Systems Engineering in complex rail projects - a state-of-the-art scoping review

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***Abstract*— As rail projects become increasingly complex, a Systems Engineering approach—widely used in various technical disciplines—can be effectively applied. This scoping review evaluates the application and current state of the art for Systems Engineering (SE) in complex rail projects and focuses on Technical Management and Technical Processes as per ISO 15288 standards. The review highlights the rationale and challenges of SE in managing the processes in ISO 15288 within rail infrastructure. Findings reveal a lack of consensus on SE practices and terminology, emphasizing the need for standardized approaches. Further research is needed to align research and industry practices with ISO standards for improved implementation.**

Keywords—Systems Engineering, Rail, Railway, Scoping review, State of the Art, Project, ISO 15288

I. Introduction

The rail system, like most transportation networks, is a large, technologically intricate system that is geographically distributed and can often be considered a system of systems [1]. Although the basic function and technology of the railway are not particularly complicated - a cart with metal wheels guided by rails - other crucial systems are required for the whole system to function safely and effectively. These include sub-systems such as substructures, bridges, and tunnels to support the railway in its environment, as well as enabling systems like electricity, signaling, and telecommunications to power the rolling stock and facilitate communication, Figure 1.

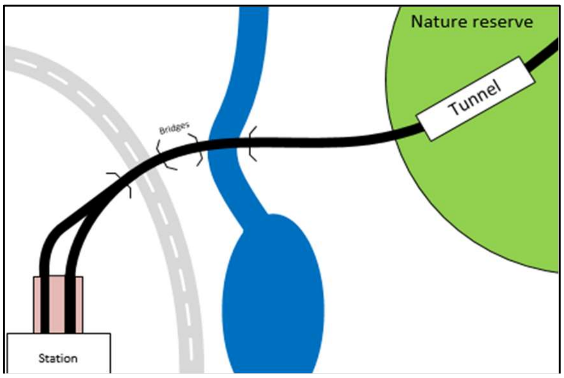

Figure 1 Schematic visualization of the rail system in its environment. The railway is a hybrid system partly located in a nature reserve, going through a tunnel, over a river, and a road ending up in a station.

The System Engineering approach originated in the aerospace and defense industries and is increasingly applied in other industries [2]. van der Ploeg [3] stated more than 20 years ago that the Civil Engineering industry does not resemble other industries in dealing with problems despite the comparableness in the characteristics of processes, products, and efficiency, due to the conservative line of business. Ten years later Elliott et al. [4] stated that *´the industry does not fully appreciate what systems engineering is´* and since then several studies have stated that System Engineering in rail is still loosely defined [5, 6].

Systems engineering is defined in *ISO/IEC/IEEE 15288:2023 Systems and software engineering — System life cycle processes* [7] as a *´transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems using systems principles and concepts and scientific, technological and management methods´*. We will use definitions according [7]. The focus will be on the *Technical Management Processes* and the *Technical Processes* as illustrated in Figure 2.

In the industry, there are initiatives towards Systems Engineering and System Engineering practices. For example: Europe´s Rail, which is a body of the European Union to deliver a high capacity at the European railway network, has defined two System Pillars named *the System of Systems (SoS) approach* and *Architecture* [8]. Other examples include a guideline for SE in the civil engineering sector in the Netherlands that has been developed and applied [9]. In Australia, Systems Engineering standards are a part of the government procurement frameworks [10] and in Germany, as well as in the UK universities have Rail Systems Engineering master programs or specializations [11, 12].

At the *Nordic Seminar on Railway Technology*, Bergseth [13] presented the findings from *Systems engineering applied in rail infrastructure – a systematic literature search.* The literature concerning Systems Engineering and Rail was divided into specific subsystems (e.g. the signal system) and it remains a challenge to pinpoint the state of the art for integration of Systems Engineering for the whole rail ´system of systems´ in a project perspective.

This paper aims to target this challenge and broaden the perspective on the current state of the art regarding the use and implementation of Systems Engineering in large rail projects, both new railway as well as reinvestment. In doing so, a comprehensive scoping review is undertaken to formulate current addressable research challenges.

