A Systems Assurance Perspective Towards Generic Systems Engineering

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Abstract

A previous paper (ref.1) was published to describe a generic system-of-systems (SoS) requirements model, which was constructed to guide systems engineering process for future Rail Transit Systems (RTS) in Singapore. In that publication, guidelines for detailed analysis of each requirements breakdown in the areas of operational, functional and physical requirements were explained.

This paper elaborates on the systems assurance aspect, as part of the generic systems engineering and generic requirements model to guide the development of non-functional requirements. In particular, management of safety and reliability is explained. The systems assurance process described in this paper is derived from valuable experience gained through management of several highly integrated driverless RTS with different procurement strategies. The new systems engineering process will be cascaded to future transit projects for improvements of requirements management, verification and validation, and optimization of available resources.

Keywords: systems engineering; systems assurance; safety; reliability; reuse; rail transit system.

1. Introduction

In Singapore, several new driverless RTS and extensions of the existing RTS have been constructed and put into operation in recent years. With the successful rollout of the North-East Line and the recent Circle Line stage 1-3, the Government will continue to invest heavily in public transport infrastructure to meet the increasing needs of economic and population growth. The Land Transport Authority (LTA) of Singapore holds the crucial role of ensuring that public transport system delivers these objectives. Based on proven project delivery experience, LTA procures most of the electrical and mechanical (E&M) systems using multiple contracts arrangement. Thus, the Authority has to define requirements across multiple contracts to ensure interface and integration compatibility of the systems. Imperatively, a systematic systems assurance process is needed to ensure the safety and quality of the system for use.
2. Project Safety Review (PSR) Process

The PSR process is defined by LTA as a mandatory framework for systems assurance of all RTS projects in Singapore in order to certify that the system is safe for commencement of passenger services. This safety certification process ensures a staged based check-and-balance on safety assurance of all RTS projects throughout their project development lifecycle (see Figure 1).

![Figure 1 Overview of PSR process](image)

The LTA uses IEC 62278 as a general guideline for Reliability, Availability, Maintainability and Safety (RAMS) management. This standard is also commonly adopted in railway industry as a comprehensive guide for RAMS assurance activities of a typical railway project lifecycle.

3. Problems and Constraints

The PSR process requires safety targets to be set for each project. In addition, it requires demonstration that a robust hazard management system has been established. This is often challenging as we need to have full understanding of the complexity of overall design and inter-systems relationships. A lack of consistent Systems Engineering (S.E.) process to support and guide all engineering activities further complicates the matter.

When managing hazards, it is noted that different projects could identify different hazards when analysing the same system. This could create inconsistencies in system design and operation. On the other hand, different projects may also recommend and adopt different hazard mitigation measures for similar hazards. Such inconsistencies became increasingly challenging for large projects that are constructed in stages e.g. Circle Line was developed in 5-stages. Inevitably, difference in hazards and mitigations would increase the risk in human error. For instance, the same operator could potentially be exposed to the same hazard mitigated using different approaches.
Similarly, inconsistencies in system design and operation would create difficulties for transit regulation.

To accomplish the goals of delivering a successful SoS, an optimum S.E. process is vital. A new concept for system engineering has been developed and described in detail in the previous publication (ref.1), this paper will outline the overall concept and management process and further elaborate the systems assurance approach as part of the generic systems engineering model.

4. **Systems Engineering for Future RTS**

We focus on four key areas where systems thinking and valuable experiences are coalesced to yield the best approach to manage the increasing complexity and expectations of future RTS projects. They are:

- A complete systemic elicitation of RTS source requirements from all possible resources.
- A generic SoS requirements model to capture all SoS design requirements.
- Reuse of a generic SoS requirements model for future projects.
- A learning and adaptable system life cycle with activities that are optimized, cohesive and continuously refined and reused for future changing needs.

Figure 2 illustrates this simple yet challenging concept of continuous refinement and reuse in a driverless RTS operational environment.

5. **Generic SOS Requirements Model**

Generic SoS requirements model is the fundamental entity for incorporating requirements elicitation and continuous requirements refinement and reuse. The entire concept hinges on knowledge preservation and accretion, in full clarity of the decision-making process and history to reach an agreeable design requirement or solution. When conscientiously developed, it may enhance the organisation’s capability to undertake any large-scale SoS challenge and deliver a cost-effective solution in a
shorter time. Indeed, fulfilling this primary objective has been our greatest goal when the concept was initially proposed.

