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Railway Systems Development Based on the Concept of Systems Engineering and Safety: A Case Study of Railway Industry Practices

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--ABSTRACT--
A railway system has been regarded as a means of safe and reliable transportation of human being and goods. However, as the running speed of the trains gets up and the mode of operation tends to be unattended, handling the complexity of the development together with safety assurance becomes a crucial issue. For this reason, systems engineering (SE)-based development of railway systems turned out to be a good candidate approach. As such, numerous attempts to accommodate SE knowledge have been made in Korea and abroad. SE activities have been forced to be performed in Light Rapid Transit projects in Korea. However, due to the lack of understanding of SE process or sometimes misunderstanding among various stakeholders of the railway systems, SE has not been applied properly. Instead, they still rely on the framework of traditional management, thereby facing a variety of design issues. Furthermore, problems arise in connection with safety management because safety requirements management is not handled with linkage to the technical processes such as system integration, requirement management, and verification & validation management. To develop the railway systems with safety ensured successfully, all these system design and safety issues must be dealt within the SE framework. To cope with the situation, an SE-based development approach is discussed in this paper. We analyze the actual cases of SE application by examining the railway system projects that have been carried out or currently being carried out in Korea and other countries. It is shown how SE has been applied and how useful the SE application is. We also focus on the activities that should be considered to be a significant part of the SE activities and then present an integrated process incorporating safety management into system design management. A case study of railway E&M system project demonstrates the appropriateness of the integrated process. The results of this study will provide a guide to more explicit understanding and usage of SE in future railway projects.

Keywords: *Railway Systems Development, Requirements Management, Safety, Systems Engineering, Verification and Validation.*

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I. INTRODUCTION

As customer requirements and technologies become more diverse and sophisticated than ever, the system development process is getting more complicated. That is true, especially for large-scale complex systems. For that reason, systems development methodologies based on systems engineering (SE) have been attracting much attention in the development of various complex systems. Weapon systems development has been on the focal point of SE applications from early on. The application has recently been extended to the area of commercial and public systems including high-speed rail systems. To meet this demand, the international standard organization established the SE standard, ISO/IEC/IEEE 15288 entitled "Systems and Software Engineering - System Life Cycle Processes." [1].

The railway system is composed of numerous subsystems/components such as rolling stock, signaling, communication, power supply, platform screen door, automatic fare collection, and other mechanical ones. To ensure that operation of the railway systems is safe and reliable, it is necessary to apply SE from the early stage of development [2, 3]. In recent years, to carry out SE activities has become mandatory for light rail transit (LRT) systems that have been built in Korea [4]. Although this direction appears to be right, an obstacle on the way could be the lack of understanding of systems engineering or sometimes misunderstanding from the viewpoints of railway operating agencies, government agencies, and contractors. It was pointed out in an earlier presentation [5] that shortening of the development period and cost reduction were pursued in the underlying LRT projects while SE was regarded as an auxiliary element rather than a necessary effort. On the other hand, safety is of great concern in railway systems. Thus, system design and safety design cannot be separated. To this end, SE should play an

essential role in ensuring safety by systematically integrating system design and safety at system level instead of carrying out safety design at component level alone, i.e., electrical and mechanical (E&M) system, rolling stock, and door to door control unit.
The objective of this paper is to discuss a useful way of rail systems development based on SE with safety considered. To achieve the goal, we refer to the related standards and references to identify how SE has been defined for railway system application. Also, through the analysis of relevant literature, it is examined how in the project management the traditional approach differs from the SE-based approach, and how SE works in project execution. Based on this result, we analyze the cases of SE applications in the railway system projects that have been practically carried out in Korea and other countries. Using this, we analyze the effect of SE application on Korean railway system projects regarding cost overrun. Also, through a study of overseas cases, we identify key activities that contribute to the successful completion of the SE-based projects. Moreover, an integrated process is proposed so that the SE-based safety management activities are carried out in conjunction with the requirements management process and the verification and validation process that are essential technical processes of the standard ISO/IEC/IEEE 15288 [1]. Finally, a case study of railway E&M project demonstrates the appropriateness of the integrated process.

This paper is organized as follows. In Section two, related work is presented including the systems engineering concept together with problem definition and methods of approach. We analyze the project cases in Section 3 to evaluate the role and effects of SE plications in practice. In Section 4, an improvement of the system design and safety process is proposed. In Section 5, a case study of safety management is discussed by presenting the integrated process for managing the safety requirements and verification through practical application. Finally, Section 6 concludes with a summary of what has been done in this study.

II. RELATED WORKS

2.1. Concept of Systems Engineering

For the subject of SE in general, there are many published definitions. For example, the International Council on System Engineering (INCOSE) SE Handbook [6] defines as follows:
"Systems Engineering is 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 about operations, cost & schedule, performance, training & support, test, disposal, manufacturing.
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".

This handbook gives other two definitions although all carry a common theme as above. If we look at the various SE standards, they also contain different scope descriptions. The ISO/IEC 26702 IEEE 1220 [7] is one of the first standards for SE. The scope statement of its latest version begins as follows:
"This standard defines the interdisciplinary tasks that are required throughout a system's life cycle to transform stakeholder needs, requirements and constraints into a system solution."

Another important standard for SE is the ISO/IEC/IEEE 15288 [1]. The latest version of this standard was published most recently in 2015. In section 5 of the standard, activities that may be performed during the life cycle of a system are listed and categorized into four process groups, namely: 1) Agreement Processes, 2) Organizational Project-Enabling Processes, 3) Project Processes and 4) Technical Processes. As illustrated in Figure 4 of the standard, there are altogether 25 activities although some of these activities are arguably project management activities with or without the use of SE.

