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Model-Based Systems Engineering for complex rail transport systems – A case study

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Abstract. The replacement of the signalling and control systems on Sydney's critical heavy-rail network infrastructure is envisaged to take years and affect many systems across the operational railway. Systems Engineering has been adopted early in the system lifecycle to manage the complexity and risks in a rigorous and consistent manner. This paper aims to document the real-life application of a Model-Based Systems Engineering (MBSE) methodology in the conceptual design stage on Transport for New South Wales' Digital Systems Program. It illustrates how this methodology was applied to capture the operational and maintenance concepts, derive the architecture and interfaces and guide resulting requirements. It provides valuable lessons-learnt for the acquiring organisation on the deployment of MBSE, its benefits and lessons learnt.

Introduction

Complexity in Rail

Modern railways are large System of Systems, comprised of several independent and geographically dispersed constituent systems (Maier 1998), where interactions are complex and prone to system level failures affecting large portions of the network. With increasing demand due to population growth, the Sydney railway infrastructure is reaching the capability limit of the employed technology, necessitating changes to increase capacity (Transport for NSW 2012). The application of digital technology promises to improve capacity, reliability and limit the effect of failures (Royal Academy of Engineering 2016) on Sydney's railway.

Traditional project delivery in the railways relies on Subject Matter Experts (SME) and their knowledge of existing systems and processes. Conventional signalling and train control projects are well understood, typically with known interfaces and processes across boundaries. This has enabled rail signalling engineers to design and deliver systems and processes with limited involvement from other disciplines.

The evolution of signalling and train control technologies has shifted the control of railway operations from trackside infrastructure to centralised control centres and the onboard train systems. These technologies are typically complex software-intensive systems with heavy reliance on telecommunications. This transformation mandates a re-think of the traditional operations and maintenance practices as well as project delivery to realise the full benefit that these technologies have to offer for the efficiency of the railway (Roodt, Nadeem & Vu 2020).

Furthermore, brownfield projects, which require construction within or alongside operating infrastructure, imposes additional complexity and constraints requiring significant additional design, construction and management resources (Australasian Railway Association 2016).

The problem can be described from several perspectives, each important to the outcome:

User perspective. The system users include the operators and maintainers of the rail network. For an existing network, users have often already developed a highly coordinated set of systems and processes over many years, to manage the network and provide a service to passengers each day. When implementing new technologies, any changes to these systems and processes, need to be carefully considered and phased into operation. As the end-user, any change will likely impact them significantly so an informed decision-making process is crucial, where traceability and rationale of trade-offs must be captured.

Acquirer perspective. The system acquirer is responsible for procuring the services and products to meet the program's Business Requirements. The acquirer needs to demonstrate sound governance with risk mitigation to the project sponsors and general public.

Supplier perspective. On large-scale projects, the solution is delivered by several consultants and suppliers. It is crucial that the solution is well integrated with legacy infrastructure as well as operations and maintenance processes. The set of requirements developed for the subsystems needs to be aligned with functions and overall system concept, but still allow the supply of configured Commercial off-the-shelf (COTS) products as far as reasonably possible.

A Systems Engineering approach is used to address this problem of complexity in rail.

Systems Engineering

Systems Engineering manages complexity and risks in a rigorous and structured manner throughout the project and system realisation lifecycle. It is an interdisciplinary approach that enables the realisation of successful systems and is based on systems thinking which focusses on understanding the system as a whole and the interrelationships of the systems elements to the whole (INCOSE 2015).

The Model-Based Systems Engineering (MBSE) practice uses tools to enhance the systems engineering effort for system requirements, design, analysis, verification, and validation activities. It provides improvements in system requirements, architecture and design quality with increased productivity through reuse of artefacts and improved communications among the development team (INCOSE 2015). MBSE captures information in a structured and relational database that can be visualised, unlike unstructured text-based documents or requirements management tools.

Systems Engineering, enhanced with the application of MBSE, is well placed to support complex rail projects achieve their outcomes.

Digital Systems Program

Transport for New South Wales' (TfNSW) Digital Systems Program (DSP) will transform Sydney's rail network to create high capacity turn up and go services to meet growing demand. It will replace legacy signalling and train control technologies, based on 1980s and earlier computer-based interlocking, with European Train Control System (ETCS), Traffic Management System (TMS) and Automatic Train Operation (ATO). The replacement of the heart of the signalling and control systems of the heavy-rail network is envisaged to take years and affect many systems across the operational railway. The DSP is a large, complex, brownfield program.

Key principals driving the project include an "integrated and collaborative approach", "whole of life thinking" and "configure not customise" as shown in **Figure 1**.

