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Increasing Systems Engineering Relevance in Transport Assets and Infrastructure

INCOSE AOSEC · 2025

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PUBLICATION DATE

July, 2026

SUBMISSION #

35

INCREASING SYSTEMS ENGINEERING RELEVANCE IN TRANSPORT ASSETS AND INFRASTRUCTURE

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Abstract. Systems Engineering (SE) provides a structured, requirements-driven methodology for defining, realising, and sustaining complex systems throughout their lifecycle. While SE is well established in sectors such as aerospace and defence, its adoption in the transport infrastructure sector remains inconsistent, despite unprecedented capital investment in New South Wales (NSW) over the past decade. This study investigates SE adoption and application across NSW transport projects at both enterprise and project levels, employing a three-phase research design comprising a synthesis of academic literature and agency standards, participatory systems modelling workshops using Soft Systems Methodology (SSM), and multiple case studies with cross-case analysis. Findings confirm that SE delivers measurable benefits in isolated instances but is hindered by systemic barriers, including fragmented governance, limited sector-specific tailoring, and misalignment between contractual structures and lifecycle-oriented delivery. Analysis of SSM workshop outputs and case study evidence led to the development of an Emerging SE Framework that distinguishes between SE Adoption, addressing socio-organisational readiness and stakeholder engagement, and SE Application implementing ISO/IEC 15288-aligned lifecycle processes tailored to project context. This dual-pathway framework provides a structured, context-sensitive approach to embedding SE in transport assets and infrastructure, improving requirement traceability, integration management, whole-of-life asset performance, and long-term value realisation.

Keywords. Systems Engineering, Transport Assets, Transport Infrastructure, Adoption, Application

Introduction

Systems Engineering (SE) is a proven discipline for defining and addressing the requirements of large-scale technical projects, overseeing the realisation of compliant solutions into operational service, and sustaining those solutions throughout their intended service life. SE was formalised in the U.S. defence–aerospace context in the mid-20th century to manage the unprecedented technical and organisational complexity of missile and space programmes, catalysing an interdisciplinary, life-cycle integration of requirements, design, verification and operations (Schlager, 1957; Goode et al., 1957). Since then, SE has matured in complex discrete-manufacturing sectors (most notably aerospace and automotive) driven by platform complexity, rigorous safety and regulatory regimes, configuration and requirements traceability across extended supply chains, and the shift to model-based practices that enable end-to-end coherence at scale (Sprock, 2019). However, despite its demonstrated efficacy in managing complexity, risk, and whole-of-life performance in these sectors, levels of maturity of SE applications in the transport domain remains uneven (Hoehne, 2023).

In sectors where SE is not institutionally embedded or prevalent, it is often perceived as resource-intensive relative to its perceived benefits (Shenhar & Dvir, 2007; Honour, 2013). These perceptions are compounded by challenges in translating SE concepts, artefacts, and processes into forms that align with the governance, procurement, and delivery structures of infrastructure projects (Sheard & Mostashari, 2009). As a result, SE is frequently applied selectively or late in the delivery cycle, limiting its integration across the end-to-end asset life cycle and constraining its potential to deliver value at portfolio, program, and project levels (Chen & Jupp, 2018).

In Australia, over the past two decades, an increasing level of investment and expenditure has occurred throughout the transport networks of state jurisdictions. The New South Wales (NSW) Government's portfolio of transport infrastructure assets amounts to $91 billion. In 2012-13 the capital budget for Transport projects was approximately $6 billion, growing year-on-year by an average of 13.1% to investment with more than $30 billion in 2025-26 (NSW Budget, 2025-26). The Transport capital program is now projected to grow by another $55.6 billion over the next four years (till 2028-2029). Like aerospace and automotive industries, maximising the return on capital investment across project, program and portfolio levels requires fulfilment of defined requirements, achievement of intended project outcomes, and assurance of value for money, together with compliance to regulatory obligations and alignment with strategic asset management objectives.

However, multiple compounding factors contribute to the ineffective and inefficient adoption and application of SE, including unevenness in organisational capability and fragmented governance structures (Chen & Jupp, 2018), limited cross-disciplinary integration (Hoehne, 2023), inconsistent interpretation of SE principles (Ninan et al. 2019), and misalignment between contractual requirements and project delivery practices (Ramos, 2018). Across the transport infrastructure sector, these issues work to collectively undermine the potential of SE to act as a unifying discipline for managing complexity, optimising whole-of-life asset performance, and ensuring value realisation on large-scale, multi-modal transport programs.