While the standard includes these overlapping activities because they are system lifecycle processes, it is nevertheless confusing and does not help the average railway project personnel to understand what SE is about and how it differs from traditional approaches to project management. In fact, Annex A of the standard is a description of "Tailoring Process" guiding practitioners how to tailor the SE activities to suit project needs and local project practice. What this means is that the scope of SE to define is expected to vary from project to project to suit local needs and practices in railway system domain. Examples of SE scope for LRT projects can be found in the systems engineering body of knowledge (SEBoK) [8]. It covers the following topics: Business Analysis, Stakeholders Needs and Requirements, System Requirements, Logical Architecture Design, Physical Architecture Design, System Analysis, System Implementation, System Integration, System Verification, System Validation, System

Deployment, Operation of the System, System Maintenance, Planning, Assessment and Control, Risk Management, and Measurement. However, in Korea, according to the SEBoK 2015 – Standard Korean Light Rail Transit System Vignette [9] the focus of SE has been more on Reliability, Availability, Maintainability, Safety (RAMS) although recognizing that requirements analysis should be more complete.

Thus far, we have seen that there is not a straight answer to the question "What is SE?". In Section 2.3, we analyze how SEs are defined and what roles they play by comparing the existing project management and SE approaches.

2.2. Problem Definition

SE approach started being adopted in railway projects around two decades ago. However, the contents of SE in these projects are not always the same. As such, interpretation of what SE is about for railway project is not an easy task to most people. Now and then, the question "Why do we need Systems Engineering (SE)?" is raised by project managers, project governance parties, and authorities of railway projects. From many study reports, SE is known to bring benefits to projects, especially projects of high complexity. The main idea of SE is the assurance of delivery of products to client's requirements in a controlled manner regarding quality, cost and time. According to the INCOSE, research indicates that efficient use of SE can save 20% of the project budget [6].

Unfortunately, these benefits are not always obvious, and hence SE does not always get recognition. In practice, railway project managers are often more interested in completing projects with minimal tasks to satisfy the client and authorities for final acceptance. This paper aims to address the question again "Why do we need Systems Engineering (SE) in railway systems projects?"

2.3. Methods of Approach

To address the question, our approach based on a study of recent research reports, standards, handbooks and relevant publications, and project reports. By traditional approach, we mean traditional project management (PM) without explicitly using SE approach. In BS EN 9200 – Programme Management – Guidelines for project management specification [10], the list of PM tasks includes, amongst others, Section 11.2 Systems Engineering, and 11.3, RAMS.

The SE activities as described in the standard (Section 11.2.2) are:

- Expression of need by customer;
- Analysis of the input requirements by the supplier;
- Design of the product or the system: structuring and requirements allocation;
- System analysis;
- Certification and validation, justification and qualification.

The IEC/ISO/IEEE 15288 [1] listed SE activities overlap with some activities found in traditional projects. The following Table 1 gives a comparison of ISO/IEC/IEEE 15288 [1] and the BS 6079-1 on project management [11].

Table 1. Comparison of ISO/IEC/IEEE 15288 and the BS 6079-1 on Project Management

SE Management – System Life Cycle Processes (ISO/IEC/IEEE 15288)	**Project Management (BS 6079-1)**
Agreement Processes	
• Acquisition	Procurement (C-7.2.13)
• Supply	Procurement (C-7.2.13)
Organizational Project-Enabling Processes	
• Life Cycle Model	Life Cycle (C-5.3)
• Infrastructure Management	-
• Project Portfolio	Costs (C-7.2.7)
• Human Resource Management	Resource (C-7.2.6)
• Quality Management	Quality (C-7.2.14)
Technical Management Processes	
• Project Planning	Project Planning (C-7.2.2)
• Project Assessment and Control	Project monitoring and control (C-7.1.6.3)
• Decision Management	Directing (C-7.1.5)
• Risk Management	Risk Management C-7.2.8)

SE Management – System Life Cycle Processes (ISO/IEC/IEEE 15288)	Project Management (BS 6079-1)
• Configuration Management	Configuration management (C-7.2.11)
• Information Management	Reporting (C-7.2.15)
• Measurement Management	Sometimes this is Part of Quality (C-7.2.1) & Stakeholder & communication (C-7.2.16)
Technical Processes	
• Business or Mission Analysis	Scope (C-7.2.3)
• Stakeholder Needs & Requirements Definition	Scope (C-7.2.3)
• System Requirements Definition	Scope & Planning (C-7.2.2.2), Change Control (C- 7.2.10)
• Architecture Definition	-
• Design Definition	-
• System Analysis	
• Implementation	-
• Integration	Project Integration (C-7.1)
• Verification	Approving a project (C-7.1.3.1)
• Transition	-
• Validation	-
• Operation	Approving a project (C-7.1.3.1), Reviewing project outcome (C-7.1.9)
• Maintenance	-
• Disposal	This is related to the cost for Decommissioning & Disposal (C-7.1.4.4)
	Documentation (C-7.2.12)

The above reflects that the real additional task of SE over traditional approach projects is the Technical Process part of the SE. The following Fig.1 depicts the relationship between SE and PM [12].

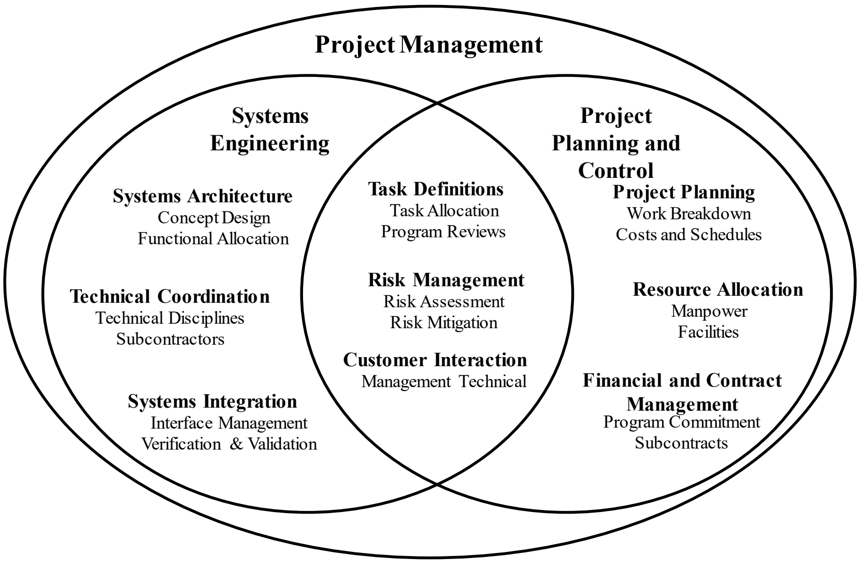

Fig. 1. Relationship between SE & Project Management [12]