From the RTS source requirements, the generic design requirements are developed using a combination of scenario-based requirements analysis and top-down partitioning methodology. Figure. 3 shows how the generic SoS requirements model takes in the RTS source requirements and translates them into operational, functional and physical design requirements. It is crucial to understand the interdependency of the systems and their relationships to better control and manage the emergent properties. Such information and knowledge is especially important in anticipation for changes to system requirements or design later in the system lifecycle since changes will typically result in alteration to and/or production of new emergent properties.

To some extent, the design requirements may assume some high-level design solutions that need to be confirmed and adapted when the contractors are on-board the project. This design adaptation will take place in the project model, which inherits these design requirements from the generic SoS requirements model. It is important to note that the generic SoS requirements model focuses on what the SoS must do, not on the exact technical details on how it does it. This aspect of the detailed design can only be performed in the project model when the system design specification occurs during the project design phase.

Non-functional requirements (e.g. Safety, Reliability and EMC) are included as part of the SoS requirements analysis. This is to ensure coherence and completeness of the specifications as well as to ensure that requirements analyses are not performed in isolation. This helps to reduce the risk of specifying requirements that may not be verifiable in later stage. Concurrent engineering of non-functional requirements with functional, operational and physical requirements will also facilitate early validation that the set of requirements is complete and correct prior to commencement of system design.

Figure. 3 Relationships among the different models
6. Operational, Functional & Physical Requirements

Typically, a driverless RTS operation can be divided into four distinct operation regions as shown in Figure 4. Each operation region has its own functions to support and maintain uninterrupted train service.

The operational requirements are identified from these operation regions and are further decomposed by the Product Breakdown Structure (PBS) to various scenarios in normal, degraded and emergency modes of operation. These scenarios are further analyzed for detailed operational requirements in a dedicated document called the Operating Modes and Principles Document (OMPD). The OMPD also contains decision flowcharts describing how the Operator will react in a specific scenario and what are the system functions available in different modes of operation. In this way, the OMPD provides a direct link to the functional requirements to ensure consistency with operational needs. Adherence to the PBS will also ensure a top-down design with a bottom-up supply chain that is consistent with the physical requirements.

A set of scenario-based, top-down driven Generic Functional Requirements (GFR) is defined in addition to operational requirements. The functional decomposition is performed from an operation perspective, where the root level of the GFR structure is partitioned by the four typical operation regions. The GFR and its modules will fulfill the corresponding operational requirements identified by the operation regions. Each GFR is derived from in-house studies, past project experiences and external references and are further broken down to GFR modules for allocation to each system provider.

![OCC Operation (FO-0), Depot Operation (FD-0), Train Operation (FT-0), Station/Trackside Operation (FS-0)](image)

Figure 4 Basic GFR structure

An example of GFR structure and the derived requirements is shown in Appendix Figure. A-2. Each function is assigned an ‘F’ prefix to denote a function, followed by a letter to denote the operation region e.g. ‘T’ for train operation. Therefore, ‘FT-0’ denotes the root function for train operation.
Concurrently, physical requirements are systematically organized by the PBS, which provides the whole system breakdown to individual systems and their equipment. The purpose is to identify all physical requirements and their interfaces with users, environment, technology, etc. The starting point for the PBS comes from the contract requirements for all systems, which are in-line with the RTS source requirements. The PBS is used to guide the development of the system architecture tree, interface matrix and the functional dataflow diagrams. A high-level representation of a typical RTS system architecture is shown in Appendix Figure. A-1. This will be further developed into a detailed system architecture document during the design phase of the project model when the contractors are on-board the project.

The next step is to construct the interface matrix which is used for the identification of interface relationships among the different systems. Appendix Figure. A-3 shows an example of the interface matrix which identifies the lead and supporting contractors, so as to facilitate clear definition the roles and responsibilities during interface design and testing. The lead contractor is responsible for leading the entire interface design, documentation, off-site and on-site test activities relating to the interface. The supporting contractor is responsible to provide system design and support to ensure that these activities are correctly performed.