Despite the well-established benefits of SE in high-reliability sectors such as aerospace and defence, its consistent and scalable application across transport asset and infrastructure agencies remains elusive. In Australian jurisdictions like NSW, where unprecedented capital investment has been channelled into transport portfolios over the past decade – there is growing concern that SE remains unevenly adopted and inconsistently applied across projects and programs. This phenomenon persists despite the increasing complexity, integration, and risk profiles of transport systems.

In this context, the overarching aim of this study is to investigate and address the persistent barriers to SE adoption and application across NSW's transport infrastructure projects. Specifically, the research seeks to answer the following questions:

What are the key organisational, procedural, and cultural factors that inhibit the consistent adoption and application of Systems Engineering across NSW transport infrastructure projects?

How can SE frameworks be adapted or tailored to support broader uptake across project and organisational levels in non-traditional SE sectors like transport?

What mechanisms can improve both the perceived and actual value of SE in multi-modal transport project delivery and asset lifecycle management?

To answer these questions, the boundaries of this research are defined by the operationalisation of SE in the context of the responsible NSW transport asset and infrastructure agency and its jurisdictions governing the planning, delivery, operations and maintenance of transport assets and infrastructure.

Figure 1 defines the system boundaries of our investigations. Within these boundaries, SE is represented as a structured methodology, and set of standards and guides that are applied to planned project outcomes and subsequently operationalised through NSW transport asset and infrastructure projects. The model shows the boundaries of the research scope and the intended causal chain from planned outcomes to actual project outcomes, mediated by SE practices, and constrained or enabled by contextual factors at project and enterprise levels. Enablers – such as policy, processes and procedures, technology, and funding – are positioned as necessary supports, while barriers – including ineffective or misapplied delivery methods, cultural factors, competency gaps, organisational silos, and commercial contract arrangements – act to hinder or prevent effective SE application.

By delineating these entities and relationships, the model establishes the operational context, interfaces, and influencing factors under investigation, defining the scope within which the study interrogates the adoption, implementation, and efficacy of SE in delivering transport project outcomes.

The remainder of the paper continues with the Research Methodology (Section 2) outlining the three-phase research design and use of Soft Systems Methodology (SSM), case study analysis, and scenario-based validation. Section 3 presents preliminary research findings, including initial observations from the Discovery and Development phases. Finally, the paper closes with the presentation of an 'Emerging Systems Engineering Framework,' supporting an integrated SE Adoption and Application Framework and a closing Discussion section on the benefits of a structured approach to consistent, scalable, and context-sensitive deployment of SE in the transport infrastructure sector.

Note this paper is the first instalment of a thesis by compilation, and as such is still a work in progress with an expected completion in mid-2027. At this stage in the research, Phase Two – Development Phase is nearing completion with the cross case analysis all that remains in that Phase. Real world application will be supplemented by a hypothetical scenario which occurs next in Phase Three- Verification Phase.