Notice that RAMS is not part of SE, but are separate disciplines. Indeed, as we can see in Table 2 of section 3, RAM and Safety Management are found in every example projects in Korea. Equally, RAMS work is found in most recent projects even in countries that do not apply SE, such as China. For critical operational subsystems such as signaling and rolling stock systems, RAMS activities are now standard requirements in technical specifications for system procurement but without most of the other SE activities.

In practice, traditional commercial railway projects mainly focus on cost and time of delivery and using the mostly off-the-shelf equipment. As such, client's requirements may not necessarily be fully met, especially when the user requirement specification is not specific, and for example, relying on a general reference to standards. The design process is therefore relatively simple as it would be just a case of minor adjustments to interfacing design of the off-the-shelf products to suit the interfacing equipment from different suppliers. Similarly, verification and validation of the subsystems are limited to standardized tests that are found in traditional projects. As examples, most of the Korean LRT projects as shown in Table 2 do not have V&V but only T&C.

Traditionally, for railway projects especially those that with a low demand of system capacity, whether the operational performance capability of a newly built system can meet user requirements may not be apparent. The advance in technology and ever-increasing attention of the media are pushing operators or project sponsors to pay more attention to system performance.

For such newly built metro systems with high capacity demand, a more tailored requirements specification is necessary to ensure that the built system perform safely and reliably to targets on day one. All these are the driving forces of implementing SE over traditional approaches to project management.

III. ANALYSIS OF PRACTICES

3.1. Projects in Korea

In this section, we derive the roles and contribution of SE through the analysis of SE cases applied in Korea and international railway sectors. At first, we start a discussion with the experience in Korea. Korea is one of the countries that have adopted SE approach in railway metro projects. In the recent study [4, 5], a comparison of the scope of SE is made on ten recent LRT projects. The table of comparison is presented in Table 2 below.

Table 2. Survey of systems engineering applied to LRT projects in Korea [4, 5, 13-16]

Items	Seoul 9th Line	Shinbundang LRT	Busan-Kimhae LRT	Uijeongbu LRT	Yongin LRT	Ui-Sinseol LRT	Incheon 2nd Line LRT	Kimpo LRT	Sillim Line LRT	Shinansan Line LRT
SE Cost (Unit: 0.1 Billion)	240	120	120	153	159	46	208	92	73	161
Total Project Cost to Date (Unit: 0.1 Billion)	9,145	15,808	13,236	6,767	10,032	9,299	24,590	To be determined	To be determined	To be determined
% SE Cost Invested = SE Cost / Initial	2.7%	0.9%	1.3%	3.2%	2.3%	0.7%	1.1%	0.6%	1.0%	0.4%
Initial Project Budget	8,995	13,694	9,058	4,750	6,970	6,465	19,555	15,086	7,422	42,859
Cost Overrun = (Total Project Cost-Initial Project Budget)	150	2,114	4,178	2,017	3,062	2,834	5,035	-	-	-
% Cost Overrun = Cost Overrun / Initial	2%	15%	46%	42%	44%	44%	26%	-	-	-
Planned Completion date	01-Apr-09	Jul-10	Apr-11	Jun-12	01-Oct-10	Sep-14	Jul-16	Nov-18	Feb-22	Jun-23
Project Completion date	24-Jul-09	28-Oct-11	17-Sep-11	01-Jul-12	26-Apr-13	02-Sep-17	30-Jul-16	On going (Target: Nov 2018)	On going (Target: Feb 2022)	Not started yet.
Time Delay (months)=Planned Completion Date - Project CompletionDate	4	15	5	1	30	36	-	-	-	
Number of stations	30	6	21	15	15	13	27	9	11	17
System Length (km)	25.50	17.40	23.20	11.07	18.10	11.09	29.10	23.63	8.10	46.96
Per Km construction cost (Unit: 0.1 Billion)	359	909	571	611	554	567	1,715	1,323	651	3,760
Km Per station (Km)	0.85	2.90	1.10	0.74	1.21	1.23	3.23	2.63	0.90	5.22
*Indicative weighed unit cost = unit cost per Km x Km per (Unit: 0.1 Million)	305	2,635	630	451	669	699	5,546	3,474	586	19,615
List of Systems Engineering Tasks										
Performance Management			O		O	O	O	O	O	To be determined
Design Management		O	O	O	O		O		O	
I/F Management	O		O	O	O	O	O	O	O	
RAM Management	O		O	O	O	O	O	O	O	
Safety Management	O		O	O	O	O	O	O	O	
EMI/EMC Management	O		O		O	O	O	O	O	
Noise/Vibration Management	O				O	O	O	O	O	
Requirements Management					O	O	O	O	O	
Configuration Management					O	O	O	O	O	
S/W Management					O		O	O	O	
T&C Management	O		O	O	O	O	O	O	O	
V&V Management						O				

* Note: This is intended to be indicative only as the appropriateness of the formula as used is arguable depending on the cost ratio of station vs Km infrastructure.

Interestingly, and as can be seen later section 3.2 of this paper, some of the essential tasks of SE found in the overseas railway projects, such as Requirements Management, V&V management, and so on, are not part of the SE elements in most of these Korean projects. In fact, the early projects were more focused in RAMS as mentioned earlier in Table 2, although also included some other "Specialty Engineering" tasks, including Noise and Vibrations, Interface Management, EMC, and so forth [6].

