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Systems engineering in the building construction industry: comparison with the telecom industry

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Abstract

When project sizes, integrated technology, and demand for sustainability increase, the construction industry faces requirements increase. Fulfilling the requirements is essential to the project's success, but fragmentation in the design and production phases makes requirements management time-consuming and complex. An approach to more systematic requirement management found in other industries is systems engineering. Through interviews and a workshop, this research project explores the applicability and benefits of a systems engineering approach in the construction industry. Several differences and similarities have been identified by comparing the systems. The results show that adopting a systems engineering approach in the construction industry can improve requirements management, understanding of the entire project scope and enhance overall project quality.

Keywords: Systems engineering; requirements; verifications.

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1. Introduction

Construction projects are facing an increase in requirements since the projects are getting larger, more technology is integrated into the buildings, and new sustainability and CO2e emissions requirements are introduced [1]. As a result, requirement management quickly gets overwhelming, and instead of having systematic requirement management, the construction industry tends to trust craftsmanship [2]. In addition, construction projects span long time intervals and often face changes during the project's progress, making requirements traceability even more complex [3].

One approach to a more systematic requirements management found in other industries is systems engineering. NASA defines systems engineering as "a methodical, multi-disciplinary approach for the design, realization, technical management, operations, and retirement of a system" [4]. Further, their definition of a system is "the combination of elements that function together to produce the capability required to meet a need" [4]. Even though the definitions of systems engineering may vary slightly between users and organizations, it is common for all to focus on wholes and the synthesis of the whole from complementary parts [5].

The construction industry is known for being largely fragmented in design and production, which causes problems with transparency and responsibility [6]. In these circumstances, to ensure that construction projects are delivered on time, within budget and to the requirements specified by the customer, there might be improvement possibilities by opting for a systems engineering approach to construction projects [1]. Therefore, this study explores the applicability and benefits of a systems engineering approach in the construction industry by comparison with the telecom industry, which has had systems engineering as a backbone since the 90s.

2. Systems Engineering

The function of system engineering can be defined as guiding the engineering of complex systems [7]. It focuses on an early definition and documentation of customer needs and then proceeds with design synthesis and system validation. Systems engineering includes the system's design and external factors such as customer needs, the operational environment, interfacing systems, logistic supports, and personnel capabilities.

2.1. The Origin of Systems Engineering

The recognition of systems engineering (SE) as an activity was greatly accelerated during World War II when the need to engineer functional systems that spanned different engineering disciplines increased [1], [5], [7]. The demand arose from the advancement of technology and the development of high-performance aircraft, military radar and missiles, and the atomic bomb. Technology advancement and compressed time schedules required new approaches in program planning, technical coordination, and engineering management [7].

Several books were published in the 1950s and 1960s, identifying systems engineering as a distinct discipline [8]. The early SE projects were primarily military and space-based [7], and the philosophy of systems engineering was developed mainly at NASA in the 1960s and 1970s [1], [5]. In 1983, The Defense Systems Management College in the US produced a SE management guide [9], describing the various steps starting with the requirement analysis and ending in the synthesis of alternative solutions [1].

In 1990, The International Council on Systems Engineering (INCOSE) was founded in the US [10]. INCOSE is a not-for-profit membership organization aiming to develop and disseminate the transdisciplinary principles and practices that enable the realization of successful systems. They are today a leading international actor in developing modern Systems Engineering.

2.2. Systems Engineering in the Construction Industry.

Historically, there have been few interests in Systems Engineering in the construction industry. One explanation given by Aslaksen et al. [2] is the construction industry's traditional trust in craftsmanship, making the process from plan to project largely implicit. Therefore, requirements breakdown, verification, and validation are not considered as crucial as in other industries. Another explanation is that relatively little money is spent on the design in a traditional

construction project compared to other sectors. Consequently, the construction industry tends to focus on creation rather than design [2].