To ensure a seamless functional interface, a functional dataflow diagram is used to represent graphically how information flows from one system to another (see Figure. 5). It is also useful for identifying the high-level interface requirements to meet the functional requirements. The functional dataflow diagrams will be captured in the interface control documents (ICD) where the detailed functional interface requirements are developed.

![Figure. 5 Functional Dataflow Diagram](image)

7. Non-Functional Requirements

Previous sections explained the approach to engineering requirements for system behaviours i.e. operational, functional and physical requirements. However, this set of requirements will not be complete without any goals set on the system behaviours. Goals or constraints on the system behaviours are also known as non-functional requirements. In essence, non-functional requirements are specified to control quality of the system in operation. In order to ensure coherence and completeness of the SoS requirements, a fundamental principle of the generic SoS requirements model is that
non-functional requirements are included in the SoS requirements analysis. This also prevents the requirements from being derived in isolation, hence easing verification and validation. As part of project RAMS management, RAMS analysis and safety requirements management is a continual and iterative process throughout the system life cycle.

7.1 Safety Requirements Management

One of the key requirements to be validated for system acceptance is that all safety risks of the system are reduced to a level acceptable by the Safety Authority. Each safety risk is measureable qualitatively and quantitatively.

Standards such as IEC 62278 are commonly used to guide implementation of control on qualitative safety risk in the system development lifecycle. In addition, specific industry best practices such as Railway Safety Principles in UK (also known as the ‘Blue Book’) could also be applied. With the well-defined guidelines and requirements in applied standards and best practices, qualitative safety risk can be managed by systematically applying the appropriate references, as well as regular monitoring and control on the implementation.

Quantitative safety risk, on the other hand is measured based on probabilistic risk assessment on the system. Hazard analysis is one of the key methods to aid identification of quantitative safety risks. Consequently, hazard management process needs to be established to facilitate elimination or reduction of exposed risk in the system so as to ensure that the system can be accepted for operation. Based on experience, complexity of hazard management increases with increasing number of interfaces due to procurement strategy and product breakdown. The potential challenges for hazard management in a highly integrated driverless RTS project therefore necessitates a more robust hazard management process to ensure allocation of hazard management responsibilities, while maintaining overall monitoring and control.

The requirements-based hazard management process is introduced as part of the generic S.E. process and requirements model. One of the key objectives of a requirement-based hazard management is to formalize the distribution and control of hazard resolutions to the respective hazard owners. In addition, this process aims to streamline available resources and efforts for verification and validation (V&V).

As early as the concept phase, potential hazards in the system are identified and analyzed through various sources (e.g. project experiences, international standards as well as specific safety studies). Appendix Figure A-5 shows a screen capture of some of the hazards identified in hazard log. In order to control the number of hazards and efficiency of hazard verification and validation, each hazard resolution identified, is in turn, used to develop a list of safety requirements by further reviews and refinements. Typical Requirements Engineering (R.E.) principles apply to the development of safety requirements, which are subsequently allocated to the primary actionees, or requirements owners. It is important that newly identified hazards and hazard resolutions are verified to be unique before adding to the existing project database to reduce repetition and inconsistency of requirements.

Introduction of requirements-based hazard management aims to minimize ambiguity and hence improves the usage and effectiveness of resources. Safety requirements are verified to be correct by tracing to specific system requirements and design. When the system design specifications are tested, the SoS requirements model ensures that the safety aspect will be
validated as well. This inevitably increases the effectiveness of test as well as provides evidence for hazard closure in a timely manner.

7.2 Reliability, Availability and Maintainability Requirements

While PBS provides the system breakdown to identify subsystems and equipment, RAM models are developed to identify every Line Replaceable Units (LRU). Reliability block diagrams are typical tools used to aid derivation of RAM requirements as well as verification of design.

From project experience, the elements and properties (e.g. hierarchical position) defined by RAM models and PBS are not always consistent despite the fact that both are used to describe the same system. Often, inconsistencies arise and increase following iterative development of each model in parallel. The problem is further aggravated since development and management of both models are usually carried out by different teams. While PBS defines the procurement strategy, RAM model specifies decisions for system acceptance. Undoubtedly, consistency between both models is important for systems engineering. The Generic SoS Requirements Model is developed to address this need by defining concurrent development of RAM model with physical modeling such that the performance requirements are derived and traced using the same PBS hierarchy. The development approach is further enforced by developing the programme plan of RAM activities to execute in parallel with other related systems engineering activities as shown in Appendix Figure A-4.