These are tasks that can also be found in traditional projects without SE. On the other hand, from the experience of an on-going Korean LRT projects, while these tasks are included in the project, they are performed without "Specialty Engineering" plans and lack the system integration approach which is one of the main elements of SE.

As described in section 3.2, one of the most important SE tasks is Requirements Management which should start at the very beginning of a project before the commencement of procurement of systems. The idea, as can be found in every single standard related to SE, is to have a total system approach from the beginning of a project to identify the requirements of the end users. These requirements are then analyzed and cascaded to different subsystems with clear interface requirements between them to minimize gaps between system supply contracts. In other words, these contracts, when put together, form a complete system with a precisely documented configuration that satisfies the identified user requirements. The data as shown in Table 2 reflects that such a process does not exist in most of the earlier projects and the current project (i.e., Sillim Line LRT).

Unfortunately, we cannot collect the operation performance data of these projects to compare their effectiveness. This would be an interesting research subject in the future especially if it can be done in conjunction with the LRT operators of these projects as listed in Table 2, which would allow access to operation performance data owned by these operators. Such research should facilitate future projects in determining what would be the optimal extent of SE for Korean LRT projects concerning achieving good operating performance.

3.2. Projects outside Korea

Outside Korea, the use of SE approach is more intensive. In cities of developed countries such as those in the western Europe, North America, Australia, and some cities in developing countries in Asia especially those without the baggage of long history of traditional railway procurement practices, projects using SE are becoming a standard practice, although not necessarily in the same form nor to the same extent.

As examples, transit agencies adopting SE approach include London Underground & Network Rail in UK, Pro Rail in the Netherlands, New York City Transit in USA, Vancouver Sky Train in Canada, Land Transport Authority in Singapore, Mass Transit Railway Corporation in Hong Kong, Bangkok Metro Corporation (in their current Purple Line Project) in Thailand, and Melbourne HMCT (requirements in tender specifications, not yet started) in Australia, Mecca LRT, Doha LRT, etc. in the Middle East. Also, some of these transit agencies have already established SE departments, e.g., New York Transit as reported by Elliot [17].

In a paper published by INCOSE [18], lots of projects were studied with SE perspectives. The document outlines many project cases, sharing lessons learned from the application (or sometimes the lack of application) of SE to transportation projects. Table 3 is a summary of some of these project cases that are railway related.

Table 3. Comparison of systems engineering case studies outside Korea [18]

Projects	SE Performed	Conclusions
West Coast Route Modernisation Project in the UK – major delay and cost overrun SRA intervened.	SRA (Strategic Rail Authority)'s intervention from 2002 introduced a program of action that included the adoption of good SE practices in the areas of requirements management and configuration management led to significant reductions in cost and timescales.	It seems very likely that, had good practice in requirements management and configuration management been adopted from the start, significant further cost savings would have been enjoyed.
Vancouver, BC, SkyTrain control center upgrade and expansion	SE practices were employed comprehensively, including detailed requirements analysis, detailed risk analysis and risk management planning, detailed system configuration management, detailed testing and verification plans were developed.	Good application of SE during the preliminary design adequately identified all the requirements and the application of SE practices during the implementation ensured a successful outcome.
Docklands Light Railway Expansion	Systems requirements were articulated and, from them, requirements were derived from the vehicles, the train control system and the interface between them.	The project could not have been delivered without an SE approach. Not only did the SE approach support successful delivery but it assisted in delivering a well-performing and extendable railway system which is one of Britain's great transport success stories.
East London Line	System engineering was central to the entire project. Requirements management tool DOORS was used. Verification tests were all structured to document satisfaction of requirements in a progressive way. During both the design and construction, scope creep was controlled because every contract requirement was linked to a business requirement or an external constraint, and contract changes were directly related to requirements.	The project met all the requirements and provided all required functionality. It has received twelve important awards, including 2011 Greatest Contribution to London award, and 2011 National Rail Project of the Year. The railway was opened for revenue service five weeks ahead of schedule. The actual reliability experienced (97% of arrivals within four minutes of scheduled time) has exceeded the target (92%). The adoption of SE practices allowed a complex and difficult project to be delivered successfully and on-time.
Jubilee Line Extension (JLEP) –	SE was not evident in the project. However, the evidence cited in the case study suggests that adopting	The JLEP was ultimately a successful project that delivered improvements to London's

Projects	SE Performed	Conclusions
The project suffered a significant cost overrun 67% /£ 1.4billion and time delay (40% / 21 months).	good SE practice (including managing requirements and specifying the system as well as the systems with which the new system must interface, and the desired outcomes of running the new system in its environment) would have revealed the oversights and allowed a more realistic scoping of the works	transport infrastructure that justified the considerable investment made in them. The evidence from authoritative accounts of the project suggests that had the JLEP adopted good SE practice from the start; the project could have avoided some of the problems listed above on the way to delivery. It also suggests that adopting good SE progress could have avoided some late changes and delivered savings in both project timescales and budget.
Jubilee Line Upgrade Project –	Considerable effort was expended on requirements management, developing the systems architecture, interface management, and configuration management.	The case study illustrates clear benefits of investing in good SE practice on the left-hand side of the V diagram but also illustrates that these techniques cannot forestall all project problems and suggests that a balanced investment in both sides of the V diagram, as is currently being made on the Northern Line upgrade, is likely to yield the best return.

Each of the cases is different: some with SE, some without. Even for the cases where SE was applied, the extent of application is different. In some cases, tasks that were performed resembled SE tasks, but the project team did not specifically identify them as SE activities. Indeed, as discussed in previous sections, some activities that claimed to be SE are also found in the traditional project management scope.