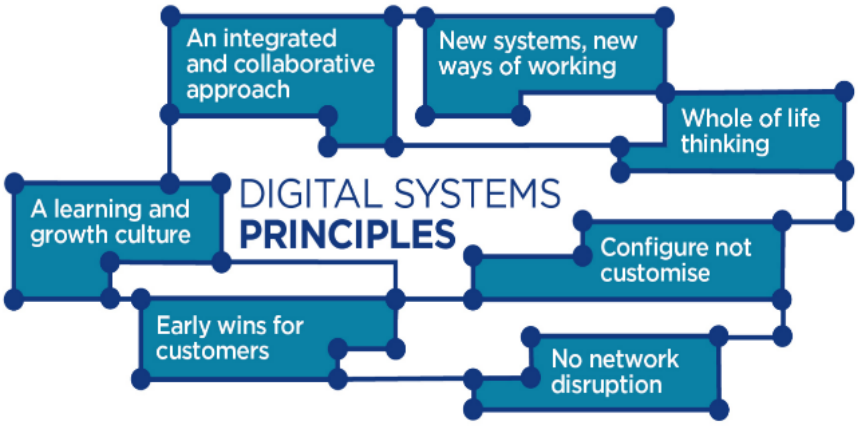

Figure 1: Digital Systems Principals

TfNSW, the system acquirer responsible for the project, planned to engage: a systems integrator; several suppliers to provide the major subsystems; and railway operators and maintainers representatives. Once suppliers for the major subsystems are contracted, the preliminary design will commence further refining the concept and specifications through a formal change control process. Implementation of the new signalling and control system will be via a phased approach.

The MBSE approach was introduced to the DSP after the Business Case and project business requirements had been agreed. These specified ETCS Level 2, TMS and ATO as key deliverables. The Business Case technology decisions were guided by: the TfNSW rail systems strategy adopting the deployment of ETCS on the TfNSW metropolitan passenger heavy rail network (TfNSW Asset Standards Authority 2017); and the implementation of ATO to provide reduced and consistent journey times and TMS to recover from disruptions quickly (Transport for NSW 2020) to meet the Future Transport Strategy 2056 vision of increasing capacity and delivering more reliable services (NSW Government 2016).

At the time of writing, the DSP is completing its conceptual design stage. This paper reports on the tailored application of MBSE on the DSP as a case study. It demonstrates the benefits of this approach for the program and can serve as an exemplar for critical rail infrastructure projects globally.

Approach

Often projects are focussed on the delivery of the solution system, whether software and/or hardware; however, this system needs to be considered in its operating context. This holistic view ensures seamless integration and migration from project to operation.

The solution system that the DSP will introduce to the railway network would therefore also need to consider operations and maintenance, and how these capabilities form part of the greater business environment as visualised in **Figure 2**.

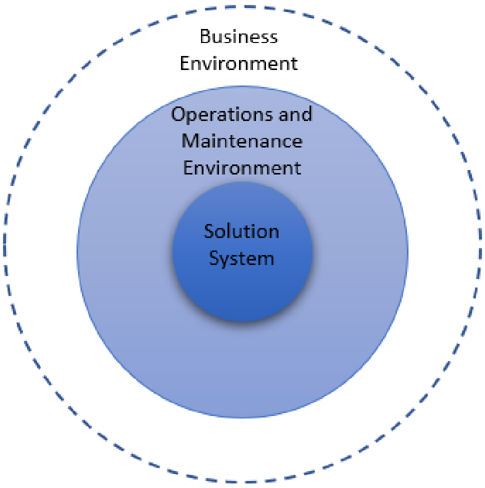

Figure 2: System context and environment

Technical solution systems, operations and maintenance are often well understood, but by different groups of SMEs. The Operations Concept Definition (OCD) and Maintenance Concept Definition (MCD) is an effective way of creating a common understanding between these groups by describing what the to-be-delivered system will do and why, from a user's viewpoint (INCOSE 2015). This aids in bridging the understanding between technical and operations.

Informed by the OCD and MCD, the acquirer produces system and subsystem requirements for several suppliers, such as the TMS, Trackside and Onboard subsystems, in a consistent manner to achieve an integrated, operational system.

Both functional and non-functional requirements are captured to describe the solution system that is needed to satisfy the project business requirements (stakeholder needs) and is written from a technical viewpoint. Requirements Management tools, when well structured, are effective in capturing and communicating requirements between acquirers and suppliers.

It is therefore important that technical requirements correctly and completely deliver the operational outcomes envisaged by the OCD and MCD within the constraints of the available technology. MBSE provides a rigorous and effective linkage mechanism and has been applied on the DSP to manage complexity and support key decision-making through the system life cycle.

