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The System (of Interest) Definitions phase: Key features and challenges in the Dutch Railway system

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***Abstract*—As systems continue to grow in interconnectedness and complexity, System Integration has become increasingly more difficult. The significance of a System Definition phase, describing a system in increasing level of detail, to facilitate integration (avoid or anticipate issues in advance) is clear from literature. However, what this should specifically entail, varies. Moreover, the term "system" as commonly used, does not correspond to a specific level of granulation or complexity. Therefore, focusing on a System of Interest is a prerequisite. The purpose of this paper is to first identify key features from literature which should be included in a System Definition phase. Secondly, in order to identify what hinders effective integration from industrial perspective and, determine how this can be related to the identified System Definition features, a case study has been carried out within the Dutch railway system. By interviews and qualitative data analysis, numerous integration issues were identified. From the case study, several features were identified which require appropriate attention to facilitate effective integration. In addition, the case study revealed features, which were not obtained from literature.**

***Index Terms*—Complex Systems, Integration, System of Interest, Railways, Stakeholders, System Definition**

I. INTRODUCTION

Within different industries, e.g. the railway industry, consumer demands are increasing, regulations are becoming more strict and the possibilities offered by technology are ever increasing. Because of the latter, the connectivity of different systems increases, which aids to achieve more optimized performances. Hence, systems, if ever they were separated are vigorously moving towards interconnectedness [1].

In order to improve system's performances, (part of these) systems are constantly improved by e.g. modifying existing elements or integrating new (sub)systems into it. These must seamlessly connect and interact with each other to prevent unwanted consequences and achieve the increased system performance. However, systems continue to grow in interconnectedness, complexity and legacy content. Additionally, humans continue to become an integral part of the system. Because of this, System Integration (SI) has become a key concern [2].

There are several factors that affect SI [3], including but not limited to: (i) stakeholders, (ii) integration resources, (iii) external influences, etc. [4]. These factors can provide the basis for a "checklist" which allow many integration problems to be avoided or detected and circumvented in advance [4]. In addition, [5] mentions that integration constraints are identified and considered in advance during previous phases, i.e. the System Definition (SD) phase. Hence, it can be stated that success of the integration (avoidance or anticipation of integration problems) efforts is highly dependent on its advance planning and preparation, accomplished during the SD phase [6].

II. THE SYSTEM OF INTEREST

According to [7], "a system is a set of interrelated components functioning together towards some common objective(s) or purpose(s)." Moreover, systems are themselves built up of smaller systems that themselves are built up of even smaller systems and so on. Something which is regarded as a system by the people who developed it, might be regarded as a subsystem by people who use it as part of their system [8]. E.g., a telephone substation, with its distributed lines to the area that it serves, can be called a system. Hotel and office building switchboards, with their local lines, may be called "subsystems" and the telephone instruments may be called "components" of the system [6].

It can be understood that systems may serve as parts of more complex aggregates or supersystems, and subsystems may themselves be thought of as systems [6]. Because this can be endless, it is important to create focus on a specific system, or part of a system, which can be referred to as a System of Interest (SoI). This is seen in context as interacting with other, sibling systems within a mutual environment (Figure 1). This can also be referred to as a system under consideration [8], [9] or system under assessment.

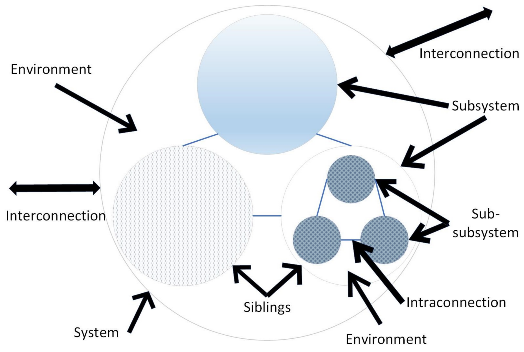

Fig. 1. SoI representation adopted from [10]