As can be seen in Table 3, lessons learned are pointing to the direction that the use of SE in projects is likely to lead to better project outcome. These lessons learned are qualitative. The recent Ph.D. dissertation by Elliot [17] attempted to quantify the evidence of SE benefits by looking at the cost saving and reduction of time delays in some of these projects. His conclusion is conditionally positive

IV. IMPROVEMENT OF THE PROCESS

4.1. Reference Models

Many studies and research work have concluded that SE benefits projects. Hamid et al. [19] concluded in their paper that SE ensures the delivery of the optimum system that best meets all requirements and provides the proper balance of technical performance with cost and schedule.

INCOSE SE Handbook [2] states that SE emerged as an effective way to manage complexity and change. With Requirements Management as one of the main SE tasks, potential risks and changes can be identified at the earliest stages of projects. Since project cost commitment increases as project progress, early identification of risks and changes will help to reduce consequential costs from project progression. In the study by Hitchins [20], he reported his finding on the importance of the early discovery of errors and omissions of requirements and design specifications. Urban rail projects are particularly risky ventures, with average cost escalation of 45%, and that 25% of these projects have cost escalation of at least 60% [21]. We note that the % budget overrun comparison as illustrated in Table 2 provides evidence of such finding.

Elliot [17] proposed in his research study a tentative theory. The tentative theory asserts that core SE contributes to reduced change latency by timely, accurate and comprehensive information. In the study, Elliot [17] found that the extent of benefit of SE depends on certain factors. In his report, he concludes from his survey findings that a railway project will see benefits of applying SE if the contractual and quasi-contractual relationships among the parties to the project, including separately-run departments within one organization, are set up in a way that allows them to collaborate efficiently towards common goals and take decisions quickly. In other words, the initial work of setting up contractual relationships and terms is an essential element of successful application of SE.

4.2. Analysis Result

As experienced in recent LRT contracts in Korea, the problem of uncoordinated contracts has been a significant constraint to the implementation of SE process. Without well written contractual requirements for SE work, contractors usually decline to support SE works. This is understandable as this involves additional costs. However, what this means is that SE cannot be effectively implemented in the project.

Another factor affecting the effectiveness of SE and its value is competency. Hawken [22] suggested that the important knowledge required is Requirements Management. Allen [23] also emphasized the importance of proper training in SE.

The two best project performers regarding cost and time of completion, as detailed below, are both with relatively high SE investment.
1) The Seoul Line 9 – SE cost at 2.7%, cost overrun at 2% but the lowest unit cost (weighed with km per station), and program overrun of 4 months.
2) The Uijeongbu LRT – SE cost at3.2%, while with a high cost overrun at 42% it is the 2nd lowest unit cost (weighed with Km per station) and a program overrun < 1 month.

For the other projects in Table 2, Yongjin LRT has a comparable level of SE investment at 2.3%. Moreover, yet, the project performance is not too impressive with a high level of cost and program overruns.

4.3. Suggestion
Another important question is how much SE effort we should expend in projects. SE effort includes human resources as well as time. In Section 2.3 above, we have shown the list of tasks as stated in Table 1. Performing these tasks requires significant efforts (hence cost) from the different parties of a project. Also, it takes time to perform analyses and to define requirements. Hence, we are going back to the same question as we explore earlier on: "What is SE" [24].
Concerning what we have reviewed from the various definitions and descriptions of SE, it can be anything between two extremes. One extreme is not to have SE at all. The other extreme is to follow all the tasks as listed in the standards to analyze and define everything. Moreover, when something changes, to re-analyze and re-define every detail at the risk of delaying progress. Surely, this does not make sense, and there should be a balancing point.
What then is the optimal balancing point of SE? In Honour's research [25], he proposes that the relationship between the additional costs of performing more SE (the X-axis) and the extent of cost overrun of projects (the Y-axis) follows an inverted curve which reaches an optimal (lowest cost overrun) point when the SE cost is at around 14% of the project cost. Table 2 above again provides an interesting set of data that appears to support Honour′s research finding. In Korea, according to the report of Public and Private Infrastructure Investment Management Center [26], the cost of system engineering activities is limited to be 5% of E&M system (mechanical, electrical, signal, communication, inspection) except rolling stock. Thus, there seems to a difficulty in performing an efficient SE. If we were to follow the postulation of Honour, and take into consideration of the fact that the main tools of SE, such as Requirements Management and V&V, have not been adopted in most of these projects, there may be potentials for better project performance if higher SE investment is applied and if such application is focused more on the key elements of SE. Such performance includes project performance and operating performance.

V. CASE STUDY OF PROCESS INTEGRATION FOR MANAGING SYSTEM DESIGN AND SAFETY

5.1. Integrated Requirements Management Process
For a typical single system development, safety assurance is possible through safety activities at the system level. However, since railway systems are complex and composed of many systems/subsystems/components, a different approach is needed to deal with safety requirements. A model of hierarchical structure used in this paper is depicted in Fig. 2. If the safety activities are managed at the system level as shown in Fig. 2, major safety functions might be omitted while doing verification and validation (V&V) activities in the final integration & test stage. To solve these problems, an integrated process that incorporates safety activities into systems design process is proposed based on a hierarchical structure.

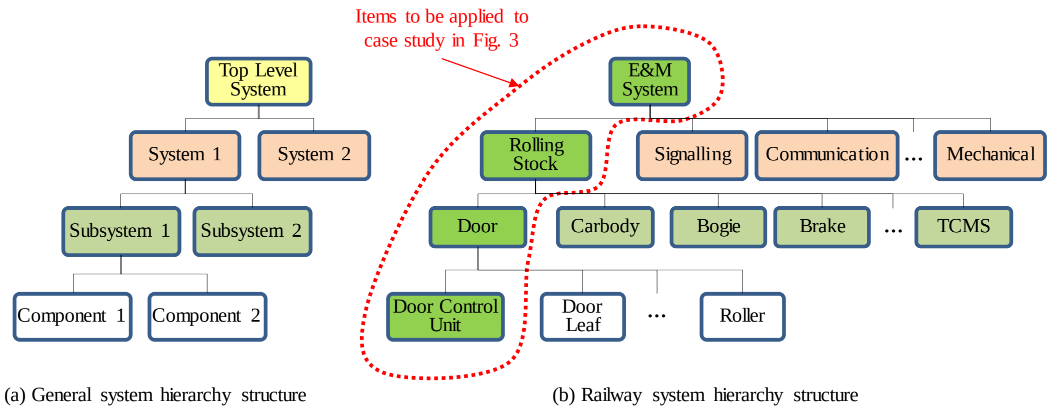

Fig. 2. System hierarchy model used in this paper. (a) General system; (b) Railway system