However, during the last 15 years, there has been an increased interest in Systems Engineering in the construction industry. Research and implementations have mainly been made within large infrastructure projects. Aslaksen et al. [2] identified advantages such as requirement transparency, a better understanding of roles and better contracts, with SE applied in construction projects. In 2012, Eames and Marjanovic-Halburd claimed potential improvements for the construction industry if adopting a system engineering approach similar to the spacecraft industry [1]. The Norwegian construction industry has attempted a SE approach called "Systematic Completion" [11]. Beste [12] made a qualitative case study following four Norwegian projects, and her findings show systematic completion positively affects performance regarding costs, schedule, and fewer defects. Furthermore, a pre-study concerning systematic requirement management in the Swedish construction industry was performed in 2019 and further investigated in 2021 [13] [14], showing an increased interest in a systems engineering approach also in Sweden.

In every successful construction project, there must be a balance between stakeholder needs, project management needs, and engineering needs. This balance may historically be handled by a single guiding master mind (implicit knowledge), but advancing technology, an increase in integrated technology, an increased number of requirements, increased project sizes, and tougher competition for winning projects require teams of specialists to work together to develop optimized solutions [7], [1], [11]. Therefore, the tasks must be broken down into smaller engineerable parts without losing the holistic project perspective.

3. Purpose & aim

The purpose of this study was to explore how a systems engineering approach can enable more systematic requirement management and propose recommendations for such an implementation. Furthermore, the aim was to identify possibilities with systems engineering applied in the construction industry by making a comparison with the telecom industry. While previous research regarding systems engineering in construction mainly focused on large infrastructure projects, this study targets traditional buildings like apartments, hotels, and office buildings.

4. Method

This study was performed in three steps:

1. Literature review of systems engineering
2. Interviews with systems engineering experts.
3. Workshop with representatives from the construction industry.

The first step aimed to give a background to systems engineering and its applications in other industries, and for this purpose the books of Kossiakoff et al. and Hitchins were used [7], [5]. Next, an understanding of the present use of the approach in the construction industry was achieved by reviewing journal and conference papers targeting systems engineering in both housing and infrastructure projects. The results from the literature review are mainly presented in section 2, while the results from interviews and the workshop are found in section 5.

4.1. Interviews with system engineering experts.

In this study, three semi-structured interviews were conducted with experts in systems engineering. The interviews aimed to investigate the use and benefits of a systems engineering approach used in the telecom and construction industries. The interviews were conducted digitally using Teams and lasted 1-1,5 hours. They were recorded and later transcribed. The key quotes from the responses were then clustered into topic groups using Miro [15]. The interviewees' profiles were as follows:

Table 1. Profiles of interviewees.

Industry	Country	Role	Years of experience in the industry	Years of experience in SE
Telecom	Sweden	System Manager	30	2
Telecom	Sweden	Manager of System Managers	15	15
Construction	Sweden	Business Developer	30	4

4.2. Workshop with representatives from the construction industry.

The workshop was performed in November 2022 and was held digitally on Teams. The first purpose of the workshop was to get an understanding of which benefits there might be by adopting a system engineering approach in the construction industry. The second purpose was to get the industry's view on how the V-model, a common model for visualizing the system engineering process, can be adapted to the construction industry. Seven participants attended the workshop, and they were selected due to their long experience in the construction industry, their process knowledge, and their interest in requirement management. The participants had the following roles: a production manager at a client company, a specialist in project management and business development, a manager for building product development, a specialist in design processes, a site- and project manager, a project assistant, and a data scientist.

5. Results and discussion

This section presents and discusses the results from both the interviews and the workshop.