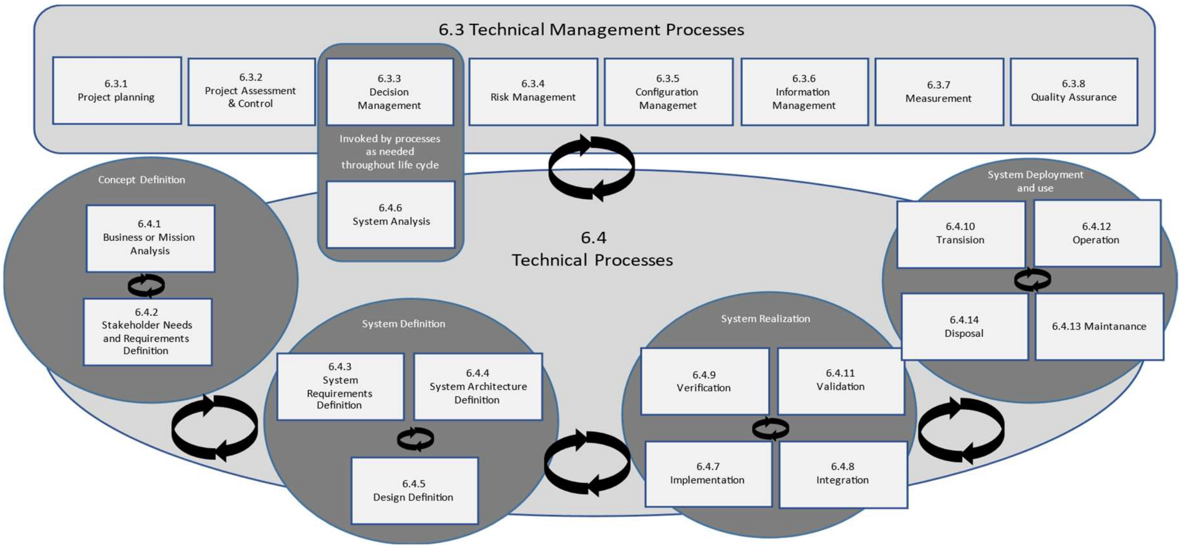

Figure 2. Technical management processes, technical processes, and the interrelationships between them. Adopted from [7].

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II. METHOD

A scoping review is a tool to determine the scope and coverage of the body of literature [14]. It is considered appropriate as the purpose is to scope a body of literature and to identify knowledge gaps. The scoping review was based on the methodological framework by Arksey and O'Malley [15]. The methodology is iterative rather than linear and is considered more flexible compared to a systematic review, as the researchers can redefine search terms and don't have strict limitations on search terms. The framework consists of five stages:

1. Identifying the research question. To guide the search strategies.
2. Identifying relevant studies. To be as comprehensive in the search for studies to answer the research question.
3. Study selection. Select relevant studies by eliminating studies that do not support the research question.
4. Charting the data. To synthesize and interpret the data by sorting, chartering, and sifting according to categories. This is similar to ´data extraction´ in systematic reviews.
5. Collating, summarizing, and reporting the result. To present an overview of the reviewed material to seek an answer to the research question. Notice that a scoping study, unlike a systematic review, does not seek to ´synthesize´ or aggregate the findings from studies.

The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) Extension for Scoping Reviews (PRISMA-ScR) were used to synthesize the available literature. PRISMA-ScR is designed to help to conduct systematic scoping reviews transparently [16]. The PRISMA-ScR checklist was used and the PRISMA flow diagram was utilized, Figure 3 [17].

During the charting and sorting of the data, step 4, a chatbot/GPT-4 was utilized as a informal support. The chatbot was used as a second reviewer of the literature, aimed to help the reviewer. After the reviewer had conducted the charting and sorting the GPT-4 was prompted to do a charting and sorting. In the case of different answers from the reviewer and the GPT-4 the reviewer reviewed the specific study again. It was always the reviewer that in the end decided the charting and sorting for each study. Landschaft et al. [18] states that the use of GPT-4 has the potential to use the chatbot as a main screening tool. However, in this research, the GPT-4 was only utilized for review and verification purposes.

A. Research Questions

The first stage of this research was to identify appropriate research questions for the scoping review. The general objective of the study is to map the research conducted as well as identify potential knowledge gaps relating to Systems Engineering and Rail. The topic was used in the literature search and to examine the literature three research questions were formulated to get specific information from the articles.