This programme plan is developed to address the need that each non-functional requirement is to be traceable to the implementing function and physical module. This inherently facilitates verification between RAM model and PBS to ensure their consistency.

8. Implementation using DOORS

The generic SoS requirements model and project models are stored and managed in-house using IBM Rational DOORS requirements management tool. This ensures all requirements defined in the initial stage of the project are explicitly traced and satisfied by the system design. The system design is then tested and verified to fulfill the RTS source requirements.

Since the generic SoS requirements model serves as a design reference for all future projects, it must be well documented to capture all the existing and new requirements. To achieve this, the following documents are maintained in DOORS:

- Design Criteria and Performance Specifications (DCPS).
- Operational concept requirements.
- OMPD.
- Functional requirements (GFR model).
- Functional requirements breakdown and allocation (GFR modules).
- Non-functional requirements (RAMS, EMC etc)
- Functional dataflow diagrams.
- Product breakdown structure.
- System architecture.
- Interface matrix.
As part of the new hazard management strategy, hazard log and safety requirements are also an integral part of the requirements reviews process in the generic SoS requirements model. The relationships among the different documents are shown in the DOORS schema in Appendix Figure A-6. In essence, measures to address the hazards are traceable to the design as the system requirements are developed for verification. Thereafter, safety validation test will be integrated as part of other system tests (e.g. type tests, integrated tests etc).

When setting up the requirements model in DOORS, some areas to be considered for implementation and management are:

a. All requirements are traceable to its source, implementation, verification and validation test results;

b. All requirements are clearly identifiable as generic requirements or project specific requirements. In addition, there must be clear indicator for items that have been baselined.

c. Editorial rights for all requirements e.g. reviewer, editor must be integrated as part of the change management process

9. Integration, Verification and Validation

A comprehensive integration, verification and validation process is crucial to ensure successful delivery of the stakeholders and users’ requirements. The progressive integration, verification and validation of the various systems are performed bottom-up, in a logical sequence from off-site to on-site testing. Appendix Figure A-7 shows the high-level S.E. process for a RTS project in a typical V-cycle approach. Systems assurance is an integral part of the overall S.E process. From the S.E. perspective, all V&V test activities, including V&V for non-functional requirements, are traceable to the design requirements through the following categories of tests recorded in the SoS test programme:

- Type tests
- Routine tests
- Interface tests (e.g. point-to-point tests)
- Functional tests
- Specific tests (e.g. Safety, EMC, RAM, etc.)
- Operational tests
- Performance tests
- Carousel tests (e.g. train wakeup, carousel run, etc.)
- Acceptance tests
- Trial run (after handover to Operator)
- Reliability, Availability and Maintainability Demonstration Tests (RAMDT)

The test breakdowns, pre-requisites and test phases where they take place are all recorded in the SoS test programme. The SoS test programme also ensures all off-site and on-site test activities are complete, correctly sequenced and traceable to design and test requirements in the project model. The same traceability process applies to the test procedures and reports generated from these test activities.

Based on experience, off-site integrated testing is found to be useful as a means to advance the
demonstration of operating principles and to validate the SoS design in terms of performance and safety in advance of site testing. This helps to reduce the risk at on-site integrated testing is shown in Appendix Figure A-8, where each progressive integration and testing leads to the next higher-level verification and validation of the SoS requirements.

By implementing the generic S.E process, it ensures a seamless integration of systems assurance related V&V activities into the whole system V&V programme. This inevitably helps to ensure a more lean verification and validation process and program. In addition, it also reduces the risk of re-evaluating tried-and-tested system design to address specific test case or condition required to satisfy the non-functional aspect.