III. The System Definition phase in literature

Anticipation of integration problems is highly dependent on its advance planning, accomplished during previous phases, including the SD phase. Moreover, SD activities build on the artifacts and decisions from the preceding Concept Definition phase (primarily articulating the mission of the SoI) [11].
Different books [5], [6], [12] and standards [8], [13] mention SD as an important phase. Here, SD activities are conducted to create and eventually describe a SoI in increasing level of detail. The SoI is decomposed into subsystems, and the subsystems are decomposed into components. As the SoI is decomposed, the requirements are also decomposed into more specific requirements that are allocated to the system components [14].
Here, one challenge of SD is to understand the level of detail necessary to define elements and their interrelations [5]. Additionally, too often the SD is viewed as a linear, sequential process [5]. However, valuable information and insight need to be exchanged between distinct lifecycle processes, in order to ensure a good SD that effectively and efficiently meets the mission or business needs [5]. Hence, iteration is needed to accommodate constraints, stakeholder decisions and evolving understanding [8].

In order to get a more in-depth understanding of the SD phase and its features, sources mentioned in the beginning of this section will be further elaborated on.

A. System Engineering Handbook

The Systems Engineering Handbook [5] mentions that the SD phase consists of three consecutive stages: System Requirements- (1), Architecture- (2) and Design Definition (3), graphically presented in Figure 2.

1) System Requirements Definition: The purpose of the System Requirements Definition process is to transform the stakeholders view of desired capabilities into a technical view of a solution that meets the needs of the user. System requirements are the foundation of the System Definition and form the basis for the architecture, design, integration and following phases [5]. As meeting each requirement carries a cost, it is essential that a complete but minimum set of requirements is established early in the project life cycle [5].

2) System Architecture Definition: The purpose of the Architecture Definition process is to generate system architecture alternatives, to select one or more alternative(s) that frame stakeholder concerns and meet system requirements, and to express this in a set of consistent views [5]. System architecture deals with high-level principles, concepts, and characteristics represented by general views or models excluding details [5]. Moreover, the notion of interface is one of the most important items to consider during this phase [5].

3) Design Definition: The purpose of the Design Definition process is to provide sufficient detailed data and information about the SoI and its elements to enable implementation consistent with architectural entities as defined in models [5]. Hence, the purpose of this stage is to make the link between the architecture of the SoI and the implementation of system elements that compose it.

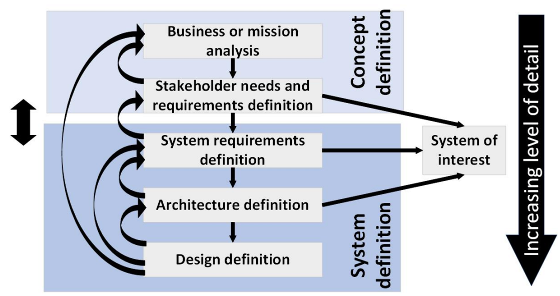

Fig. 2. Iterative SD phase describing the SoI in increasing level of detail, adopted from [5]

From the comprehensive description of these stages in [5], key features were identified within the SD phase, summarized in Table I[1].
In similar manner like [5], [15] and [6] mention the need for a SD phase and highlight its features. These are also summarized in Table I.

TABLE I
Comparing System Definition features

		[5]	[15]	[6]	[8]	[16]	[17]
1.	Objective	X	X	X	X	X	X
2.	Boundary	X	X	X	X	X	X
3.	Scope				X	X	X
4.	Elements	X	X	X	X	X	X
5.	Environment/context	X	X	X	X	X	X
6.	Functions	X	X	X	X	X	X
7.	Requirements	X	X	X	X		
8.	Views	X	X	X			
9.	Approach	X					
10.	Interfaces	X	X	X	X	X	X

[1]Concept Definition phase also included

Besides [5], [6] and [15], the railway industry appears to pay considerable attention to SDs. After an extensive search process, it appeared that [8], [13], [16], [17] all mention the necessity of a SD. Two of which will be elaborated in subsections III-B and III-C.