Any changes in stakeholder viewpoints, project interdependencies and constraints are traceable, and the impacts of the changes can be quickly and effectively assessed to support the decision process. This is analogous to pulling one string in a spider's web and following the path of effect through attached strings. This enables a common, current and consistent information repository and is achieved using an architectural framework.

This approach allows acquiring organisations to understand and demonstrate how proven systems engineering methodologies can be translatable and implementable in the transport context to achieve the benefits observed in other domains, such as in Defence, Aerospace and Automotive.

Framework and Model

The definition of the linkage between the operations viewpoints and the technical viewpoints is captured and applied using an architectural framework. The framework captures, in a model, complex viewpoints relating people, process and technology into one comprehensible whole. Model outputs are tailored based on purpose and target audience, which varies from technical artefacts for supplier engagement to rich visualisations of program concepts for operations.

The framework used is derived from the Whole-of-System Analytical Framework (WSAF) (Power, Jeffrey & Robinson 2018) and influenced by recognised architectural frameworks such as the Department of Defense Architectural Framework (US DoD 2020). It was selected because functional and non-functional requirements are demonstrably traceable to user classes, the functions performed by the user class that generates the requirements, and the context in which the requirement occurs (Logan & Harvey 2010).

The framework metamodel, shown in **Figure 3**, has been simplified for readability. Classes are depicted as blocks and relationships as the labelled lines between the classes. All relationships are bidirectional and are read as follows (example): Existing Function is *allocated to* an Existing System Component. Conversely, an Existing System Component *performs* an Existing Function. Classes have been grouped logically. Several classes include decomposition relationships (not shown).

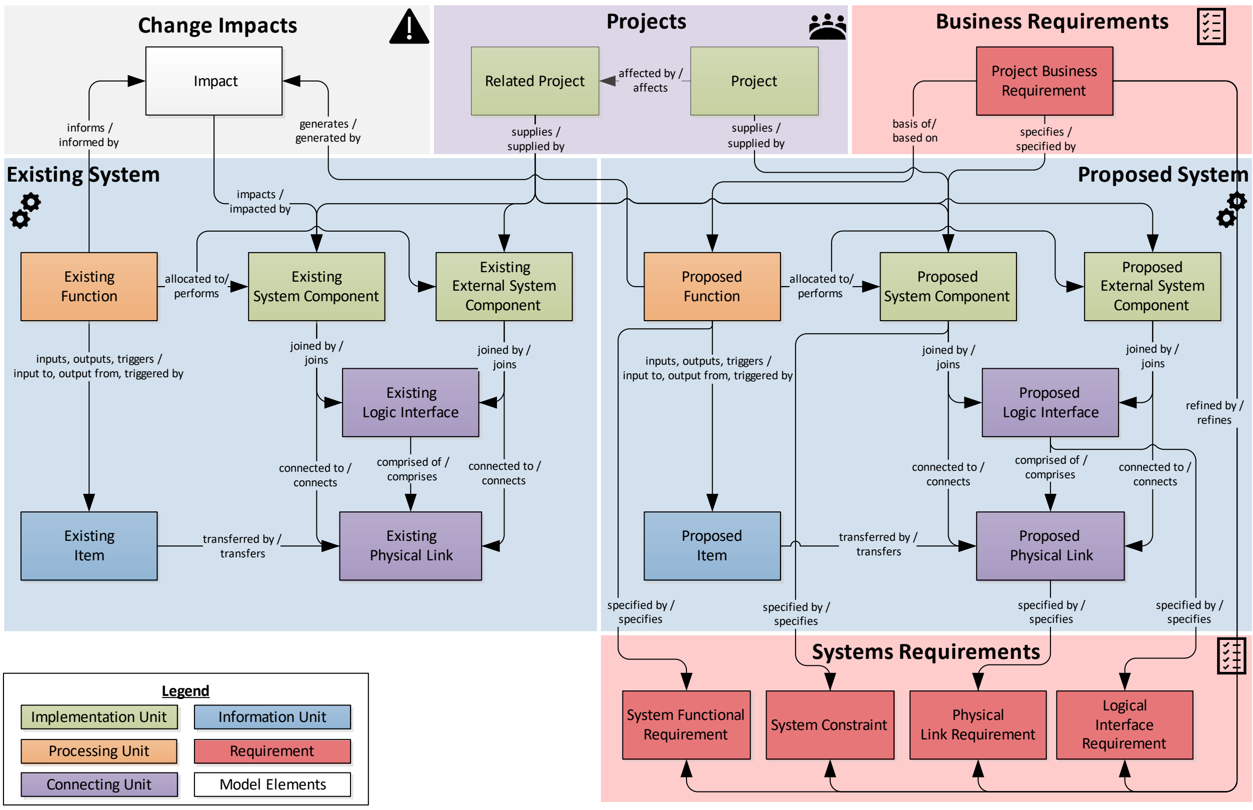

Figure 3. Subset of the systems metamodel

Broadly, the flow of information starts with Business Requirements leading to Proposed System and Existing System analysis, which in turn lead to System Requirements. Differences between Proposed and Existing Systems are captured in Change Impacts.