In the proposed model, system and safety design activities are performed in top-down direction whereas the design V&V process in a bottom-up direction. Specifically, system requirements are derived from system design activities at the initial stage of system design. On the other hand, safety requirements are derived from hazard analysis. The core concept of the model is focusing on how these two set of requirements should be integrated and managed when the design and V&V activities are performed. As an example, we consider an E&M system whose structural model is depicted in Fig. 2. Safety requirements at the system level (i.e., the E&M System) are derived through the preliminary hazard analysis (PHA) activity at the initial design stage. The safety requirements at the E & M system level are then assigned to the rolling stock subsystem, which allows the rolling stock to reflect the assigned requirements in the system design. To meet the safety requirements assigned by PHA to the rolling stock level in the same form, we perform system hazard analysis (SHA), interface hazard analysis (IHA), and operation hazard analysis (OHA) at the rolling stock level according to the functional requirement analysis. In the same way, progress is also made in the lower devices. The resulting safety requirements are integrated into the hazard log at each level and reflected in the system design at the system level. After that, the verification activity is performed to verify whether the safety requirements derived from the initial stage of the design are reflected in the design document (e.g., design specification) and whether the relevant safety requirements are properly tested and evaluated on the test report at the final test & commissioning phase to perform validation activities. As a result, whether or not all safety requirements are reflected in the system is recorded in the final hazard log. In the integration process, the safety requirements can be systematically managed along with the system hierarchy using the safety requirement traceability matrix (SRTM) so that the basis of the V&V activity can be traced to the hazard log. Fig. 3 presents an integrated process involving key deliverables and requirements activities and V&V procedures through safety activities across the system hierarchy of the rolling stock that constitutes the E&M system shown in (b) of Fig. 2.

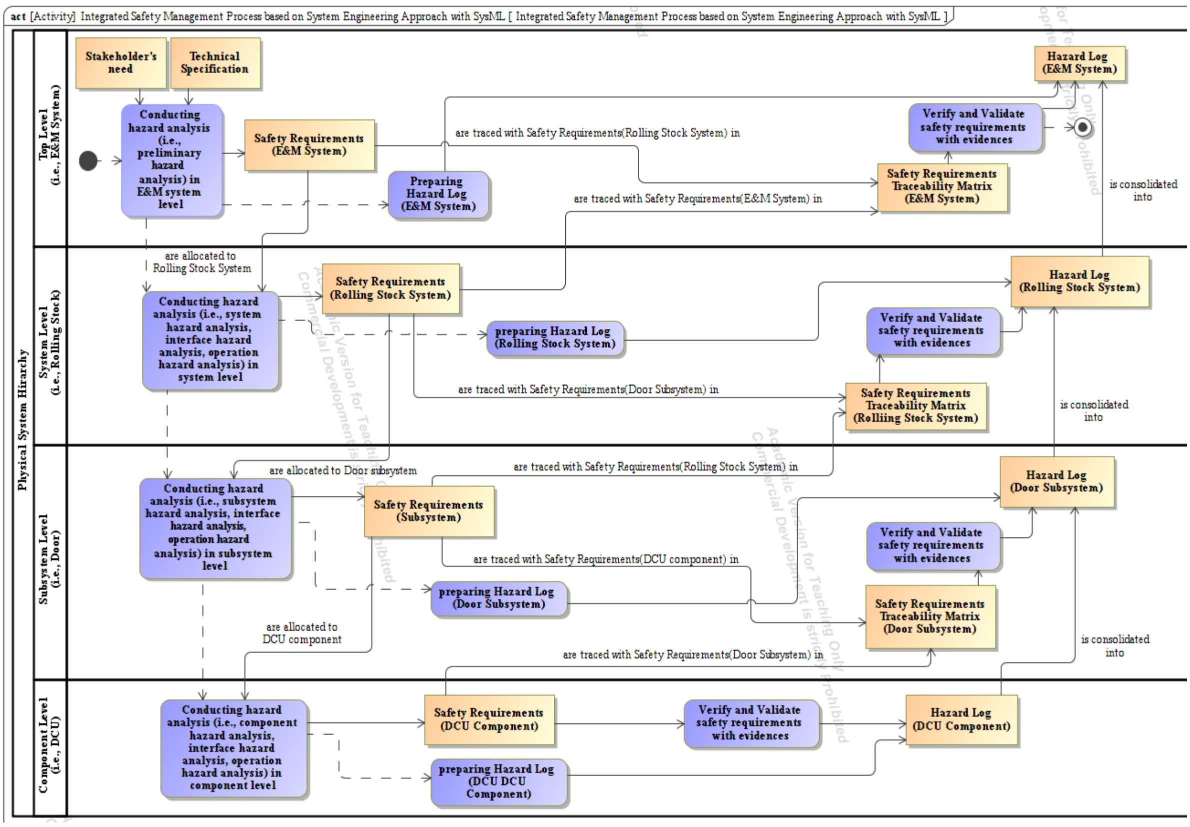

Fig. 3. Integrated safety requirements management process according to system hierarchy structure

5.2. SE-based safety requirement management between E&M system and rolling stock

In this section, based on the process presented in Section 5.1, the appropriateness of the integration process is verified using the safety calculation document applied to the actual railway system project. Emphasis is placed on the management of safety requirements between the E&M system and the rolling stock rather than the content at all levels of the system hierarchy. That is, the E&M system requirements confirm that any requirements have been assigned to the rolling stock by the PHA and that the system design of the requirements has been verified and validated through the safety requirement traceability matrix. It shows how the termination of each V&V item described in the SRTM conforms to the hazard log. Based on this, it is proved that the safety requirements derived from the parent system are reflected in the subsystem design and systematically managed through the final V&V activities. Figs. 4 and 5 show how overall safety requirements are managed for the door unit and the coupler unit constituting the rolling stock, respectively.