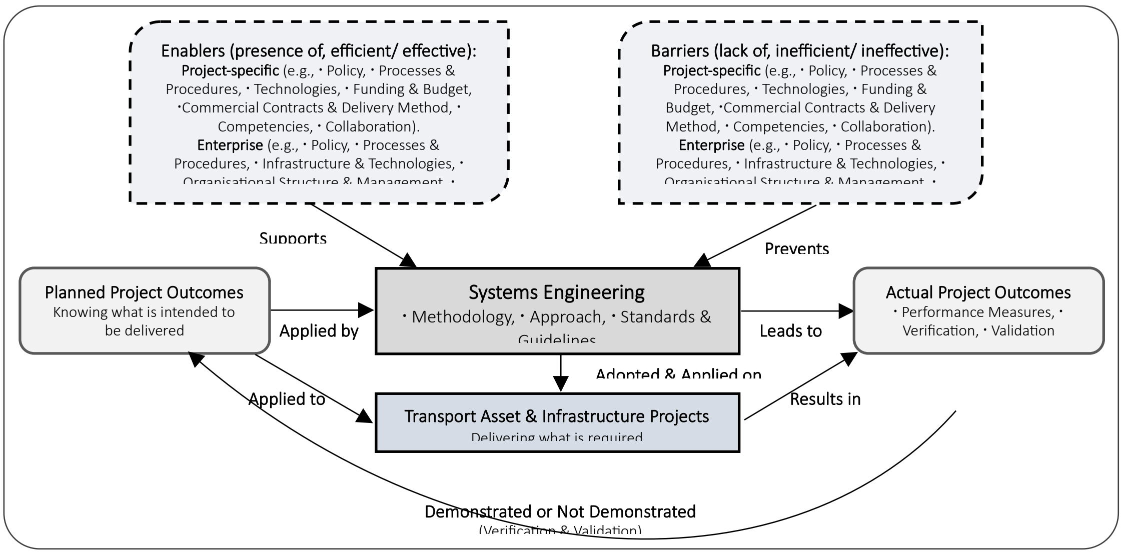

Figure 1. Systems Engineering on Transport Asset and Infrastructure Projects

Research Methodology

A three-phase research design was implemented, combining qualitative systems inquiry with empirical case analysis and experimental validation as shown in Figure 2. The research design is predominantly a Case Study Analysis supported by Soft Systems Methodology (SSM) (Checkland & Scholes, 1990), which was implemented in the initial research phase and at the end in a scenario-based validation process. This triangulated design enables progressive theory-building and ensures that findings are both contextually grounded and analytically robust.

The three methods are applied in the following phases:

1. Discovery Phase: an understanding of the current NSW transport project context and creation of an 'Initial SE Adoption and Application Framework' using SSM (Checkland & Scholes, 1990).
2. Development Phase: exploration, demonstration and reinforcement of the current context and development of an 'Emerging SE Adoption and Application Framework' via four transport case studies using Yin's Case Study Analysis method (Yin, 2018).
3. Validation Phase: Validation of a 'Final SE Adoption and Application Framework' via a hypothetical transport project scenario using the Solomon Four Group Design method (Sekaran, 2003).

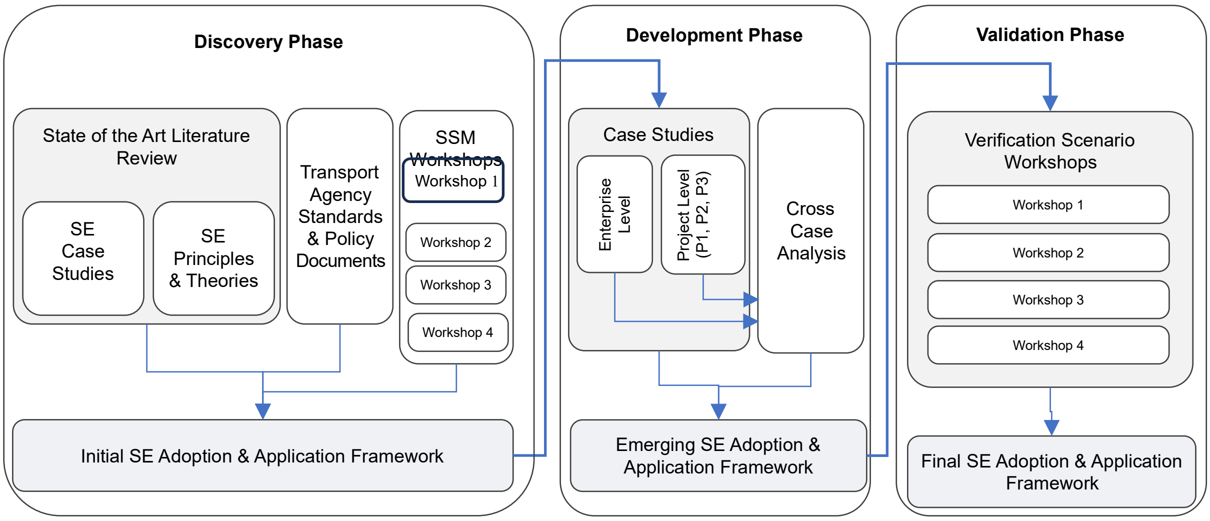

Figure 2. 3-Phase Research Design consisting of Discovery, Development and Validation.