1) How is the current research in Rail and Systems Engineering distributed and classified? This question can be broken down into the following sub questions:
   - What is the distribution of articles over time?
   - What is the distribution between conference, journal, and thesis publication?
   - What typical research methods are used?
   - Where do the papers originate from according to countries/continents?
2) What is the distribution of the Technical Processes and Technical Management Processes from ISO 15288 in the literature?
3) What is the main subject of the articles other than the Technical Processes and Technical Management Processes?

The first question was used to get the overall state of the research area. Questions 2) and 3) were used to get specific insights into the state of the research area. Question 2) was formulated to frame the articles into the predefined processes according to [7] and question 3) was formulated to categorize and understand other conducted research.

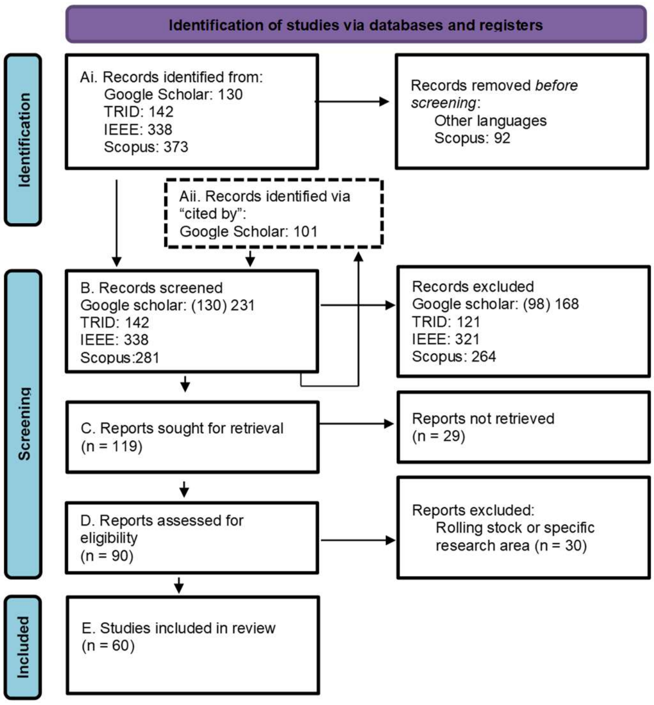

Figure 3. PRISMA flow diagram visualizing the process of the scoping review. Adopted from [17].

B. Applied Method

Literature searches were conducted by the main author in Google Scholar (accessed 2024-05-16), Transport Research International Documentation (TRID) (accessed 2024-05-22), IEEE (accessed 2024-05-30), and Scopus (Accessed 2024-06-24). The search string was *allintitle: rail OR railway OR railroad ("systems engineering" OR "System engineering")* except for Scopus as the search string where *allintitle: rail* ("systems engineering" OR "System engineering")*. The result from the identification is presented in Figure 3 box Ai. In Google Scholar a second identification was conducted screening all the ´cited by´ articles of the remaining articles using the same criteria, box Aii.

The identified records were screened by reading the title and abstract using the inclusion and exclusion criteria's, Table 1. The rolling stock is excluded as it is identified as a considerably different application area. Articles that cover specific sub-systems are also excluded as the research area regards the railway as a whole. Articles that have the main focus on the later stages of a system's lifecycle, operation, and maintenance are excluded as the focus is the early stages (the concept and design phases) of a railway project. Articles in other languages than English and when no full text is available were excluded.

TABLE 1. INCLUSION AND EXCLUSION CRITERIA'S USED IN SCREENING PROCESSES.

Inclusion:	**Exclusion:**
• Whole system	• Rolling stock, for example: Vehicles, Operators
• Construction	• Specific subject areas, for example, Safety, Signaling, Electronics, Level crossing, RAMS, Education
• Project	• Operation, maintenance
	• No full text
	• Articles in other languages than English

The inclusion criteria had a higher value than the exclusion criteria. This means that if an article's main focus is e.g., operation, which is an exclusion criterion, but it also focuses on a project perspective or managing the whole system for operation it is included anyway.

The main review was conducted by the main author but the articles that were retrieved were also uploaded to GPT-4 which was utilized as an informal second reviewer. The main author first reviewed the title, abstract, keywords, and conclusion of each article to answer all the research questions. Three main categories with subcategories were identified, Table 2.