5.1. Interviews

The most important findings in the interviews could be categorized into the topics:

- Requirement breakdown responsibility
- Benefits of a systems engineering approach
- Verification and validation
- Similarities and differences between the telecom and construction industry

5.1.1 Requirement breakdown responsibility

The two industries have different approaches to the role of system management and the breakdown of requirements. In the telecom industry, requirement analysis is so essential that there is a dedicated professional role for it: the system manager. The system managers are very experienced within their field. Very early in the project process, they transform market requirements, regulatory requirements, and demands into more technical solutions and detailed product requirements. In one of the interviews, a construction pilot project using the SE approach was discussed [14]. In that project, they decided to look strictly at project responsibilities. Since the primary responsibility for the project performance lies with the project manager, the responsibility for the breakdown and fulfilment of the requirements was also given to the project manager. One disadvantage with this, also mentioned in the interviews, is that the requirement breakdown is rather time-consuming, and the project managers have limited time to spend on this task.

5.1.2 Benefits of a Systems Engineering Approach

In the telecom industry, the systems engineering approach is the backbone of their process, seen as essential for project success. On the question, "What is the main benefit for your company with having a systems engineering approach?" one of the interviewees answered, "We can break down the system into different parts and then have tailored development processes that are both efficient and effective. We can both backward and future-proof and still maintain a very high degree of quality on our product." The answer indicates that the SE approach is seen as a success

factor for product quality and development. Other benefits mentioned were the ability to foresee problems and identify risks, as well as getting an understanding of the complete project scope.

In the construction industry, the primary purpose of using SE tends to be more towards risk identification and problem foreseeing. The requirement breakdown in the pilot projects seems to generate a better control and project scope overview, but it is also mentioned to increase the workload. An explanation for this is that the breakdown of the requirements is new to the construction industry, and therefore the impact on the process efficiency has not been seen yet. Another explanation from the interviews is that no SE software has yet been adopted in the construction industry. The most common approach has been registering the requirements in an Excel file and attempting to create a requirements traceability matrix, but as a consequence, the workload has been overwhelming in large projects.

5.1.3 Verification and Validation

Verification is often defined as the answer to the question "Are we building the thing right?" whereas validation is the answer to the question "Are we building the right thing?" Testing is an essential part of the verification and validation process in the telecom and software industry. Three different testing purposes are found in telecom:

1. To find faults. This testing tries to break the system and find bugs before a customer sees them.
2. Verification and validation. This testing is very connected to the requirements and aims to verify that the thing is built right (verification) and that the right thing is built (validation)
3. Testing characteristics. This testing pushes the boundaries and shows how far a program can be stretched. It aims to answer questions like: How much can we do? Where are our limits? The results are fed back into the development process and serve as input for updating requirements.

The third testing purpose is not as explicit in the construction industry. However, different sources define verification and validation differently. For example, Meertins et al. [16] define all controls made in the planning phase, like drawing reviews and simulations, as verification and all controls and inspections made during production validation. However, one of the interviewees defined all controls, both in the planning and production phases, as verification and validation as going through the requirements and seeing how well the build solution fulfilled the conditions after the project was closed. With this specific definition of validation, the purpose becomes similar to testing characteristics in the telecom industry, but the test actions are somewhat different.

The construction industry would benefit from a more explicitly pronounced testing of characteristics. It would help in understanding the capacity of the building produced and serve as an essential input for a continuous requirement update. Regarding characteristic testing, interviewee 2 said, "We can tell that our product is capable of not only going 200 km/h, but it can actually reach 250 km/h and still work". If applied to the construction industry, characteristics testing could give information about system redundancies, for example, how much more wind load the building can resist or how much the airflow in the ventilation system can be increased in case desired. The characteristic testing will therefore be an important input for a continuous requirement updating process and to identify over and under-performances of standardized solutions. Since the construction industry is not doing characteristics testing to any considerable extent, except the prefabrication industry, buildings with better capacity than needed without awareness or benefiting from it might be produced.