Research Design

Discovery Phase. The Discovery Phase employed Soft Systems Methodology (SSM) (Checkland & Scholes, 1990) to map the problem space and reveal the underlying tensions, constraints, and opportunities influencing SE use across NSW transport projects. Four facilitated SSM workshops were conducted with two stakeholder groups drawn from key agencies and industry, capturing perceptions via Rich Pictures, Root Definitions, and conceptual models. This exploratory inquiry led to the development of an Initial SE Adoption Model, which captured the socio-technical dynamics influencing SE practices. Complementary to this, an 'Initial SE Adoption and Application Model' was developed, synthesising insights from a targeted literature review of best-practice SE frameworks (e.g., Faulconbridge & Ryan, 2020; Locatelli et al., 2013), published SE practice and the suite of SE standards and guidance documents used within NSW transport agencies.

Together, these two models formed the foundation of an Elementary SE Framework, tailored to reflect both theoretical best practice and sector-specific contextual realities.

Development Phase.

The Development Phase adopted a multiple case study methodology (Yin, 2018) to test and refine the Elementary SE Framework. Four case studies were selected to provide analytic breadth across project scale, system complexity, and organisational maturity:

- One organisational-level case study within NSW Transport , focused on policy, governance, and capability factors.
- Three project-level case studies, each representing a different mode and delivery model:
  - North West Metro Line (NWML) – a high-complexity, integrated metro rail project;
  - Parramatta Light Rail Stage 1 (PLR1) – a mid-scale light rail initiative; and
  - M4 Smart Motorway (M4SM) – a hybrid civil engineering-Intelligent Transport Systems (ITS) Managed Motorway System upgrade.

Data collection across the case studies included the following:

- Semi-structured interviews with project and organisational stakeholders (n ≈ 25),
- A structured survey examining attitudes toward SE adoption and maturity, and
- Document analysis of relevant and available project artefacts and related project material.

Following individual case analysis, a cross-case synthesis was conducted to identify replication logic, surface patterns of resistance or success, and extract transferable insights. These findings informed the next iteration of the SE Framework, now termed the Emerging SE Adoption and Application Framework.

Validation Phase

To test the operational feasibility and implementation potential of the refined framework, the final phase will employ the Solomon Four-Group Design (Sekaran, 2003) – a quasi-experimental approach that controls for validity threats. Participants will be divided into four groups: (i) Two pre-test groups (experimental and control) drawn from the original SSM workshop cohorts, and (ii) Two post-test groups (experimental and control) composed of new participants unfamiliar with prior phases. All groups will engage with a hypothetical, but representative, transport project scenario, in which the experimental groups will apply the SE Framework and the control groups will not. Performance will be assessed against predefined criteria including requirement traceability, integration efficacy, and whole-of-life planning. Data from theses scenario-based workshops will then analysed using mixed methods, including: Quantitative scores from structured evaluation rubrics; Qualitative feedback from participant debriefings; and Comparative analysis of experimental vs. control group outcomes. The results will then be used to inform the final refinements to the framework, culminating in a validated, context-specific model for SE adoption and application in transport infrastructure programs.

Findings

This section presents the key findings of the research to date, integrating insights from academic literature, agency standards, participatory modelling, and case studies to inform the development of a fit-for-purpose SE framework for the NSW transport sector. It begins with a synthesis of best-practice literature and local standards, followed by outputs from Soft Systems Methodology (SSM) workshops that shaped a six-stage SE Adoption Model. Core enablers and barriers identified through thematic analysis are then outlined, providing the foundation for the Elementary SE Framework.

These components are tested and refined through multi-level case studies, leading to the formulation of an Emerging SE Framework designed to support consistent and scalable SE adoption and application across transport infrastructure projects.

Synthesis of Academic Literature & Agency Standards

The development of the Elementary Systems Engineering (SE) Framework was informed by a critical review of international academic literature and NSW-specific agency standards. This combined review served two primary functions: (1) to identify state-of-the-art practices in systems engineering applicable to infrastructure contexts, and (2) to derive practical principles for embedding SE into the governance, procurement, and delivery structures of transport projects. The insights gleaned from this literature informed the construction of the SE Application Model, one of the two interlinked components of the Elementary and Emerging SE Framework (refer to Figure 4).

At the governance level, Locatelli et al. (2013) advocate for a paradigmatic shift from conventional project management to a systems governance mindset–an approach particularly suited to managing complexity, uncertainty, and long asset lifecycles in infrastructure domains. Their model emphasises the integration of systems thinking into strategic decision-making, offering a compelling justification for repositioning SE as a core organisational capability, rather than an auxiliary technical discipline.