A Digital Systems Model (DSM) was generated based on this framework, using the Vitech GENESYS (Vitech 2019b) MBSE software tool, and populated with DSP relevant data. Requirements are managed in a dedicated requirements management tool, IBM DOORS Next Generation (IBM 2020), with traceability between elements of each database. The GENESYS base schema and methodology (Vitech 2016) was largely used, with specific updates made for Change Impacts.

Process

The iterative concept design life cycle (Aluwihare, Waite & French 2014), shown in **Figure 4**, guided the generation of the DSM.

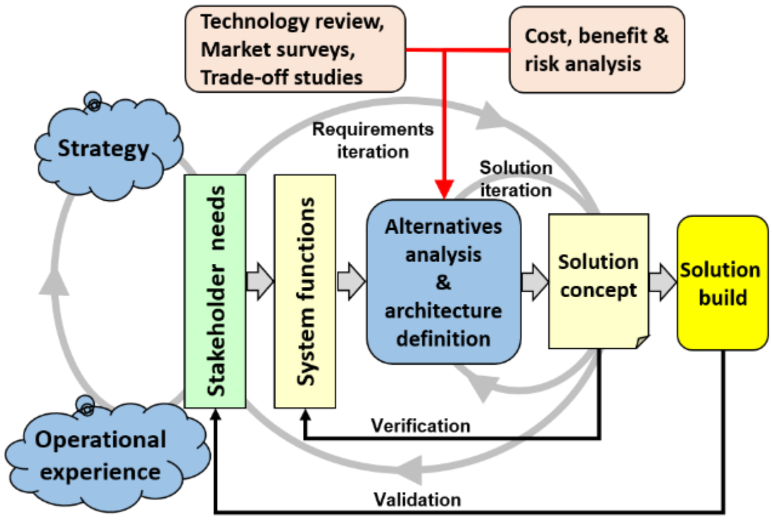

Figure 4: Concept design life cycle

This process facilitates the elicitation of operational and other stakeholder needs, determines what must be done to meet these needs and identifies the critical issues and key effectiveness measures in doing so.

The traceable, iterative nature of this process supports consideration of costs, benefits and risks as part of systems definition and subsequent alternatives analysis. A model-based approach to design provides robust strategy-to-concepts-to-requirements traceability.

This delivers a range of benefits including rapid design iteration, evidence-based design decision-making, change impact assessment, traceability to contract specification, baseline management throughout the lifecycle, reduced integration risk, traceable requirements verification and validation, and efficiency through model reuse.

The operational needs are captured by the project business requirements. System functions were defined during the capturing of conceptual scenarios. Options analysis and architecture definition was then explored through the architecture analysis process and system solution options defined through requirements allocation. Each of these processes are described in the following paragraphs.

Given that the DSP is a brownfield project, with technology constraints imposed in the project business requirements, a middle-out approach was applied. The iterative nature of the process coupled with well-defined framework (**Figure 3**), enabled the incremental development of the DSM.

Conceptual Scenarios were used to capture the behaviour (process) relating to people and technology. "A scenario is a step-by-step description of how the proposed system should operate and interact with its users and its external interfaces under a given set of circumstances (context) …ties together all the parts of the system, the users and other entities by describing how they interact… into a comprehensible whole" (IEEE 1998).

Enhanced Functional Flow Block Diagrams (EFFBD) were used to visualise various scenarios. "EFFBDs unambiguously represent the flow of control through sequencing of functions and constructs as well as the data interactions overlaid to present a more complete picture…(and) also display resources - the third critical aspect of executable behaviour" (Vitech 2019a).

An example of a scenario EFFBD is provided in **Figure 5** modelled on the ERTMS/ETCS standard (UNISIG 2014). This scenario describes the generic process of setting routes and providing Movement Authorities (MA) to drivers.

