MANAGING COMPLEXITY ON DIGITAL SYSTEMS; A MODEL-BASED SYSTEMS ENGINEERING APPROACH

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SUMMARY

Modern railways are large 'system of systems' where emergent properties are hard to identify and predict, and interactions within and between systems are complex. Railway systems technologies are becoming typically complex with a heavy reliance on telecommunications. Furthermore, project delivery teams grapple with socio-technical interactions, multiple operational and technical stakeholders and numerous interfaces all within a dynamic project environment.

The Sydney rail network is an example of a complex railway undergoing modernisation. 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. The DSP consists of three main elements:

1) Replacing traditional trackside signalling equipment with the latest 'in cab' train control technology – European Train Control Systems (ETCS) Level 2
2) Implementing Automatic Train Operation (ATO), which assists drivers – who remain in control – to provide reduced and more consistent journey times
3) Introducing a Traffic Management System (TMS) to help the railway recover from any disruption quickly and manage the overall network as effectively as possible.

As a brownfield project, the DSP has many multidisciplinary stakeholders and external interfaces.

A Model-Based System Engineering (MBSE) approach has been applied to manage the complexity of the DSP system solution. It is based on a recognised architectural framework and a Digital Systems Model (DSM) has been produced. A concept design lifecycle, incorporating conceptual scenarios, architectural analysis, requirements allocation, change impact analysis, related project analysis, configuration management and artefact generation processes, is used in this approach.

The benefit of this approach is the reduced risk of rework on the program, realised as a result of the following:

- Creating a common understanding of the socio-technical behaviour through flow block diagrams;
- Improved understanding of software intensive systems functionality and interfaces through the system architecture;
- Earlier and better stakeholder involvement and communication through scenario modelling and review, change impact identification and tailored artefacts;
- Rigorous interface identification and management though architectural analysis;
- Increased related project awareness and analysis; and
- Better structuring and rigor in the subsequent requirements engineering task.

Lessons learnt for the deployment of MBSE on the DSP include:

- The need to justify the value of the approach;
- Use of the DSM to improve change impact assessment;
- Review scenario flow block diagrams in smaller focused workshops;
- Development of dashboards, produced from the DSM, to measure and communicate level of coverage;
- The greater the usage of MBSE models for review, the greater the increase in efficiency unlocked by automatic artefact generation; and
- The need to provide MBSE entry-level training.

The application of MBSE early in the project life-cycle, prior to the development of requirements, and engaging the operator and maintainer early, is supporting the DSP in managing its socio-technical and project delivery complexities.

1 INTRODUCTION

1.1 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 that affect 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 network 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.

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 network 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 thousands of passengers each day.

When implementing new technologies, any changes to these systems and processes, would need to be carefully considered and phased into operation. As the end-user, any changes 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 project Business Requirements. The acquirer needs to demonstrate sound governance with risk mitigation to the project sponsors and general public.

Supplier perspective. It is crucial that the solution is well integrated with legacy infrastructure as well as operations and maintenance processes. From the supplier perspective, the set of requirements developed for the sub-systems needs to be aligned with functions and overall system concept, but still supply 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.

1.2 Systems Engineering

Systems Engineering manages complexity and risks in a rigorous and structured manner throughout the project and system realisation life-cycle. Systems Engineering is an interdisciplinary approach that enables the realisation of successful systems (INCOSE 2015). It 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 related 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.

1.3 Digital Systems Program

TfNSW's 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 principles driving the project include an "integrated and collaborative approach", "whole of life thinking" and "configure not customise" as shown in Figure 1.