TABLE 2. IDENTIFIED AND USED MAIN- AND SUBCATEGORIES

1. *Overall application of System Engineering in rail*
1a. Rational and benefits of adopting Systems Engineering
1b. Barriers and challenges of adopting Systems Engineering
1c. Framework and implementations of Systems Engineering
2. *Technical management processes and technical processes*
List of all the technical management and technical processes (see Figure 2)
3. *Specific IT tools*
3a.Model-Based-Systems-Engineering (MBSE)
3b. Other tools

For each article, the question *Based on Article X in what category would you place the article:* followed by Table 2 was asked the GPT-4. When the category differed from the main authors' categorization a follow-up question was prompted *Elaborate on why that category was chosen.* For some articles, the main author read more of the content from the article if the author and GPT-4 made different categorizations.

III. INCLUDED LITTERATURE REVIEW

The result is based on the study selection [3-6, 10, 19-26, 30-76] presented in *Appendix 1. Study selection for the scoping review*

A. Overall results

The origin of articles is from Europe, Australia, North America, and Asia, with the UK followed by the Netherlands and Australia as the most common origin, Figure 4. 24 of the articles are conference proceedings, 18 are Journal Articles, 7 are Thesis and one is a report.

The articles identified in the scoping review are spread out over the last thirty years with a continuous increase over the last decade, Figure 5. The collection comprises 39 empirical studies, 19 conceptual articles, and 2 literature reviews.

B. Main aspects and findings

Overall, the rail system is described as a complex and sociotechnical system. Different variations of system thinking are brought up in the articles and the railway system is described as a system of systems. Identified and used main- and subcategories are presented in Table 2, which includes the ones shown in Figure 2. The result from the review is presented in Figure 6.

1) Overall application of System Engineering in rail

A total of 20 articles give some type of general overview of Systems Engineering. The benefits and rationale of applying Systems Engineering in rail are the main focus of seven of the articles. It is stated that Systems Engineering is effective [19] or necessary [20] to manage major rail projects. It is described as ´creating better systems´ [21], ´reduced risk of rework´ [22], and ´potentials for better project and operation performance´ [5]. Hocking et al. [23] state that the return on investment can be 10:1 in the best cases and 1:1 in the worst cases.

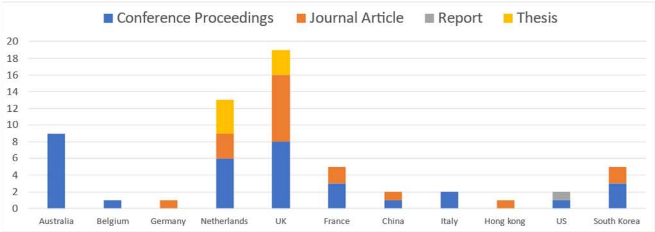

Figure 4. The country where the included papers' main author is located and the number of papers per type of article.

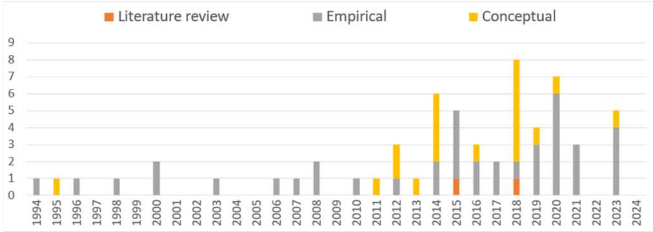

Figure 5. The number of papers per year and the trend.

Challenges and barriers, which are the main focus of five of the articles, for Systems Engineering in rail projects are described as, having no common definition [5, 6, 24] and are not fully applied [25, 26]. The lack of definition leads to confusion and inconsistent application and is considered a major barrier to the application of Systems Engineering [24]. Even though a standard exists Systems Engineering is applied sporadically and not uniformly across the industry. To get the full benefits of systems engineering it should be applied early in the project [22, 27].

Eight articles present some type of framework or how to implement Systems engineering practices in rail projects. The focus on the framework differs but focuses on describing how System Engineering has been tried or could be implemented.

2) Technical Management Processes and Technical Processes

Of the 60 articles, 19 have some *Technical Management Processes* or *Technical Processes* as the main content, Figure 6. Number of articles that cover seven of the 22 processes are 18 in total. One out of the 60 article covers three of the processes as its main focus is the *System Definition phase* consisting of the *System Requirement Definition Phase, System Architecture definition process*, and *Design Definition* and is therefore categorized into all three processes. The two processes with the most articles are the *System Requirements Definition Process* and the *Integration Process*.