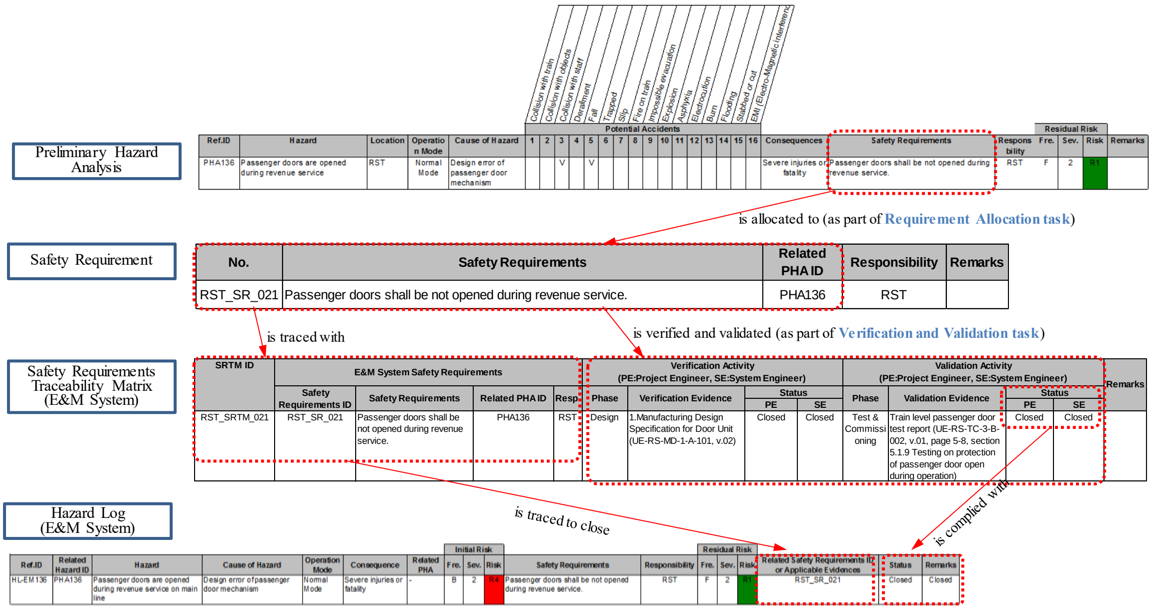

Fig. 4. Overall safety requirements management for E&M system and rolling stock: case of door unit

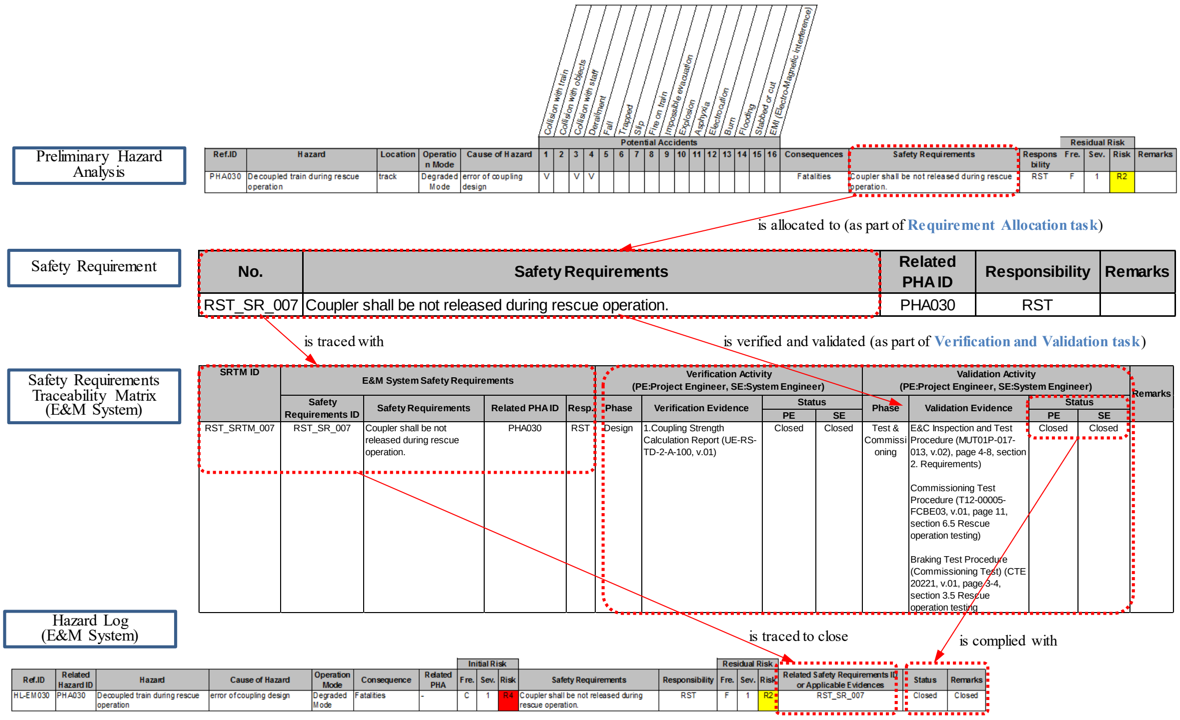

Fig. 5. Overall safety requirements management for E&M system and rolling stock: case of coupler unit

VI. CONCLUSIONS

In this paper, we analyzed SE-related standards and reference documents, as well as SE application cases of railway projects carried out in Korea and abroad. The analysis result has confirmed the concept of SE and the contribution of SE to railway projects and identified the activities to be considered essential for the successful execution of SE. Also, an integration process was presented to provide safety assurance measures by considering SE-based safety requirements management and verified through the actual cases from project implementation. The

results of this study can be useful as primary data for accurate understanding and proper execution of the SE among ordering organization, contractor, subcontractors and suppliers in future railway projects.
For future research, practical effectiveness of the SE application needs to be verified. In doing so, it might be necessary to analyze actual operational data (i.e., failure and safety-related data). Also, an improved SE model is recommended, which is tailored to each project and defines the SE role of each stakeholder.