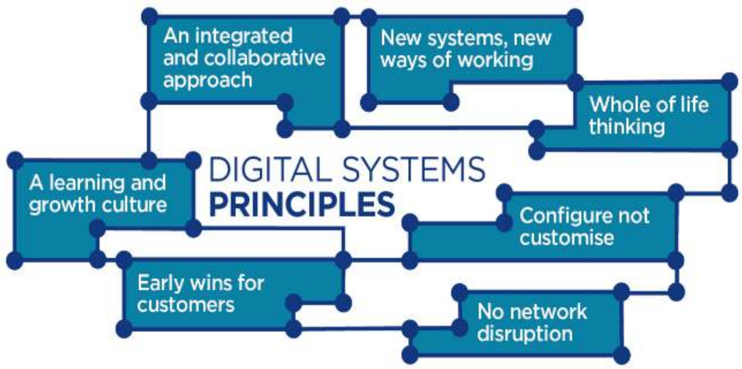

Figure 1: Digital Systems Principles

At time of writing, TfNSW, the system acquirer responsible for the project, planned to engage: a systems integrator; several suppliers to provide the major sub-systems; and railway operators and maintainers representatives. Once the suppliers for the major sub-systems were contracted, the preliminary design would commence further refining the concept and specifications through a formal change control process. Implementation of the new signalling and control system would be via a staged approach. This project would be the first stage of the Program, which involves developing, testing and validating Digital Systems on parts of the T4 Line, from Sutherland to Cronulla and from Bondi Junction to Erskineville (Transport for NSW 2020).

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); 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.

2 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 the operations and maintenance environment within which it will reside, and how these operational 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, operations and maintenance groups.

Informed by the OCD and MCD, the acquirer produces system and subsystem requirements for several suppliers, such as the TMS, Trackside and Onboard systems, 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. This is achieved using an architectural framework as described in section 2.1.

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 the Defence, Aerospace and Automotive industries.

2.1 Framework and Model

The definition of the linkage between the operations viewpoint (OCD/MCD) and the technical viewpoint (Requirements) 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 high-level view of the framework metamodel (Roodt, Nadeem & Vu 2020) is shown in Figure 3.

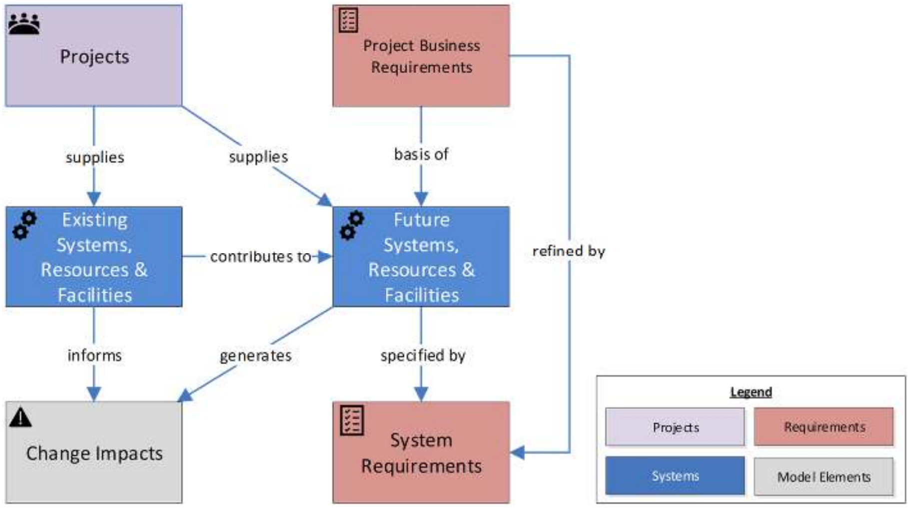

Figure 3: Framework metamodel

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) has been generated based on this framework and has been populated with DSP relevant data. The DSM was developed using MBSE software and captures enterprise, system and project information. Requirements are managed in a dedicated requirements management tool and linked to the DSM.