B. The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS)-NEN-EN 50126-1 Railway Applications

This specification aims at introducing the application of a systematic RAMS management process in the railway sector [8], which is depicted in Figure 3. The system-level approach developed by this standard facilitates assessment of the RAMS interactions between elements of railway applications even if they are of complex nature [8]. Additionally, the standard promotes co-operation between the stakeholders of railways and aims to facilitate European railway interoperability.
In this process, SD is also mentioned as an early life cycle phase with the objectives to [8]: (i) define the system its mission and (ii) boundary of the system; (iii) Determine operational requirements influencing the system (including: constraints imposed by existing infrastructure); Define (iv) elements outside of the system which still influence the system, or vice versa (environment); (v) Identify elements: technological systems, humans etc. making up the system; (vi) Identify interfaces and interactions with other technological systems, humans etc. Based on this, key features were identified within the SD phase, also summarized in Table I.

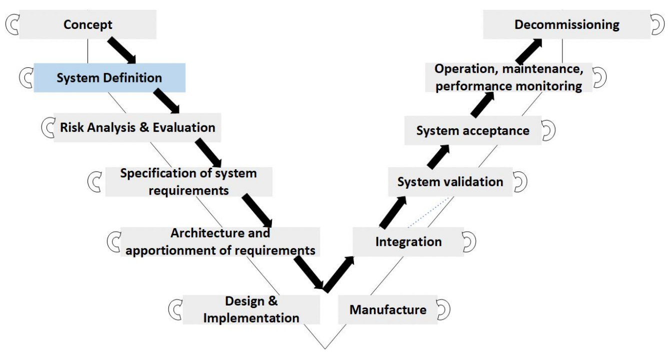

Fig. 3. SD in the V-cycle representation adopted from [8]

In addition to [8], the European Railway Agency provides several documents for application of Common Safety Method (CSM) Regulations, all of which include a SD phase as well.

C. Common Safety Methods-European Railway Agency

The CSM is applied at the beginning of projects to ensure that all applicable hazards are identified and managed. As indicated in Figure 4, the process commences with a preliminary SD. [17] states that whenever a change is proposed on a railway system (whether technical, operational or organizational) it needs to be considered if this change has a significant impact on the system. In order to assess this significance, a preliminary SD should be conducted. This is in effect an analysis of what is being changed of the current working system [16]. The SD required by regulation should provide a basis for risk assessment and an understanding of interfaces and functionalities which will be affected [16]. After the significance is proven, it is followed by the SD. As the details of the project emerge and are clarified over time, the SD is updated on a rolling basis [17].
In similar manner like [5], [8], [15] and [6], key features which should be included in the SD according to [16] and [17] were also identified and summarized in Table I.

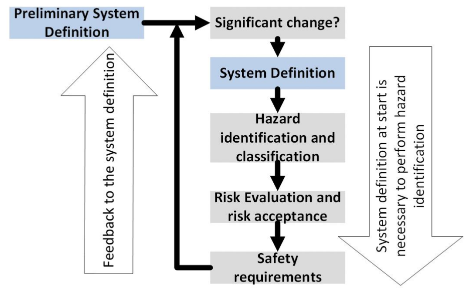

Fig. 4. SD for risk assessment, adopted from [16]

Based on this section, and information summarized in Table I, it becomes apparent that a SD phase should cover the following features to effectively describe a SoI:

- **1. Objective**: the intended purpose of the SoI, or of the change;
- **2. Boundary**: distinguishing between the SoI and its environment. This helps to limit e.g. risk assessment;
- **3. Scope**: defining what the SoI comprises e.g. technical subsystem, organisational change. Whatever the SoI's scope, understanding of the reality of the underlying change (and its implications) will gradually develop over time;
- **4. Elements**: elements making up the SoI and elements interacting with the SoI e.g., technical systems, humans, hardware, software, etc;.
- **5. Environment**: everything outside of the SoI that still interacts with it;
- **6. Functions**: SoI functions which are to be included and SoI functions which are to be excluded in the analysis;
- **7. Requirements**: the stakeholder requirements for a SoI that can provide the capabilities needed by users and other stakeholders in a defined environment & system requirements, which describe the functions which the SoI should fulfill in order to satisfy the stakeholder requirements;
- **8. Views**: integration of a number of disparate views, which may not necessarily be harmonious. Each of the stakeholder's views of the needed SoI can be translated to a common top-level SoI description that is understood by all;
- **9. Approach**: establish an approach for e.g. defining the SoI architecture. This can include methods, modeling

techniques, tools, etc.