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REFERENCES

[1] *Systems and Software Engineering - System Life Cycle Processes*, International Organization for Standardization/International Electrotechnical Commission/Institute of Electrical and Electronics Engineers Standard, ISO/IEC/IEEE 15288, 2015.
[2] J.H. Yoon, J.C. Lee, and S.H. Hong, A study on integrated SE process for the development of the railway systems with safety assessment included, *Journal of the Korean Society for Railway, 10* (4), 2007, 438-443.
[3] Korea Railroad Research Institute, *Railway safety systems engineering*, Korea Railroad Research Institute, Tech. Rep., 04 Railway Safety A-01, 2011, 6-9.
[4] C.H. Kim, M.D. Han, and J.H. Lee, A study on the analysis of SE process implementation for the light rail transit project, *Journal of the Korea Society of Systems Engineering, 8* (2), 2012, 1-10.
[5] L. Lee, Y.G. Baek, J.S. Park, B.T. Lee, and J.C. Lee, Review of system engineering - perspectives from railway projects, *Proc. 9th Asia-Pacific Conference on Systems Engineering*, Seoul, Korea, 321-329, 2015.
[6] INCOSE, *System Engineering Handbook - A Guide for System Life Cycle Processes and Activities*, International Council on Systems Engineering, San Diego, CA, 2010.
[7] *Systems Engineering - Application and Management of the Systems Engineering Process*, International Organization for Standardization/International Electrotechnical Commission Standard, ISO/IEC 26702 IEEE 1220, 2007.
[8] Body of Knowledge and Curriculum to Advance Systems Engineering(BKCASE) Editorial Board, *Guide to the Systems Engineering Body of Knowledge (SEBoK), Part 7: SE Implementation Examples, Matrix of Implementation Examples*, SEBoK steward organizations (INCOSE/IEEE/SERC), 2015, 2-5.
[9] Body of Knowledge and Curriculum to Advance Systems Engineering(BKCASE) Editorial Board, *Guide to the Systems Engineering Body of Knowledge (SEBoK), Part 7: SE Implementation Examples, Standard Korean Light Rail Transit System Vignette*, SEBoK steward organizations (INCOSE/IEEE/SERC), 2015, 76-79.
[10] *Programme Management - Guidelines for Project Management Specification*, British Standards Institution Standard, BS EN 9200, 2004.
[11] *Project Management. Principles and Guidelines for the Management of Projects*, British Standards Institution Standard, BS 6079-1, 2010.
[12] A. Kossiakoff, W. N. Sweet, S. J. Seymour, and Biemer S. M., *Systems engineering principles and practice. 2nd ed.* (New Jersey, CA: John Wiley & Sons, Inc., 2011).
[13] The Board of Audit and Inspection of Korea, Audit report on Busan-Kimhae light rapid transit project implementation status, The Board of Audit and Inspection of Korea, Audit Report, 2005, 21-27.
[14] Public and Private Infrastructure Investment Management Center & Hanul Choongjung LLC Member Crowe Horwath International, *Research report on railway Public Private Partnership project activation*, Ministry of Land, Infrastructure and Transport, Korea, Research Report, 11-1613000-000275-01, 2014, 43-114.
[15] Public and Private Infrastructure Investment Management Center, *Feasibility study report for Incheon metro line 2 construction project in 2008*, Korea Development Institute, Korea, Report, 2008, 20-21.
[16] Public and Private Infrastructure Investment Management Center, *Feasibility study report for shinansan line double track railway construction project in 2010*, Korea Development Institute, Korea, Report, 2010, 24-29.
[17] B. J. Elliott, *Benefits of adopting systems engineering approaches in rail projects*, doctoral diss., School of Civil Engineering College of Engineering and Physical Sciences, University of Birmingham, Birmingham, UK, 2014.
[18] International Council on Systems Engineering Transportation Working Group, *Systems engineering in transportation projects - A library of case studies*, Tech. Rep., 2014, 1-41.
[19] U. Hamid, M.K. Raza, and R.F. Naqvi, Impact of system engineering practices on the performance of R&D projects, *International Journal of Computer Theory and Engineering, 5*(1), 2013.
[20] D. K. Hitchins, Systems engineering in search of the elusive optimum, *Engineering Management Journal, 8*(4), 1998, 195-207.
[21] B. Flyvbjerg, Cost overruns and demand shortfalls in urban rail and other infrastructure, *Transportation Planning and Technology, 30*(1), 2007, 9-30, 2007.
[22] D. Hawken, System engineering in DE&S, *IET Seminar on Model Based Systems*, 2007.
[23] J. Allan, S. Burdett, P. Neal, and J. Williams, Introduction of systems engineering and appropriate tools to a mass transit railway project, *Proc. INCOSE International Symposium*, Boston, MA, 1996, 38-45.
[24] J. M. Fraser and A. Gosavi, What is systems engineering?, *Proc. 2010 Annual Conference & Exposition, IE Applications and Systems, Industrial Engineering*, Louisville, Kentucky, 2010, 1-10.

[25] E.C. Honour, *Systems engineering return on investment*, doctoral diss., Defence and Systems Institute School of Electrical and Information Engineering, University of South Australia, 2013.
[26] Public and Private Infrastructure Investment Management Center, *Study on standard guidelines for pre-feasibility study on road and railway projects (5th Edition))*, Korea Development Institute, Korea, Report, 2008, 188.

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