3) Specific IT tools in Systems engineering for rail

Figure 6 shows that 21 of the article's main focus is on specific IT tools. Model-Based Systems Engineering (MBSE), which is the main content in eight articles, has the last decade been tried as a specific tool to manage Systems Engineering in Rail. In the other 13 articles, the main content mainly model-based tools but also some other IT tools, such as Requirement Management tools.

IV. Discussion

In this chapter the findings of the scoping review will be discussed in the context of the research questions, how to interpret the results, and possible errors. The chapter will focus on identifying remaining research gaps to guide future research studies within the area of applying SE principles to the early stages of railway projects.

A. Method and screening

The PRISMA-ScR and scoping review were suitable for answering the research questions. The PRISMA-ScR was an easy-to-follow framework and supported the transparency of the conducted review. Using the scoping review as the main method framed the research area, an understanding of state of the art and possible gaps in the research field. However, a search string with some more words could be suitable, which will be further discussed.

The chatbot/GPT-4 was initially expected to be of more help in the research but as the research where conducted the chatbot was inconsistent in the answers and reviews. Instead, the Chatbot got a passive role as a secondary reviewer, which still was useful in the reviewing process, providing instant second opinions on the categorization and content of the papers. It was always the reviewer that in the end decided the charting and sorting for each study.

Most of the articles originate from the UK, the Netherlands and Australia. These countries together with Germany have public initiatives concerning Systems Engineering and Rail e.g. master programs, and SE frameworks in government procurement. Germany and the US only have one and two identified published articles respectively which was surprisingly few. For Germany, the exclusion criteria to exclude articles in other languages than English probably excludes some articles from Germany but may not explain the whole discrepancy. After suggestions from other researchers knowledgeable about US rail projects other search strings were tested, which confirms this discrepancy. A different search string would have generated more articles from the US. For example, using the search string (*"California high speed" AND "system engineering")* gave 39 hits on Google Scholar including [28] and [29] which both would be relevant for the study.

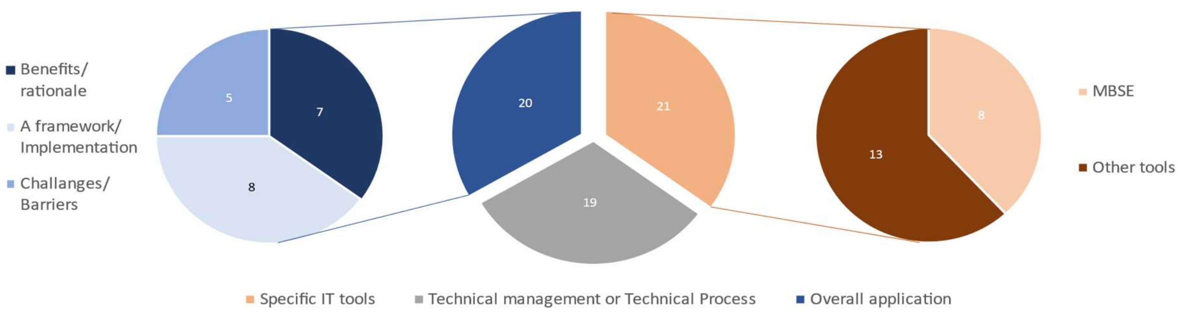

Figure 6. The number of articles for each category (middle) and subcategory for the Overall application (left) and Specific IT tools (right). Subcategories for the Technical management or Technical Process are presented in Figure 8.