- **10. Interfaces**: interfaces and interactions between subsystems making up of the SoI and with the environment of the SoI. Consideration of interfaces is important, as actions and decisions on one side of the interface might have repercussions on the other.

Consequently, whether it is for system development, systematic RAMS management or risk evaluation, the SD phase appears to be an important stage. It is possible to avoid recalls and rework in later stages, if proper attention is paid to features mentioned in table I early on [5].

IV. Case Study: the Dutch Railway System

In order to identify what (i) hinders effective integration in the Dutch Railways system (ii) and how this can be related to the identified SD features in table I, a case study has been carried out, elaborated in this section.

All railways have the same basic targets: beyond manifesting a safe railway, they are working to maximise the capacity at which they can operate their networks, minimise passenger and freight delays, maximise the reliability of the infrastructure and rolling stock, and do all of these at minimum costs [18]. In addition, numerous stakeholders can be involved within distinct life cycle phases of the railway system. The number & variety of stakeholders can differ due to social, political or legal considerations, but also because of size and complexity of the railway system or its subsystems.

An example hereof is the Dutch railway system which is divided in a core network and peripheral lines [19]. ProRail, the Infrastructure Manager (IM), manages the rail infrastructure of the complete network. Moreover, the Netherlands Railways (NS) is the main railway-operating company (RO). ProRail's main task is to provide infrastructure availability to railway-operating companies [19].

The separation of railways IM and ROs means that there is a limit to the improvements that can be achieved if they cannot work together effectively [18]. These stakeholders have different views, skills, responsibilities, objectives, and interests, adding to the complexity. Consequently, adequately sharing information between these organizations is prerequisite for the whole railway to be managed adequately. Hence, there is a strong interdependence between all (sub)systems, which all-together cohere into the total functioning railway system. These (sub)systems must seamlessly connect and interact with each other, to prevent disastrous consequences. One cannot induce a change on one part of the system, without in parallel having insight on other consequential adjustments required in interdependent parts. This is required to achieve system-level performance.

Within the IM and the main RO organization, 42 semi-structured interviews were carried out to identify what hinders effective integration/opportunities for improvement. Interviewees included but were not limited to: train-drivers, safety managers, safety specialists, project managers, operation managers, (system) engineers, asset managers, network designers, change managers, quality managers, innovation managers, program managers, system/infrastructure architects, etc. Hence, interviews were carried out through different organizational layers, within distinct departments to obtain a comprehensive overview.

V. Approach

After carrying out the interviews and documenting these, the obtained data was analyzed using ATLAS.ti (qualitative data analysis (QDA) software). The computer-assisted QDA consists of various consecutive phases: prepare data, code the data, sort and structure the data with the aim of discovering patterns and relationships [20].

The first step in ATLAS.ti consisted of separately grouping interviews according to organization (NS, ProRail). Afterwards, all interviews were analyzed on issues/improvements/bottlenecks concerning integration. In parallel, these were coded. Using the coding options provided by the software: (i) Open coding: assigning codes to part of the text while scanning through the documents and afterwards, return to the codes to standardize these. (ii) In-Vivo coding: a portion of data that itself is representative of a concept/feature, this can be used as its code name. (iii) List coding: This helps to choose from formerly applied codes. (iv) Auto-Coding: find certain word instances, except it provides an option to code those occurrences and set specifications as to what and how much to code. Auto-Coding can also help quickly code strings of words related to a certain concept in the text.