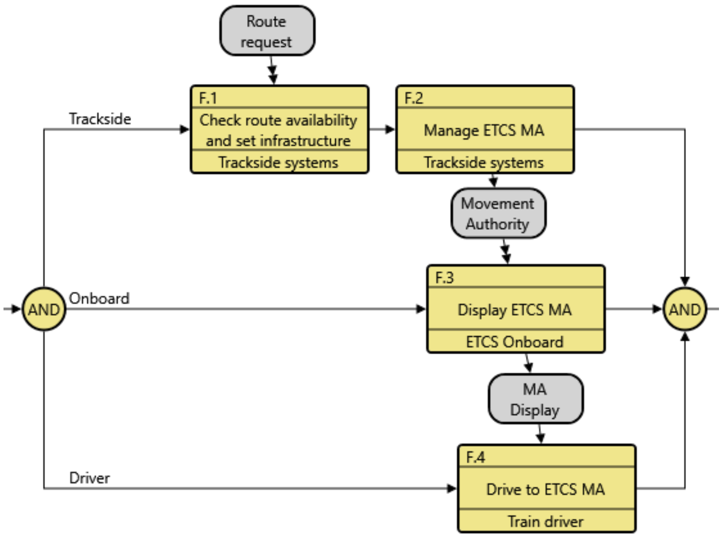

Figure 5. Example of a scenario EFFBD

From **Figure 3**, EFFBDs therefore visualise the Functions, Components, Items and their relationships for both the Existing System and Proposed System, which include the System of Interest (SoI) and external system components. The SoI was decomposed and modelled to subsystem level components as *specified by* the Project Business Requirements, which intentionally constrained the solution. This provided the necessary understanding of behaviour between external and internal system components, as well as, between internal system components.

The scenarios modelled normal, degraded and emergency modes and teased out functions and systems pertaining to each. Each scenario is *based on* one or more project business requirements to ensure the validity of the scenario is within the scope of the project.

The scope of the project was focused on the systems that support the day-of-operations. Therefore, the scenarios were broken down into four main perspectives namely: managing operations, running trains, managing work on track (operational scenarios), and maintain assets (maintenance scenarios) as shown in **Figure 6**.

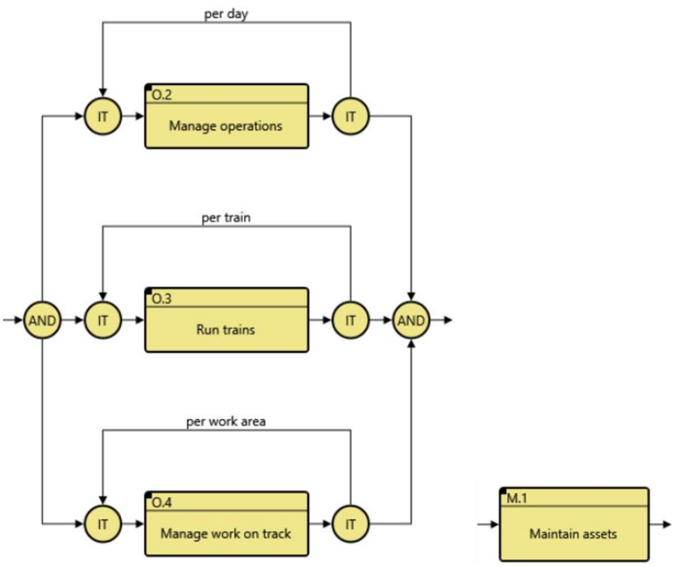

Figure 6. High-level set of operational and maintenance scenarios

Current state scenarios captured the starting state of the system prior to the project implementation. The functional allocation to components were selected to align with the same level modelled in the proposed state. Current state scenarios were found to be easily reviewed by end-users and yielded insights into how the people, processes and systems currently operate, and highlight shortfalls.

Proposed state scenarios is defined as a combination of interim and end-state scenarios. An interim state is defined as a unique selection of components at one or more points in time to enable a phased approach to the rollout of the system across the network. The interim state typically includes legacy system and interfaces. The end-state is the completed project.

Traditional unstructured text or raster-diagram based scenario descriptions do not adequately capture functionality, performers and interactions in a structured way often making the translation into technical requirements difficult, subjective and incomplete. This increases the risk of misalignment between the operations and technical stakeholders.

Modelled scenarios implicitly structures the data and challenges the scenario developer to achieve agreement between operations, technical and other stakeholders, as well as adequately capture the information for architectural analysis.

Architecture analysis was performed to derive the functional and physical architecture of the system, and the corresponding logical and physical interfaces. This process translates the operational view of the DSP into a technical view to which technical requirements could be structured and written.

System components are identified through the allocation of functions. From the scenario in **Figure 5**, examples of system components may be Trackside systems (technology) and Train drivers (people). By deciding which identified components formed part of, or not part of, the DSP scope the functional and physical boundaries for DSP could be agreed. This enabled the rationalisation of the components and functionality to only those required by DSP.