2.2 Process

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

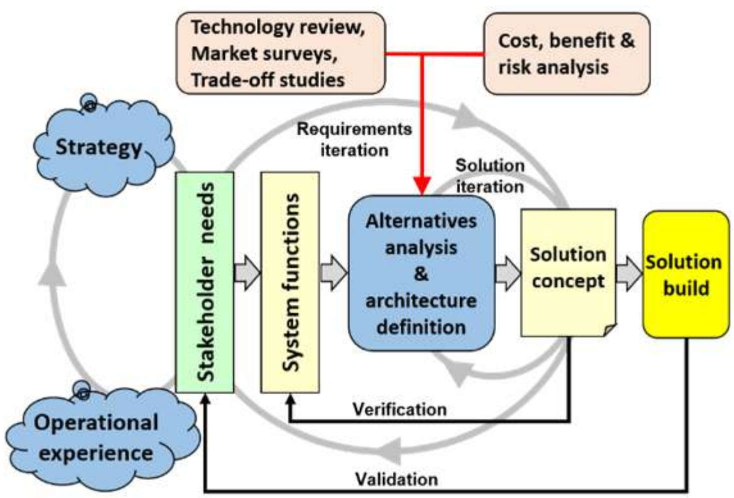

Figure 4: Concept design life cycle

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 future 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, enabled the incremental development of the DSM.

Conceptual Scenarios were used to capture operational behaviour relating to people and technology including operational experience. A scenario is a step-by-step description of how the system should operate and interact with its users and its external interfaces within a given context, and collectively ties together all the parts of the system, including operators and technology, into a comprehensible whole (IEEE 1998). The conceptual scenarios were influenced by the set of business requirements.

In these scenarios, functions are allocated to performers and structured according to their hierarchy and sequence. This enabled them to be viewed in many formats such as Enhanced Functional Flow Block Diagrams (EFFBD) (Vitech 2019) or activity diagrams (SysML.org 2020).

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

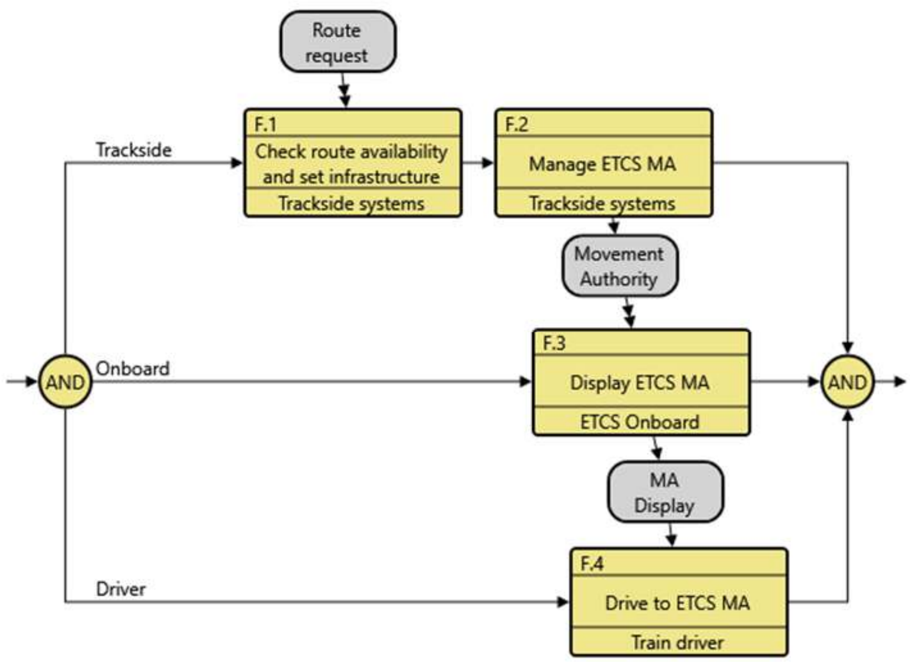

Figure 5: Example of a modelled scenario

The set of scenarios focussed on the day-of operations and included managing operations, running trains and maintaining assets operating within normal, degraded and emergency modes. These were reviewed and refined by various operational, maintenance and other SME stakeholders. Both current and proposed (future) state scenarios were modelled representing the system prior to project implementation and the system at interim and end-states after implementation.