Previous steps resulted in coding all data obtained from interviews. Afterwards, these codes were grouped in larger clusters (further referred to as Code Groups (CGs)) in case there was a relationship between codes (e.g. identified problems which were coded "information dispersion" and "sharing information" were all clustered in CG "Information"). In addition, the determined codes were clustered as much as possible according to identified features mentioned in Table I. Then, the coded data and CGs were analyzed by using the QDA options to quickly gather, sort and compare data. These results will be discussed in section VI.

VI. Case Results

After clustering codes and creating CGs as explained in section V, several coded issues could not be clustered according to features summarized in Table I. For these, different CGs were determined. Based on the author's interpretation of the data, this resulted in additional CGs: "Complex system" (11), "Information" (12) "Structure" (13), "Governance, ownership & responsibilities" (14).

The results of this analysis are presented in Figure 5 below and are discussed in more detail forwardly.

1. Objectives

This CG included the codes: (i) "Problem description", (ii) "Stakeholders objectives", (iii) "Translation of objectives".

(i) 1% of the time, interviewees mentioned a lack of an appropriate problem description. Consequently, often

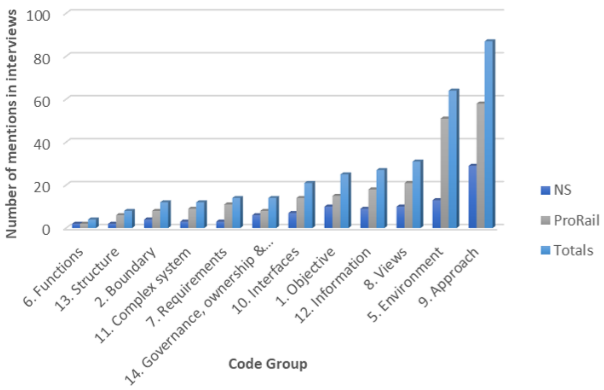

Fig. 5. Identified code groups in order of significance (ATLAS.ti)

starting with a solution to a not-well defined problem. (ii) Differences in objectives between stakeholders were mentioned approximately 5% of the time. (iii) This includes translation of system-level objectives to different organizations, but also different organizational layers.

2. Boundary & 3. Scope

Within this CG, both (i) "Boundary" and (ii) "Scope" are included, as these concepts are closely related to each other and were not distinguished during interviews. From the interviews, roughly 4% of the time related issues included: difficulties to determine the scope of the projects and boundaries of a SoI i.e. what to include/exclude for further analysis.

4. Elements

As can be seen in Figure 5, "Elements" has not been created as a CG. This is more or less included in "Environment" and "Complex system", i.e. which elements are outside of it, but still interact with it and which make up the complex SoI.

5. Environment

This CG includes the codes: (i) "Environment", (ii) "Impacts", (iii) "Integral overview". Around 12% of the time, the lack of an integral overview of the SoI was mentioned as an issue. This is closely linked to understanding the coherence between different systems and the environment of the SoI. Moreover, because of this, there are limitations for determining the impacts of a change on (sub)systems in the environment of the SoI.

6. Functions

This CG does not include other codes. In case a change is proposed on the railway system, it is often unclear how this influences existing functionalities of the railway system i.e. which ones will be discarded/added.

7. Requirements

This CG includes the code "Traceability" of requirements. E.g. traceability of certain requirements to the objectives of a change to the railway system. Additionally, system requirements and stakeholder requirements are closely related, and were not distinguished in interviews.

8. Views

This CG consists of the codes: (i) "Different views", (ii) "Various stakeholders", (iii) "Silo mentality". People/departments have different views or mental models of a SoI which need to be combined to get an integral overview. Additionally, this will depend on the expertise which is brought together. Furthermore, there are different views of the SoI e.g. functional, physical view. Moreover, people are concerned with their own work (individual/department/specialization), and not how this might effect other departments. This CG accounts for approximately 16% of the identified issues.