Complementing this perspective, Faulconbridge and Ryan (2020) propose a lifecycle-centric SE model structured around three interdependent elements: SE processes, SE management, and SE tools. This end-to-end model provides a conceptual foundation for the structural design of the SE Application Model, enabling traceability between high-level governance and practical delivery activities across the asset lifecycle. The foundational role of requirements engineering in transport projects is underscored by Lwin et al. (2017) who elucidate the need for early and continuous requirements definition and verification throughout project lifecycles, particularly for urban transit systems. This principle is further validated by Ramos (2018), whose analysis of the Sydney Metro North West project demonstrates how rigorous requirements traceability can facilitate progressive assurance in complex multi-stakeholder environments. These studies directly informed the inclusion of robust requirements management mechanisms in the proposed framework.

Adoption of SE in non-traditional sectors also requires tailoring to project and organisational contexts. Orhof (2016) illustrates how SE can be adapted for airport readiness in conjunction with the Diamond-of-Innovation Framework and Capability Analysis (CA), while Ninan et al. (2019) integrate SE with the TRIZ methodology to address stakeholder alignment in metro rail systems in India. These studies highlight the value of methodological hybridisation–a design principle embedded within the SE Application Model to promote contextual agility. Elliott et al. (2011) reinforce this principle through their work in the UK rail sector, showing how SE can be translated into domain-specific language and practice. This translation function making SE intelligible and relevant to non-SE practitioners–emerged as a core objective of the framework's adoption strategy.

To ensure value realisation beyond initial delivery, the literature advocates for applying and integrating SE across the full lifecycle. Tongur & Sundelin (2016) examine system-of-systems integration challenges in electrified transport corridors, arguing for early and continuous integration planning. Similarly, Roodt et al. (2020) demonstrate the value of Model-Based Systems Engineering (MBSE) to manage integration complexity in the NSW Digital Systems Program, reinforcing the need for scalable enduring modelling approaches. López del Puerto et al. (2019) extend this view by emphasising whole-of-life (WOL) considerations, positioning SE as a vehicle for sustained asset performance and operational readiness.

These WOL insights informed the framework's requirement for early integration of operations and maintenance perspectives into design and delivery processes.

Quality assurance and the cost of non-conformance have long been recognised as systemic issues in infrastructure delivery. Love et al. (2022) present empirical evidence of persistent quality failures in large transport projects, providing a potential avenue for stronger integration of SE principles to mitigate downstream rework. Andersen et al. (2011) similarly call attention to post-project rectification cycles, highlighting the long-term risks associated with inadequate front-end engineering. These studies informed the inclusion of progressive verification, validation, and assurance loops within the SE Application Model.

The role of procurement models in enabling or constraining SE practices is addressed by Regan et al. (2015) and Jobling and Smith (2018). Both studies critique traditional contracting paradigms, particularly in megaproject contexts, and advocate for more collaborative, performance-based approaches that align with systems thinking. Jobling and Smith notably argue for the use of engineering artefacts to support contractual traceability and interface management–mechanisms directly incorporated into the framework to support integration across commercial boundaries. Flyvbjerg (2014) situates the rise of megaprojects within broader societal, technological, and economic trends. His concept of the "technological sublime" underscores the seductive allure of scale and innovation, while simultaneously drawing attention to the endemic cost overruns and benefit shortfalls that accompany them. Flyvbjerg's critique reinforces the need for rigorous, systems-based approaches to managing complexity, risk, and stakeholder expectation.

Collectively, this body of literature provides both a normative foundation and a contextual justification for the Elementary SE Framework developed in this study. By synthesising insights across governance, delivery, integration, assurance, and procurement domains, the SE Application Model aligns best practice systems engineering principles with the operational realities of transport asset and infrastructure delivery in NSW. Its integration with NSW Transport's SE standards and guidance ensures contextual relevance and operational feasibility, while addressing persistent fragmentation in SE uptake across projects and programs.

Participatory Systems Modelling Workshops using Soft Systems Methodology

Two distinct participant cohorts were engaged in four workshops, each comprising mid to senior level professionals from across NSW public transport agencies and industry, including representatives from rail, road, and multi-modal infrastructure planning divisions. Each group participated in four SSM workshops (n = 4), designed and facilitated according to the classic seven-stage SSM cycle, with emphasis on the logic-based stream of analysis (Checkland & Scholes, 1999). This approach was grounded in the pragmatic aim of this phase: to generate actionable insights to inform a structured SE adoption model, rather than to critique underlying cultural assumptions (as would be the focus in the cultural stream). The workshop protocol comprised the following structured activities:

- Elicitation of Problem Situation: Using Rich Picture techniques, participants collaboratively constructed graphical representations of the current situation regarding SE adoption and application in their respective domains. These artefacts captured systemic tensions, conflicting priorities, and key constraints. In doing so, they identified a range of existing issues affecting SE uptake in the NSW Transport sector.

