessary competence to reflect on what, how, and why's of the approach to create a higher level of insight. The researcher might guide the reflection, but this exposes the results to confirmation bias.

Future Research

As Beste (2020) pointed out, taking other actors' perspectives will contribute to improved insight. Furthermore, complementing perspectives may contribute to generalizability. Conducting more studies with the same perspective will also increase generalizability. For the technical contractor, we suggest re-assessment of the three case projects throughout their execution and trial operation phase while systematically building Systems Engineering capabilities among project personnel.

Moreover, after completing more projects, we recommend conducting a more extensive study analyzing to what extent projects apply Systems Engineering methods using the framework of de Graaf et al. (2016) (or similar), at what process quality, and with what results. To make sense with such quality, cost, and impact analysis, contractors must systematically collect and store effort- and performance information about their projects (inputs and outputs).

Finally, we suggest researching how substituting the dominant bottom-up integration and test strategy with a top-down approach for parts of a building construction project (e.g., building automation control system) might reduce project delivery time.

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Biography

Tobias Lynghaug. is a Project Engineer at Bravida Norge AS. He received his mechanic certificate in 2011 and a BSc in Mechatronics from the University of Agder in 2017. In 2021, Tobias completed continuing education in building automation systems from Oslo Metropolitan University and graduated with a master's in Systems Engineering with Industrial Economics from the University of South-Eastern Norway. At Bravida, Tobias is working with project planning, construction management, cost control, and improvement of Systems Engineering practices.

Satyanarayana Kokkula. received his Master's degree in Applied Mechanics from IIT Delhi (Indian Institute of Technology, Delhi) in 2000. Later, he worked as an Assistant Systems Engineer at TATA Consultancy Services Pune, India. In 2005, he received his PhD from the Norwegian University of Science and Technology (NTNU), Trondheim, Norway. After finishing PhD, he joined FMC Kongsberg Subsea AS, as a Specialist Engineer in Structural Analysis from 2006 to 2016. In August 2017, he joined the University of South-Eastern Norway as an Associate Professor of Systems Engineering.

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