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 structure the data and challenge the scenario developer to achieve agreement between operations, technical and other stakeholders, as well as adequately capture the information for architectural analysis.

Architectural Analysis was performed to derive the functional and physical architecture of the system from the set of scenarios, as well as the corresponding logical and physical interfaces. This process effectively translates the operational view of the DSP into a technical view to which technical requirements were structured and written.

System components are identified through the allocation of functions. From the scenario inFigure 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 derived from scenarios by identifying the transferring item ("Movement Authority") between functions allocated to components as shown inFigure 6.

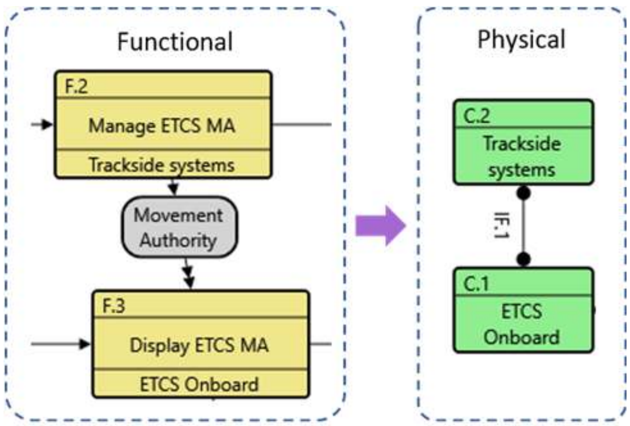

Figure 6: Interface derivation example

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 inFigure 7.

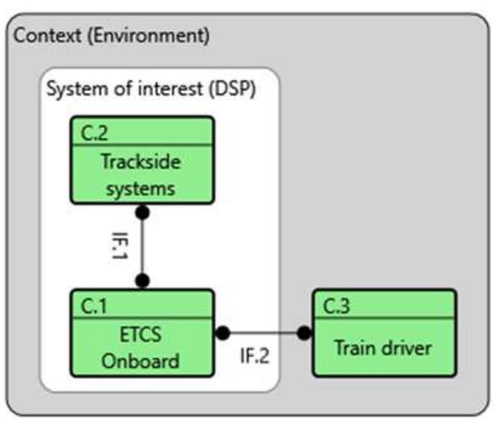

Figure 7: Example of system interface block diagram

Analysis of the scenarios provided the set of logical interfaces. By deciding which identified components formed part, or not part of, the DSP scope the functional and physical boundary for DSP could be agreed and external interfaces identified.

The current-state, interim states and end-state interfaces were thus identified, understood and managed within the DSM.

Through this rigorous analysis process, several additional interfacing system elements and their functions were identified, which would have otherwise been missed and likely resulted in significant cost and schedule impact 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 main source of interface identification on DSP.

With the set of DSP functions, their allocated components and interfaces defined provided the necessary information to define requirements for various subsystem suppliers.

Requirements Allocation. A pool of requirements was initially obtained for each subsystem from other equivalent projects. Functional requirements for each subsystem was then related and explicitly traced to the appropriate function allocated to the relevant subsystem. The set of functions and functional requirements that could not be related were analysed resulting in an update of scenarios or amendment of requirements. The conceptual process is shown in Figure 8.

The types of requirements that were related are:

- System/subsystem functional requirements
- Machine-to-machine interface requirements
- User interaction requirements

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.