- Formulation of Root Definitions and CATWOE Analysis: Participants selected two core issues, from which they developed root definitions of purposeful activity systems, supported by structured CATWOE analyses to surface stakeholder roles, perspectives, and transformation logic.
- Conceptual Model Development: Based on each root definition, participants constructed conceptual activity models to represent idealised systems of purposeful activity.
- Comparison with Perceived Reality: Each conceptual model was then contrasted against the original problem situation to identify feasible and desirable changes.
- Identification of Improvement Actions: Final workshop outputs included action-oriented proposals for enhancing the adoption and application of SE, grounded in participants' contextual knowledge and practices.

The two groups independently identified four core issues that constrained effective SE adoption and application:

(i) A lack of demonstration of the achievement of intended benefits from projects;

(ii) Disconnection between workforce capability development and the operational requirements of systems-informed project delivery;

(iii) Enterprise/organisation wide utilisation of SE, and

(iv) An inability to provide traceability for project requirements throughout the project life cycle, preventing progressive assurance and end achievement of planned project goals from being met.

Each group developed distinct activity system models addressing these concerns, resulting in four SSM-derived conceptual models, which collectively served as the foundational data set for subsequent thematic synthesis (refer to Table 1).

Analytical Method and Thematic Synthesis

A comparative thematic analysis of the four conceptual models was conducted using a qualitative coding schema informed by grounded theory principles and SE literature. Coding focused on identifying recurring elements of effective SE practice and common systemic interventions proposed across models. Through this process, a six-stage logic of change was distilled, representing the emergent structure of an SE Adoption Model. This six-stage model – derived from the workshop-generated conceptual activity systems – is summarised as follows:

1. Understand: Establish a shared appreciation of the problem context, including the institutional, technical, and cultural dimensions that shape SE engagement across the transport sector.
2. Develop and Tailor: Co-design SE approaches that are responsive to the specific requirements of each project environment, stakeholder group, and delivery model.
3. Support: Identify and integrate enabling inputs, including workforce capability, digital toolsets, and procedural guidance, mapped to unique needs of different transport modes and organisational units.
4. Trial: Implement pilot applications of the tailored SE approach in low-risk or early-phase projects to validate assumptions and gather operational feedback.
5. Deploy: Roll out the refined SE practices across broader project portfolios, ensuring alignment with existing governance, procurement, and assurance structures.
6. Measure: Establish longitudinal measurement and feedback mechanisms to track the impact of SE practices on project outcomes, stakeholder satisfaction, and whole-of-life asset performance.

This emergent model encapsulates a structured yet flexible approach to SE adoption that is grounded in the lived experiences and operational contexts of NSW transport practitioners. Unlike traditional top-down implementation strategies, it reflects a participatory, iterative, and context-sensitive method for embedding SE into organisational practice.

The outputs of the SSM workshops (conceptual models, thematic codes, and the derived six-stage adoption process) together constitute the foundation of the SE Adoption Model within the Elementary SE Framework. Notably, the emphasis on tailoring, integration, and progressive rollout mirrors best practice principles identified in the literature review, demonstrating methodological coherence across research phases.

The workshop findings also confirm the need for a dual-model approach: one that distinguishes between the adoption of SE as a socio-technical change process, and the application of SE as a set of structured practices aligned with ISO/IEC 15288 Systems and Software Engineering – System Lifecycle Processes (ISO/IEC 15288) and related lifecycle standards. This distinction became a defining feature of the framework as it evolved in subsequent phases.

The collective output of the Discovery Phase is shown in the Elementary SE Framework, consisting of the SSM Adoption Model together with the recognised best practice literature, shown in Figure 3. The SE Adoption Model (SSM Model) in the centre of the diagram, surrounded by the SE Application Model with supporting best practice frameworks, supporting SE literature, SE standards and guides.