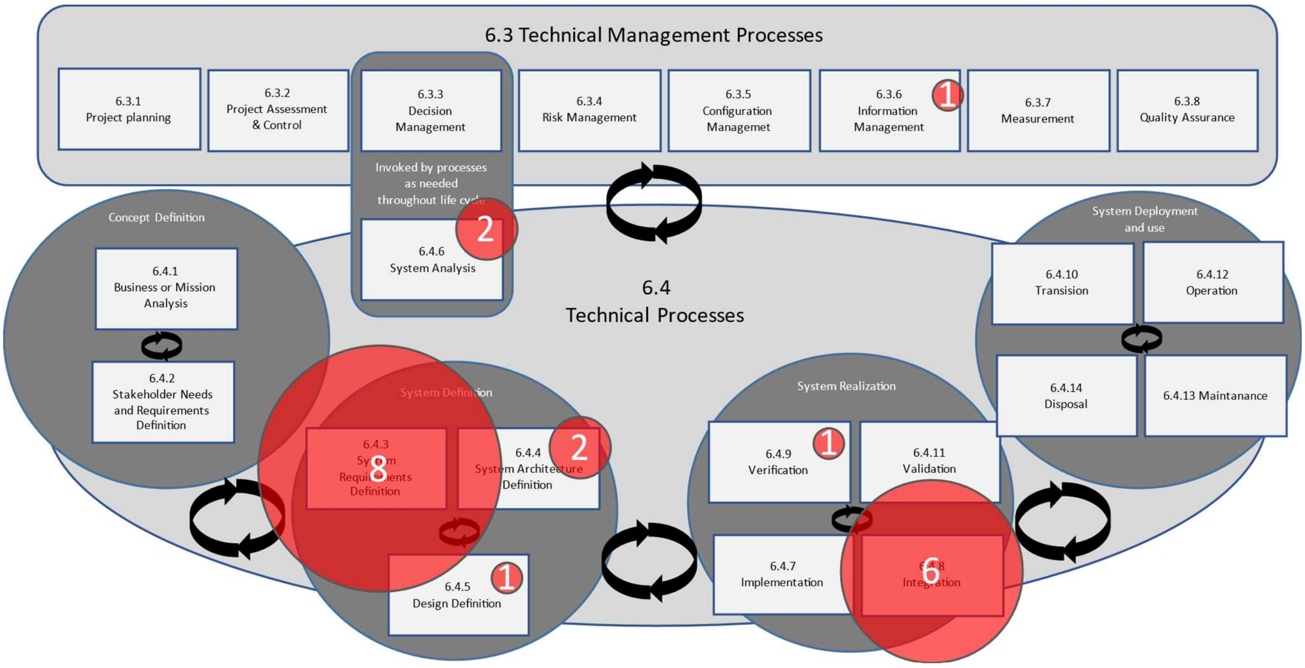

Figure 7. The number of articles for each technical management process and technical process. Adopted from [7].

B. *Specific IT tools*

Among the 60 reviewed articles, Model-Based Systems Engineering (MBSE) has emerged as the predominant topic, with approximately one-third of the articles focusing on it since 2018. Prior to 2018, MBSE was not the primary subject of any articles. In recent years, MBSE has likely become the principal term related to modeling Systems Engineering, replacing earlier terminology used for modeling and model management. This trend is not unique to the rail industry; a Scopus search indicates that nearly 70% of MBSE-related articles have been published after 2018.

The prevalent use of tools for managing models is evident in the existing literature. This trend can perhaps be attributed to the relative ease of testing specific tools or models and evaluating their effectiveness, as opposed to the more complex task of investigating Technical Management Processes and Technical Processes. This could probably also to some extent contribute to the general practice of solving a problem by introducing an IT system as a quick fix rather than as a part of a long-term improvement project.

C. *Systems Engineering in rail*

The literature indicates that Systems Engineering principles are applied with varying degrees of success in major rail projects. While some authors suggest guides or frameworks for implementation, there is no consensus on the optimal timing and methods for introducing and applying these practices. A common recommendation is to implement Systems Engineering early in the project lifecycle and at the organizational level. But it's not clear what ´early´ means. Almost all rail projects involve brownfield legacy systems meaning (i) a new railway will almost always connect to an old railway, some disciplines are totally dependent on the existing standards e.g., signaling, telecommunication, track and (ii) the railway is always located in a legacy environment where it's totally dependent on the physical conditions e.g. houses need to be moved, roads and water need to be passed by tunnels or bridges. Because of this legacy, there are overwhelming tasks that must be addressed early in the project lifecycle, such as understanding the often undefined requirements, architecture, and interfaces for the existing systems. This complexity of the ´system of systems´ rail project presents unique challenges that perhaps are not typically encountered in other sectors. Further studies on what makes the rail project stand out from other sectors should be conducted.

D. *Technical Management Processes and Technical Processes*

The result shows that no articles cover the processes in the *System Deployment and Use phase*, Figure 8. This is in line with the prerequisites for the studies as both maintenance and operations were used as exclusion criteria for articles. There seems to be overlap between Asset Management and Systems Engineering and the differences are often not clear in the articles. Including ´Asset Management´ instead of Systems Engineering would probably also yield more articles.