5.1.1.4 Similarities and Differences between the Telecom and Construction Industry

Some differences between the telecom and construction industries that were identified and discussed during the interviews were:

- The telecom industry has maintenance responsibility for the product delivered. In contrast, in the construction industry, it is not the contractor who has built the building that has the maintenance responsibility but the property owner.
- Telecom works systematically with the requirement breakdown and adds verification levels where client requirements are unspecific. This allows for requirement feedback and updates, and control of product characteristics. In the construction industry, there is more trust in craftsmanship and gut feeling, resulting in a higher acceptance of unspecific client requirements.

- Buildings are very site-dependent, meaning that the product delivered is, to some extent, always unique. The telecom industry, on the other hand, can resell the developed software more easily. As a comparison, telecom can build “one hospital” and then reuse it several times. New features and updates are then developed for one hospital but can be applied and sold to all hospitals.
- The testing in the telecom industry aims to verify a specific requirement. The construction industry relies heavily on self-inspections and inspections, but it is not always clear which requirement the control corresponds to.

The difference having the most significant impact on processes and requirements strategies is the telecom companies’ possibility to develop one software which can be sold to several clients. However, there have been successful attempts to establish standardized building concepts targeting several clients. Examples from the Swedish market are Skanska’s and IKEA’s concept BoKlok [17] and NCC’s design products [18].

Some of the similarities found between the two industries were:

- The requirement types are similar. They can be regulatory, client-defined, and contractor/developer-defined requirements. They can also be categorized as functional, component/product and process requirements.
- Both industries frequently use consultants and outsource tasks. However, the telecom industry has a more pronounced strategy of keeping highly complex projects in-house and outsourcing standard and maintenance jobs.
- Both industries must fulfil both international and local standards. An example of an international standard in the construction industry is using Eurocodes for the design. An example of a local standard is how different municipalities put minimum sustainability requirements.
- Telecom companies often use an anatomy plan similar to the construction industry’s connected time plan as a work-plan tool.

Even though the industries seem different, they handle the same requirement categories and must address international and local requirements. Both industries suffer economic and juridic consequences when the requirements are not fulfilled. Regarding the question of why the construction industry hasn’t adopted systematic requirement management, two explanations were given in the interviews. One was that if you start going through the never-ending list of requirements, you risk taking responsibility for them all. Another explanation was that project managers today have a false sensation of being aware and in control of all requirements. Additionally, the clients might not be competent to write precise requirements that are possible to verify. The requirement specification is often outsourced to an external consultant, which means that the standardization is low, and the reason behind a specific requirement might be unclear to the contractor.

5.2. V-model implementation in the construction industry

The possibilities with the V-model applied to the construction industry were discussed both in the workshop and the interviews. The V-model presented at the workshop is illustrated in Figure 1. The workshop participants showed a high interest in the V-model and could not see any hindrance to implementation. However, the workshop participants saw a need to identify which actions within the typical construction process correspond to specific requirements and break down the requirements on task levels.

The interviews also confirmed the possibility of adopting the V-model in the construction industry. For example, a reference project using SE within the Swedish contractor company Skanska [14] proved successful, and one interviewee claimed, “SE and the V-model are definitely relevant for the construction industry.” However, during the interviews, it was also mentioned that implementing the V-model requires a lot of work initially. Therefore, starting on a smaller scale is recommended, for example, while making the requirements specification for doors and windows in a project.

The workshop discussed using verification and validation data as a business case. The clients claimed to be willing to pay for the contractor's data monitoring and processing help during the warranty time. In addition, neither the clients nor the contractors saw any problems sharing the data ownership during the two to five years discussed.