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Stages \ SSM Tasks/Issues	SSM1: Primary Task System Focus: Benefits Realisation	SSM1: Issue Based System Focus: SE Application, SE Workforce + Transport Modes	SSM2: Primary Task System Focus: Enterprise-wide SE Application	SSM2: Issue Based System Focus: Requirements Tracking + Verification and Validation (V&V)
Stage 1: Understand	Step 1: Identify stakeholder incentives "What's in it for them."	Step 1: Identify why stakeholders don't know about, understand, or want to apply SE and consult with them, then obtain agreement on and develop a tailored mode specific approach.	Step 1: Understand the needs of all key enterprise functions. Step 2: Define what is meany by effective decision making. Step 3: Identify the necessary flow of communication and information.	Step 1: Understand why projects don't track requirements well (drivers – e.g. not doner properly or too many to track) Step 2: Establish a definition of and guidance for high value risk project outcomes (as defined within requirements) Step 3: Understanding the project context and considerations – what type of SE effect is required to assist a particular project (Also applies in Develop and Tailor Phase).
Stage 2: Develop & Tailor	Step 2: Identify SE outcome that satisfies the incentive. Step 3: Identify the SE process that delivers the outcomes (if no process exists, go to Step 5). Step 5: Check for SE process best practice elsewhere (if no option in Step 3 exists). Step 4: Adapt SE for application.	Step 2: Develop education program to highlight, improve and make SE relevant and applicable to all of NSW Transport and transport modes. Step 3: Rollout education program to all of NSW transport, highlighting adaptability and flexibility of SE application to NSW Transport. Step 8: Develop improvement program for NSW Transport areas already using SE, but not seeing results or planned outcomes. (Also applies in Trail Phase)	Step 4 Tailor SE processes. Step 5: Plan for deployment.	Step 4: Develop a requirement tracking mechanism and checklist to apply to SE project requirements and recommended V&V plan/ approach.
Stage 3: Support		Step 4: Develop and maintain overarching governance process, retaining SE good practice and altering areas to improve. Step 5: Identify and recruit best SE practitioners into NSW Transport. Step 6: Deploy, expose and expand SE skills and retain best SE practitioners in NSW Transport.		
Stage 4: Trial	Step 6: Pilot SE Process.	Step 7: Trial SE in NSW Transport areas not using SE in application.		Step 5: Simulate selected group of projects using new processes/ tools to determine effectiveness.
Stage 5: Deploy	Step 7: Execute SE on projects.	Step 9: Execute SE on NSW Transport projects, including looking for opportunities to expand good practice SE on the project.	Step 6: Identify and deploy the SE Framework with stakeholders indicating accountability. Step 7: Deliver the business outcomes value.	Step 6: Deploy SE requirements tracking mechanism, checklist and V&V plan to NSW Transport projects. Step 7: Rollout and educate NSW Transport on the requirements mechanism and checklist.
Stage 6: Measure	Step 8: Define Measures of Performance. Step 9: Monitor Steps 1-5. Step 10: Take control action.	Step 10: Define Measures of Performance. Step 11: Monitor Steps 1-5. Step 12: Take control action.	Step 8: Define Measures of Performance. Step 9: Monitor Steps 1-5. Step 10: Take control action.	Step 8: Define Measures of Performance. Step 9: Monitor Steps 1-5. Step 10: Take control action.

Table 1. Six-Stage SE Adoption Model (Outputs of Soft Systems Methodology Workshops)