The *System Requirement Definition Process* is the most common technical process in the literature. In this review most of the articles that have the main subject of *Requirement Management* are categorized in the *System Requirement Definition Process,* however, *Requirement Management* could correspond to several of the technical processes. The terminology from ISO 15288 [7] is not commonly applied. Therefore the correlation between *Requirement Management, System Requirement Definition Process,* and other technical processes tailored for rail should be further studied.

The lack of common terminology is also prevalent in the categorization of the *Integration process*, which is the second most commonly researched process. The *Integration Process* is about synthesizing a set of elements to fulfill the requirements [7]. However, *Integration* mentioned in the research articles often goes broader, handling not just the specific process for integration but also several other technical processes.

Only one article has a *Technical Management Process* as the main subject. Perhaps the *Technical Management Processes* are more common in research without Systems Engineering as a keyword. This could also be an indication that the terminology from ISO 15288[7] is not commonly used.

No articles identified have the *concept definition* phase, which includes the *Business or Mission analysis* and *Stakeholder Needs and Requirement Definition,* as the main subject which is quite surprising. Stakeholders are commonly mentioned in the literature but not as the main subject, Table 3. It is a challenge to apply the articles to the specific categories as the terminology differs. The processes should and must be tailored to the specific needs of the discipline (rail in this case), but it should be possible to determine which process is researched.

V. Conclusions and further research

This research took its start in the desire to evaluate the state of the art regarding research in the application of systems engineering in the early phases of rail projects. To lead the research the following three research questions were posed with a desire to answer them within this research publication: 1) *How is the current research in Rail and Systems Engineering distributed and classified?,* 2) *What is the distribution of the Technical Processes and Technical Management Processes from ISO 15288 in the literature?* and 3) *What is the main subject of the articles other than the Technical Processes and Technical Management Processes?*

In response to the first question, the findings indicate that the United Kingdom, the Netherlands, and Australia have contributed the most research on systems engineering for rail, and have also initiated various local initiatives in the field as well to improve the practice of employing systems engineering in rail. Research on tools and especially the application of MBSE in rail is the most researched topic.

The two other questions have also been answered, however, the research brought interesting questions and gaps. Both the direct findings from the *Overall application of System Engineering* in rail and the indirect findings from the *Technical Management Processes and Technical Processes* converge on the same conclusion. It appears that there is a lack of consensus on the best practices for managing Systems Engineering in rail projects, indicating a need for standardized guidelines and frameworks. In this study, the inconsistent use of terminology for Systems Engineering highlights a disconnect with the standardized terms outlined in ISO 15288[7], which can hinder standardization and development of frameworks.

This study did not examine the industry's practical application of ISO 15288[7]. Future research should prioritize harmonizing terminology for Systems Engineering in both research and industry, aligning it with ISO 15288[7] to ensure consistency and clarity. Subsequent reviews should incorporate the harmonized terminology which can be broader beyond Systems Engineering, as it sometimes overlaps with other terms such as requirement management and asset management. Two potential titles for future studies are 1) *´Systems Engineering Terminology in Rail Projects: A Comparative Analysis Between ISO 15288, Academia and Industry´* and 2) *´Examining the Differences and Similarities of Systems Engineering, Asset Management, Requirement Management, and Other Processes in Rail Projects´*.

Lastly, based on the reviewed literature from this study, the question *´How complex is the rail project system*? ´ has emerged. Regardless if the system of interest is a new railway or reinvestment in an existing railway, there is almost always overwhelmingly legacy to address. Another study could be suggested with the somewhat proactive title: *´Mega Railway Projects: The Most Complex Systems of Systems?´*.

VI. Statement of contribution

An increasing number of articles concerning Rail and Systems Engineering have been published over the past 30 years. This study describes which areas that are researched and state of the art for the research. This study further supports the need for common definitions and the consistent use of terminology.