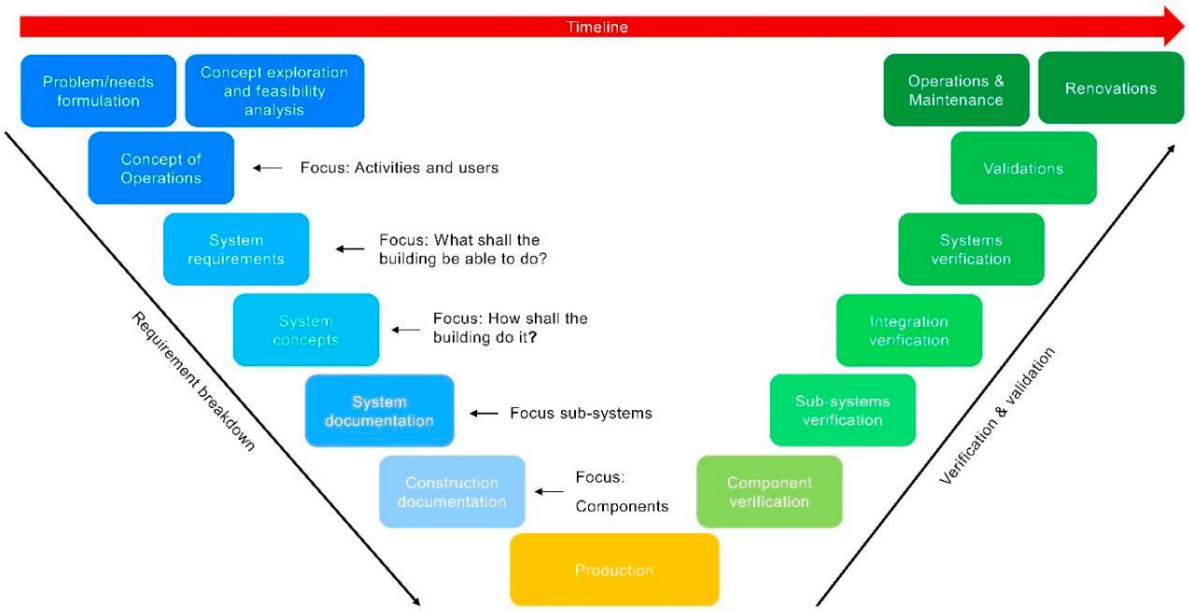

Fig. 1. The proposed V-model for the construction industry was explored during the workshop. The left wing symbolizes the requirement breakdown and which specific focus the requirements shall have on each level. The requirements get more detailed for each step. The right wing represents the verifications and validations. Each verification box aims to verify the requirements on the same horizontal level.

In both the workshop and interviews, there was a belief that digitalization would facilitate requirement verification. Since the time from receiving a project tendering procurement to submitting a contracting bid is often very short, it is crucial to automate the requirement analysis. Attempts to automate the requirement analysis process have been made [19], and by connecting the requirements to specific verifications, requirements lacking verification methods can easily be identified. The result can be a helpful work tool for requirement risk management. Padala & Maheswari [20] developed a requirement traceability matrix for hospital construction projects, enabling possibilities to predict change propagations. Their methodology showed challenges with the tedious process of finding and generating relationships between entities. However, machine learning techniques may be useful for automating the requirement matrix generation.

4 Conclusions

The results from the interview and the workshop conducted in this study show that adopting a systems engineering approach in the construction industry can enable more systematic requirement management. Additionally, it will lead to a better understanding of the complete project scope and improve the overall building quality. If implemented successfully, it might also lead to higher process efficiency.

However, to succeed with the implementation of SE in the construction industry, the following is recommended:

- The requirements shall be written better and stricter.
- Higher levels of standardization would facilitate the verification.
- A person in every project shall be assigned the role of requirement manager.
- Development of SE software adapted to the construction industry.

The verification process will be facilitated with a higher standardization of both requirements and technical solutions. With new machine learning techniques, such as natural language processing, requirements can be automatically extracted and matched with suitable verification methods. Requirements missing a known verification method can be highlighted and considered in risk management.

Even though the systems engineering approach has primarily been applied in large infrastructure projects, there are benefits for traditional building projects in terms of increased quality control and predictability. In addition, the SE approach can benefit a project, even if not applied to the complete project, but on specific tasks, like the requirement management of door environments.

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