Logical interfaces, the logical connections between system components, are then derived from scenarios by identifying the transferring item (“Movement Authority”) between functions allocated to components as shown in **Figure 7**.

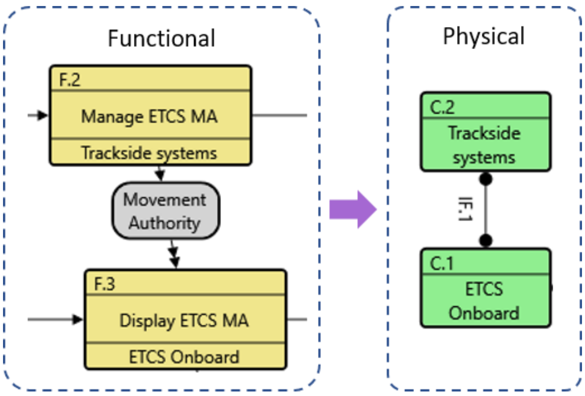

Figure 7. Example of the derivation of a logical interface from an EFFBD

Given a complete set of scenarios, system interface and physical block diagrams for the current, interim and future states could then be rendered. An example of a system interface block diagram derived from the scenario in **Figure 5** is provided in **Figure 8**.

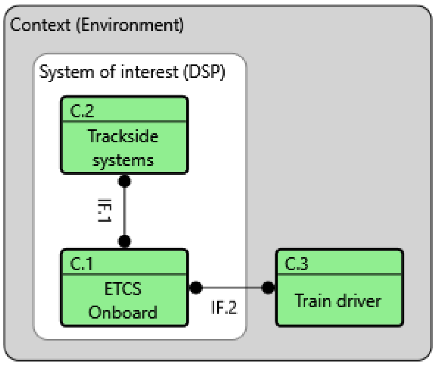

Figure 8. Example of system interface block diagram

Analysis of the scenarios provide Logical Interfaces. As interface requirements were specified, several interfaces were further decomposed, or *comprised of*, Physical Links, shown in the metamodel **Figure 3**. Components decomposition created the distinction between SoI and context components.

In **Figure 8**, IF.1 is an example of a logical interface between subsystems of the SoI. If required, it can be decomposed by three physical Links as defined by the ERTMS/ETCS standard (SUBSET-037) namely: [1] ETCS Onboard to GSM-R Mobile, [2] GSM-R Mobile to GSM-R fixed network, and to [3] GSM-R fixed network to ETCS Trackside (UNISIG 2014). IF.2 is an example of an external logical interface. Both internal and external interfaces were defined in the DSM.

Through this rigorous analysis process, several additional interfacing system elements and their functions were identified, which may have otherwise been missed and likely resulted in significant cost and schedule impacts at a later stage. MBSE greatly enhanced this process by providing the single source of information that dynamically linked conceptual scenarios to architecture, and which were computationally analysed for gaps and inconsistencies. As a result, the DSM became the primary source of interface identification on DSP.

With the set of DSP functions, components and interfaces defined, the requirements for various subsystem suppliers could then be specified.

Requirements allocation. A pool of requirements was initially developed and/or obtained for each subsystem. Functional requirements for each subsystem was then related to the appropriate function performed by that subsystem. The set of functions and functional requirements that could not be related were interrogated resulting in either an update in scenarios or an amendment or deletion in requirements.

The types of requirements that were related, as shown in **Figure 3**, are:

- System functional requirements, specifying the functions performed by each component forming part of the SoI;
- Interface requirements specifying the logical and physical interfaces that have been related to the relevant Interfaces and Links pertaining to machine to machine interfaces;
- User interaction requirements specifying the logical and physical interfaces have been related to the relevant Interfaces and Links pertaining to user to machine interfaces; and
- Non-functional (constraint) requirements specifying subsystem Components.

The process of requirements allocation supported the production of a structured, comprehensive and consistent set of requirements, covering functionality suited to software-intensive systems and its multitude of interfaces, all of which were grounded in the operational concept.

Relating functions and interfaces to requirements spurred several discussions to the applicability and level of requirements needed for the DSP and uncovered potential gaps in concept coverage. This improved the quality of both the concept scenarios and technical requirements, in terms of consistency, completeness and through the capturing of decision-making rationale.

A process of publishing data from the MBSE tool to requirements management tool was developed to explicitly relate requirements elements to Functions, Components, Interfaces and Links as shown in **Figure 3**.

Configuration management. Formal configuration management is applied across all artefacts used on the DSP to ensure any local changes are considered holistically. The DSM is extensively used to trace the impact of design changes. For example, if a functional requirement change is requested, the impact assessment would require tracing from the requirement entity to its related function, its allocated component, derived interfaces and potentially further up to the related project business requirement.