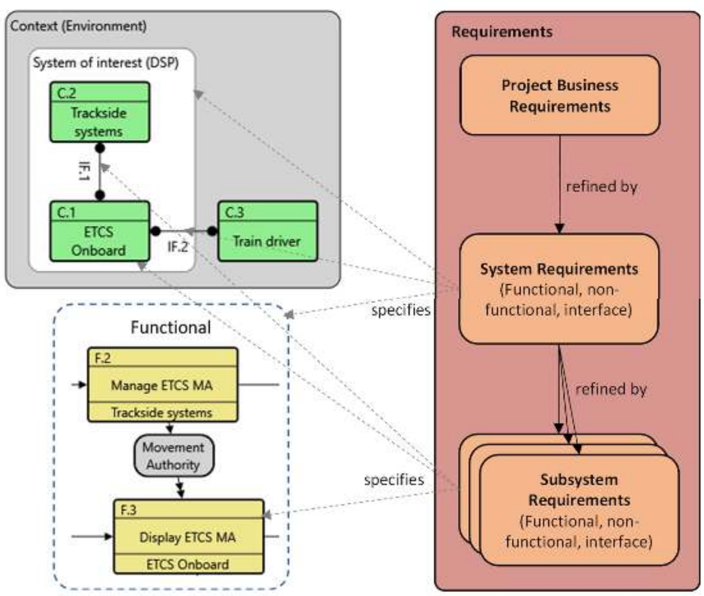

Figure 8: Requirements allocation

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. Time required to analyse and apply changes is reduced by the DSM. Moreover, the 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 life-cycle.

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. 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 the necessary 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 as shown in Figure 9.

The artefacts generated from the DSM include: the operational scenarios and impact analysis sections of the OCD and 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 editing 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.

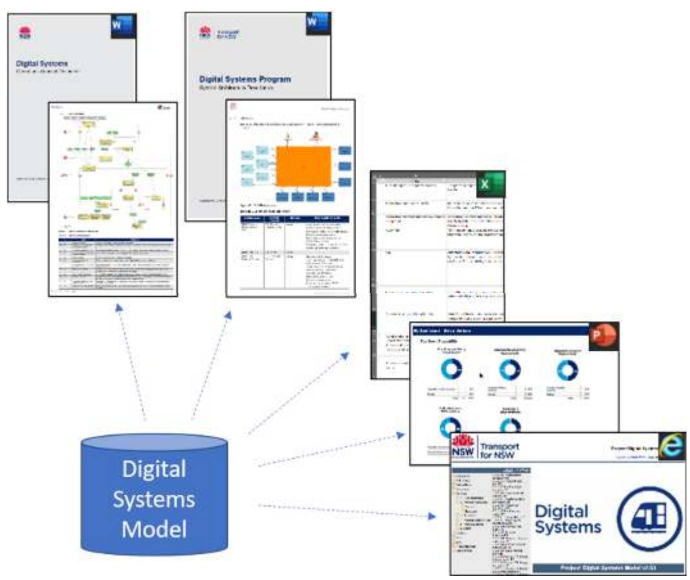

Figure 9: DSM Artefact Generation

3 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. From these, statistics could readily be generated to measure progress.

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 System of Interest 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 System of Interest 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.

4 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 acquirer, 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 and several in-project training sessions conducted. This enabled the project stakeholders to understand the approach to support an aligned system definition for DSP. Training should be provided at the earliest opportunity to project stakeholders.

Change impact assessments. Changes to the conceptual design continually occurred during early supplier engagements. The OCD, MCD, System, Sub-system requirements specifications 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 sub-system 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. The DSM continues to support requirement change impact assessments.

Scenario functional modelling. Using flow block diagrams for scenario visualisation 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 flow block diagram 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 satisfied with the results and 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. Dashboards should be generated at the earliest opportunity to project stakeholders to measure progress or highlight gaps.

Model-supported vs. model-based. Artefacts such as the OCD and MCD documents were partly generated from the model, and in many cases reviewed in word processors. The review comments were then back populated 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.

5 CONCLUSION

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

This approach addresses the following key complexities:

- **Socio-technical**, through the capturing of behaviour of technology and people in conceptual scenarios which is collectively understood by the program
- **Software-based or software-intensive systems**, through the capturing of functions and interactions between system 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 to create a common understanding. 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 and best practice, 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 for each supplier package have been well structured and defined, each with supporting reasoning through the architecture to the project business requirements. The application of systems engineering and in particular MBSE early in the project life-cycle, prior to the development of requirements, and involving the operator and maintainer early, is supporting the DSP in managing its challenging complexities and risk.

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