Acknowledgment

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Appendix 1. Study selection for the scoping review

Ref.	Year	Type of article	Land	Study	Main focus
[10]	2023	Conference Proceedings	Australia	Empirical	System requirements Definition Process
[19]	2010	Conference Proceedings	UK	Empirical	Benefits/rationale
[20]	2023	Conference Proceedings	Australia	Empirical	Benefits/rationale
[21]	2014	Journal Article	UK	Conceptual	Benefits/rationale
[22]	2020	Conference Proceedings	Australia	Empirical	MBSE
[23]	2018	Conference Proceedings	Australia	Empirical	Benefits/rationale
[24]	2019	Thesis	UK	Conceptual	MBSE
[25]	2017	Journal Article	South Korea	Empirical	A framework/ implementation
[26]	2018	Thesis	Netherlands	Conceptual	Challanges/ Barriers
[3]	2014	Conference Proceedings	Netherlands	Conceptual	A framework/ Implementation
[30]	2023	Thesis	Netherlands	Empirical	Integration process
[31]	2023	Conference Proceedings	Belgium	Empirical	MBSE
[32]	2023	Conference Proceedings	France	Conceptual	MBSE
[33]	2021	Journal Article	Germany	Empirical	MBSE
[34]	2021	Conference Proceedings	Australia	Empirical	System Requirements Definition Process
[35]	2021	Journal Article	China	Conceptual	MBSE
[36]	2020	Conference Proceedings	Netherlands	Empirical	System Analysis Process
[37]	2020	Conference Proceedings	Netherlands	Empirical	System Analysis Process
[38]	2020	Thesis	Netherlands	Empirical	A Framework/ Implementation
[39]	2020	Conference Proceedings	Australia	Empirical	MBSE
[4]	2012	Journal Article	UK	Empirical	Challenges/Barriers
[40]	2020	Journal Article	Netherlands	Empirical	Information Management Process
[41]	2020	Conference Proceedings	Netherlands	Conceptual	System definition
[42]	2019	Journal Article	UK	Empirical	Architecture Definition Process
[43]	2019	Thesis	Netherlands	Empirical	Challenges/Barriers
[44]	2019	Conference Proceedings	Netherlands	Conceptual	Other tools
[45]	2018	Conference Proceedings	Australia	Empirical	Other tools
[46]	2018	Conference Proceedings	Australia	Conceptual	MBSE
[47]	2018	Journal Article	France	Literature review	Other tools
[48]	2018	Conference Proceedings	Netherlands	Empirical	Integration process
[49]	2018	Report	US	Conceptual	A framework/ Implementation
[5]	2015	Conference Proceedings	South Korea	Conceptual	Benefits/rationale
[50]	2018	Journal Article	France	Empirical	Other tools
[51]	2017	Conference Proceedings	Australia	Empirical	Other tools
[52]	2016	Journal Article	Netherlands	Empirical	A framework/ implementation
[53]	2016	Conference Proceedings	France	Empirical	Other tools
[54]	2015	Journal Article	UK	Empirical	System Requirements Definition Process
[55]	2015	Conference Proceedings	Italy	Conceptual	Other tools
[56]	2015	Conference Proceedings	Italy	Conceptual	Other tools
[57]	2015	Conference Proceedings	UK	Empirical	System Requirements Definition Process
[58]	2014	Conference Proceedings	South Korea	Conceptual	A framework/ implementation
[59]	2014	Conference Proceedings	UK	Empirical	A framework/ Implementation
[6]	2016	Thesis	UK	Literature review	Integration process
[60]	2014	Conference Proceedings	UK	Empirical	Integration process
[61]	2014	Conference Proceedings	France	Empirical	Other tools
[62]	2013	Journal Article	UK	Empirical	Other tools
[63]	2012	Journal Article	UK	Empirical	Challenges/Barriers
[64]	2012	Conference Proceedings	China	Empirical	System Requirements Definition Process
[65]	2011	Journal Article	Netherlands	Empirical	A framework/ implementation
[66]	2008	Conference Proceedings	UK	Empirical	Challenges/Barriers
[67]	2008	Conference Proceedings	US	Empirical	Integration process
[68]	2007	Journal Article	UK	Conceptual	Benefits/rationale
[69]	2006	Journal Article	UK	Conceptual	Other tools
[70]	2003	Conference Proceedings	UK	Empirical	System Requirements Definition Process
[71]	2000	Conference Proceedings	South Korea	Conceptual	Other tools
[72]	2000	Journal Article	South Korea	Conceptual	System Requirements Definition Process
[73]	1998	Journal Article	Hong kong	Empirical	Integration process
[74]	1996	Journal Article	UK	Empirical	Other tools
[75]	1995	Conference Proceedings	UK	Conceptual	Benefits/rationale
[76]	1994	Conference Proceedings	UK	Empirical	Verification