The inherent traceability in the DSM has significantly increased the efficiency of change assessment and update for the DSP, and continued consistency of system artefacts. SME time required to analyse and apply changes is reduced by the DSM. Moreover, SME decision rationale is captured in the DSM for analysis by a potentially different set of SMEs at a later stage. This increase in efficiency and persistence of decision rationale will continue to pay dividends as the DSP progresses through subsequent phases in its system lifecycle.

Related project analysis. The solution system provided by the DSP will be replacing and/or interfacing with systems in the current, interim and future states of the operational network. With multiple upgrade and acquisition projects running concurrently, many of these future systems will be supplied by related (ongoing and future) projects within the agency. To ensure that this dependency is flagged, related projects are captured in the DSM and traced to the impacted DSP system components.

This facilitated the communication and coordination between projects, with any changes to either the DSP or related projects triggering an impact analysis on subsequent related projects. Regular reviews of the known related projects and the components they supply are undertaken, and the DSM updated.

Change impact analysis. Using the information captured in the DSM, a change impact analysis was conducted to capture a comprehensive set of operational and organisation impacts as a result of the DSP.

This analysis involved the comparison of current, interim and future state scenarios and architecture (functional, physical and interfaces) to understand the changes throughout the implementation stages. For each impact identified, a Proposed Function *generates* the impact which was is *informed* by the comparison of Existing Functions. The Impact will *impact* existing System components.

As the current and proposed modelled scenarios were structured and well aligned, the change impact analysis could be effectively performed.

This information proved useful for operational integration planning and provides change managers relevant and up-to-date information to engage users, including Sydney Trains (the network operators) and the customers.

Artefact generation. The information captured in the DSM in the form of operational scenarios, architectural elements, related projects elements and change impact elements where used to produce several automated artefacts tailored for communication to specific stakeholders. Artefacts included documents, spreadsheets, presentations and webpages.

The artefacts generated from the DSM include: the operational scenarios and impact analysis sections of the Operational Concept Definition (OCD) and Maintenance Concept Definition (MCD); and the complete System Architecture Definition, subsystem architecture definitions (for each supplier) and individual scenario reports. This has reduced operational and technical SME time spent "wrangling" documentation in word processors freeing intellectual capacity for decision making rather than text formatting.

Dashboards were also developed, by analysing the information and relationships in the DSM, to report on the systems definition level of coverage and quality. Specific database queries were also regularly run for various stakeholders. With the information maintained in the DSM, artefacts were produced only when a snapshot of the current understanding was required

Outcomes

Through the application of MBSE, tangible outcomes have been realised for the project in the form of traceability from project business requirements through to system, subsystem and interface requirements via the operational concept. This process has highlighted information elements that do not have full traceability and prompted investigation into the validity of its inclusion.

Project business requirements relationship to conceptual scenarios. This has ensured all operational scenarios considered by the project are consistent with the project requirements. From this, the project scope boundary was refined, and the functions of planning operations was excluded from the scope of the project.

Conceptual scenarios. These have been developed to cover the change to the operational and maintenance processes that is envisaged to be impacted by the SoI in the brownfield existing environment. Several additional components and their functions were identified through this rigorous process. It clarified responsibilities between subsystems in defined contexts and clearly captured the resources interfaces with the functions through the structured MBSE approach. Traditional, text-based descriptions of conceptual scenarios would have made understanding the change to the being delivered by the project difficult to communicate, manage and control.

Architecture. Deciding which identified components formed part of the SoI clearly articulated the physical system boundary for the project. The functions related to those components in turn formed the functional boundary for the project. This reduced the list of components and functionality to only those required by the project.

Interfaces. Through the application of the MBSE approach, interactions between the components were captured and assessed, which facilitated the identification of interfaces. This rigorous interface identification process identified multiple critical interfaces than were originally envisaged and became the main source of interface identification on the project.

Requirements. Relating functions and interfaces to requirements spurred several discussions to the applicability of requirements to the project, as well as potential gaps in concept coverage. This improved the quality of both the concept scenarios and requirements.

Related projects. Several related projects were identified and related to the specific components that they supply. The components identified proved useful to ask the question if a project was going to change it, or conversely, analysing the list of other projects in the agency, the components they were changing could be requested.

Change impact. The operational and organizational impacts identified through the change impact analysis process could be easily performed due to the scenarios modelled in aligned current and proposed state. The result was a comprehensive list based on agreed behaviour and proved useful for operational integration planning.