9. Approach

Mentioned 27% of the times during interviews, this is the largest CG and includes the codes: (i) "Early involvement", (ii) "Generalizability/approach", (iii)"Level of Detail", (iv) "Mutual start". (i) Different stakeholders are not involved early on i.e. at the start of projects. Consequently, it cost significant amount of time and energy to align afterwards. (ii) Numerous system models and system (start) architectures exist within organizations, which are only applicable to a certain project. Because there is no standard or generalizable approach available, the energy and time spend here is wasted after the project is finished. (iii) There often is discussion about the level of detail, too abstract does not result in e.g. determining critical interdependencies. However, too detailed result in a lack of overview.

10. Interfaces

Around 7% of time, interviewees indicated the significance of interfaces and the proper description of these for effective integration. However, all indicate that there is a great opportunity for improvement here. Especially interfaces with environment, as these are essential to provide insight in impacts on interfacing systems.

11. Complex system

This CG includes the codes: (i) "Increasing system complexity", (ii) "Model of railway system". (i) Includes the increasing complexity of the railway system over time. This results in limited understanding of the coherence between different (sub)systems making up the railway system. In addition, (ii) interviewees mention the lack of a model describing the railway system as a whole, as an issue approximately 2% of the time. When trying to grasp the coherence of distinct elements that make up the rail system, they do not have a mutual basis to: to demarcate different projects, make a joint departure point for inter-organizational projects and indicate impacts of a change on interdependent parts. Moreover this hinders finding interdependencies where cooperation is required.

12. Information

This CG contained the codes: (i) "Information sharing", (ii) "Information dispersion", (iii) "Fact- vs opinion-based information". The quality of information (sharing) is often mentioned as an opportunity for improvement. Due to the fact that both IM and ROs are large organizations, there is information dispersion. Accounting for almost 9% of the gathered issues, this CG is within the top 5 issues, as indicated in Figure 5.

13. Structure

Within this CG, the codes (i) "Hierarchy" and (i) "Layers/levels" were mentioned around 3% of the time. This entails that the railway system consists of different layers/levels, which is not recognized by everyone. Moreover, discussions often occur concerning the effect of a change to different layers and concerning resources required at different levels of the system to achieve increased system level performances. Although not specifically mentioned in Table I, when referring back to subsection III-A, this CG is highly related to the System Architecture Definition phase.

14. Governance, ownership & responsibilities

Approximately 5% of the time, interviewees mention ambiguity in governance, ownership & responsibilities as cause of integration issues.

VII. Discussion & Conclusion

SI has become a key concern [4]. Nevertheless, the avoidance or anticipation of integration issues is highly dependent on its advance planning and preparation, accomplished during the SD phase. Whether for system development, systematic RAMS management or risk evaluation, the SD phase appears to be an important stage. After a literature review, key features included within this phase converged to: objective, boundary, scope, elements, environment, functions, requirements, views, approach & interfaces. Moreover, the SD is too often viewed as a linear, sequential process [5]. Iteration is needed to accommodate constraints, stakeholder decisions and evolving understanding to ensure a good SD that effectively and efficiently meets the objectives [5]. After carrying out a case study in the Dutch railway system and conducting 42 semi-structured interviews within both IM and RO, identified issues were clustered as much as possible in CGs related to identified SD features. From this, it can be concluded that there are more features to pay attention to including: "Complex system", "Structure", "Information" and "Governance, ownership & responsibilities". Moreover, from Figure 5 it can be concluded that the top 3 mentioned CGs included issues related to: "Approach", "Environment", "Views". Furthermore, one of the reasons that "Approach" could be the largest CG, is that all reviewed literature indicates the need for a SD phase and its features, but do not specifically provide an approach how this could be conducted. Although [5] does mention that an approach is necessary (Table I), no specific approach is mentioned. In addition, ATLAS.ti proved to be a very useful, user-friendly tool, with numerous options for analyzing the interviews. Although the QDA software provided useful insights in the results, coding is still based on the author's interpretation of the data and could be subjective. In order to prevent this, the analysis could be improved by conducting it by multiple researchers.

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