10. Continuous Process Refinement

To realise the goal of building better and more robust SoS, the generic SoS requirements model is regularly reviewed, enhanced and updated. This process of iteration and learning will account for new stakeholders’ requirements, design initiatives for new technologies, lessons learned from past projects, process and design improvements due to better understanding of emergent properties, as well as a new safety risk identified due to changes in the system and its environment. New projects will benefit from an up-to-date SoS design requirements which will lead to improved understanding and interactions among stakeholders, in-house designers, contractors and operators in the early phase of the project.

11. Potential Benefits

With increasing project cost and complexity, there is an impelling force for systems engineering process to be established in railway industry. Even at the early stage of implementation, the generic model and processes developed had revealed potential benefits as follows:

a. Assure compatibility of systems specifications and development – Systematic decomposition of the systems and interfaces as well as performance specifications using the GFR model had facilitated progressive verification and validation and early rectification of any potential problems for the integrated system. This inevitably reduces the risk of project failure;

b. Reuse of information – Use of a centralized requirements management and storage tool had facilitated traceability and reuse of information for current as well as future projects;

c. Promote S.E. in railway industry - The continual development and refinement of the process had facilitated learning and the use of S.E. principles and processes in ongoing project work. With our specification of S.E. requirements for all our new RTS projects, it should systematically steer our contractors and consultants towards appreciation and use of S.E. process as well.

Actual project cost savings can only be determined at later stage. However, early benefits had evidently outweighed the current costs and motivated the team to continue
the research and development of this work for railway applications in Singapore and overseas consultancy projects undertaken by LTA’s subsidiary, MSI Global.

12. Challenges and Uncertainties

There are numerous challenges and uncertainties associated with every new process initiation. Some of the issues were clear to us at the beginning but others surfaced only during implementation. The first challenge is the grueling effort to consolidate all RTS source requirements from all possible resources. Regular updates and reviews are also required to ensure all parties agree with the source requirements. New lessons learned from past and on-going projects are also an important source of enhancement to improve user visibility and risk management.

When the source requirements are consolidated, there is a need to go through extensive design reviews and tap on valuable experiences to select the best solution to fulfill these requirements. Due to its wide-ranging operational impacts, to reach an agreement among stakeholders, in-house designers, contractors and operators on critical SoS design issues is extensively time-consuming.

Another area of difficulty lies with new or non-existing requirements, which are harder to analyse compared to those tried-and-tested ones. Such requirements demand more attention since the extent of the design effort to meet the users’ needs may not be fully understood. Design iteration with the participation of all concerned parties will serve to minimise any misinterpretation and oversight on the part of the design team.

Some of the contractors’ system constraints are also areas that require more attention. The contractors’ system constraints are usually unknown at the start of the project and they may introduce design uncertainties when developing the project model. At the beginning, the project model should not contain too many details to avoid major design changes that have a destabilising effect. Design adjustments will be catered during the design phase to allow flexibility for such changes when the contractors are on-board the project.

To integrate the entire effort, teamwork, communication and commitment are essential ingredients for a successful implementation. All parties should agree to implement the process and work towards achieving the design objectives for the project. Close partnership and cooperation from the authority and contractors’ system managers are also vital throughout the project life cycle to ensure these design objectives are successfully implemented and tested for the project.

13. Conclusion

To successfully deliver a SoS that is built upon continuous design improvement and reuse can be a cost-effective solution to counter the escalating high-cost and the inherent system complexities that plagued many large-scale SoS developments today. With increasing high demands placed on our public transport system, delivering a robust and efficient RTS within project budget and schedule is a major challenge that requires a different engineering mindset to optimize the best S.E. practice available. A generic, adaptable approach to S.E. described in this paper is a practical process to realize that goal, at the same time, it is constantly improved to accomplish any new mission objectives for future large-scale RTS projects.
NOTE These two interfaces are not shown in the diagram:
1. LV to provide power for all station and depot equipment if required.
2. LV to provide UPS for SIG, ISCS, MMS, Comms, AMS, TV-ECS, FPS.

Figure. A-1 RTS system architecture
Figure. A-2 Generic Functional Requirements (GFR) structure
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Figure. A-3 Interface matrix
Figure. A-4 RAM Programme Plan
Figure. A-5 Hazard Log in IBM Rational DOORS
Figure. A-6 DOORS S.E. Schema
Figure. A-7 Typical S.E. process flowchart
Figure. A-8 Overall T&C approach
References


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