Lessons learnt

Several lessons were learnt during the process of applying MBSE on this rail project. These have been summarised as follows:

- **Justification of approach.** Requirements management has been formalised in many rail projects managed by the agency, however capturing the conceptual design and architecture in a model proved to be novel to the immediate project stakeholders. The MBSE approach therefore had to be continually advocated with in-project awareness sessions provided on several occasions. This enabled the project stakeholder to understand the approach to support an aligned system definition for DSP.

- **Change impact assessments.** Changes to the conceptual design continually occurred during early supplier engagements. The OCD, MCD, System, Subsystem requirements and interface requirements were analysed by various SMEs and refined. The inherent traceability of the MBSE approach significantly assisted these impact assessments with a near end-to-end visibility from project business requirements to functions and interfaces to system and subsystem requirements. This has enabled trade-offs to be made against the user's operational requirements and COTS products offered by suppliers, with the intent to minimise customisation in products.

- **Scenario functional modelling.** Using EFFBDs for scenario modelling were found to be novel to the rail system acquirer, supplier and user, and considerable time was spent on advocating the benefits of using this method. The best EFFBD scenario review results came from preparing the reviewers with a simple flow block diagram example, explaining the purpose of the information captured in them, and keeping the review session numbers low (1 – 3 people). Following a few sessions, majority of the reviewers were able to utilise the diagrams to create a shared understanding of socio-technical interactions between multiple operational and technical stakeholders.

- **Dashboarding.** Dashboards were created for the DSM to measure the level of coverage and were an effective way of communicating progress and areas of improvement to senior management. Model data in the DSM enabled these representations.

- **Model-supported vs. model-based.** Document artefacts such as the OCD and MCD were partly generated from the model, and in many cases reviewed in word processors. These review comments were then back populated into the model into the DSM with the associated overhead. Generating complete artefacts and reviewing information directly in the DSM would increase review and assurance efficiency. As members of the project team trained in the approach, they were able to easily navigate through the DSM to access information.

Conclusion

The application of MBSE on a real-life complex rail transportation project has significantly improved the understanding of its system boundary, subsystem functionality and interfaces in a full traceable model.

This approach addresses the following key complexities:

- **Socio-technical**, through the capturing of behaviour of technology and people in conceptual scenarios

- **Software-based or software-intensive systems**, through the capturing of functions and interfaces of the digital systems

- **Multiple stakeholders**, by capturing several scenario viewpoints involving operators, maintainers and technical SMEs using information-rich unambiguous flow block diagrams. Artefacts and change impacts are tailored to enhance communications to various stakeholder groups and are generated from a single source. Changes to any part of the DSM allows for an efficient impact assessment and update spanning several SME focus areas through its traceability, thereby reducing the “silos” between operations and technical SMEs.

- **Multiple interfaces**, by the methodical identification of interfaces and their management within the DSM.

- **Dynamic project environment**, by the methodical identification and linkage of related projects. Changes due to the DSP or related project can be communicated or interrogated efficiently and rigorously.

Through the application of Systems Engineering international standards, tangible outcomes have been realised for the DSP in the form of traceability from project business requirements through to system, subsystem and interface requirements with linkages to the operational and maintenance concepts. This process highlighted information elements that were not fully traceability and prompted investigation into the validity of its inclusion.

The overall benefit of this approach is a better-defined solution system, where additional components, functions, and interfaces were identified, which were not previously captured through traditional systems engineering approaches.

The subsequent set of requirements have been well structured and defined, each with supporting reasoning through the architecture to the project business requirements. The traceability is allowing faster impact analysis on changes to concept or requirements and documentation generated from the model has increased the turn-around time while maintaining consistency. The MBSE approach has been entrenched in the project under the ownership of the system integrator.

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Biography

Donovan Roodt. Donovan is a certified professional systems engineer with more than 16 years’ experience in both the defence and transport industries. He holds a bachelor’s degree in electrical, electronic and computer engineering, honours degree in technology management and a MBA. His experience includes electronic engineering officer in the South African Air Force, systems engineer responsible for tactical land-mobile electronic warfare systems and contractor to the Transport for NSW Digital Systems Program.

Malaeka Nadeem. Malaeka is a certified professional systems engineer, currently working as a Systems Engineering Manager at Transport for NSW on the Digital System Program. Malaeka has over 15 years' systems engineering experience in both defence and transport industries. Projects include FFG Upgrade Project, Waratah and Sydney Growth Train Projects, Inland Rail and Parramatta Light Rail.

Lam-Thien Vu. Lam-Thien is a professional engineer with experience in systems engineering, mechanical and reliability engineering, and risk management. She is a first-class honours graduate with a Bachelor of Engineering in Mechanical and Sustainable Energy and is certified as an Associate Systems Engineering Professional.