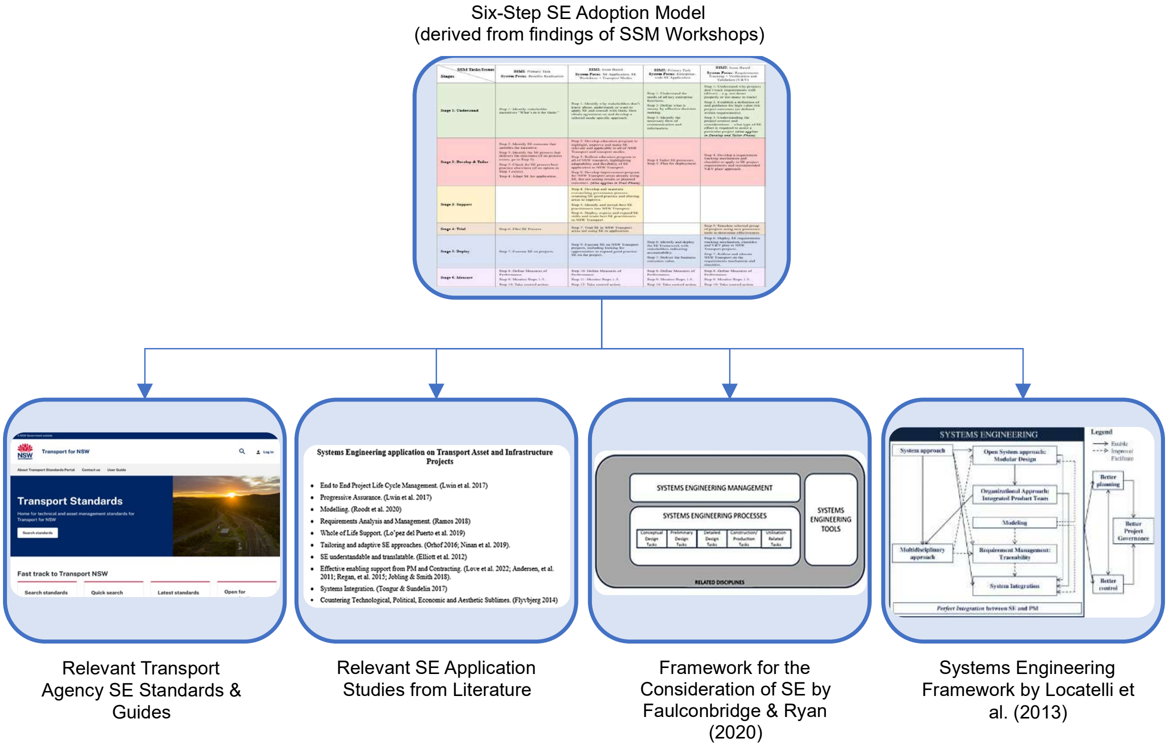

Figure 3. Core Enablers of Elementary Systems Engineering Framework

Case Study Findings

The second stage of the Development Phase consisted of four separate case studies as outlined in the Research Methodology Section. These case studies collectively demonstrated that SE was not adopted across the transport agencies in a consistent organisation wide manner. There were however isolated examples of SE being applied effectively on projects and within individual agencies, such as the NSW Metro Rail Agency.

Organisational Level Case Study

From the set of interviews undertaken amongst key leadership roles, both past and present, which asked about how these participants thought NSW Transport as whole was using SE, it was apparent that SE was not viewed as an approach that was able to assist in project delivery, or was widely adopted. The survey which followed on next in this case study, indicated that more traditional forms of project management focusing on cost, schedule and quality, were the preferred method of project delivery to be used on transport projects. SE was seen as a supporting methodology to provide progressive assurance and to manage risk, rather than being the driver on projects. An inclination towards the familiar seemed to be apparent. Even where SE had been applied, there were doubts about its effectiveness and success.

Project Level Case Studies

North West Metro Line (NWML). NWML by comparison showed how the application of SE could occur effectively across a novel, highly technical, heavily integrated, large scale project with high public interest. Whilst the number of identified requirements on the project was extensive and required a good deal of effort to verify, the project was considered a great success. The complex delivery arrangements and partnerships used on NWML required an all-encompassing project delivery approach that was able to manage a diverse group of interrelated metro rail activities in a coordinated and a seamless as possible manner, providing high degrees of assurance along the way. SE was the primary and main project delivery method used on NWML to achieve this and was a clear example of the benefit of applying a methodology which is capable of controlling and delivering projects of this nature and scale, with differing interwoven systems that were unique and not without potential risks.

Parramatta Light Rail – Phase 1 (PLR1). PLR1 was a project which started well with the use of SE during the business case and early high level design phase, however after tendering, had some difficulty ensuring contractors continued to apply the approach. Whilst PLR1 did ultimately deliver a functioning light rail system, whether that was done in a verifiable and optimal manner, is a question that should be asked. The Design and Construct (D&C) Contractors approached the delivery phase of the project from a more traditional project delivery method more akin to traditional PM methods again focussed on cost, schedule and quality and delivering to fixed outcomes, rather than applying SE. Whilst no major problems occurred, other than some experienced during testing, the potential for risk arising by moving to a different project delivery method at key phases, was nevertheless increased as a result.

M4 SMART Motorway. This Managed Motorway System (MMS) project was a testament to the efforts of two predominate and different technical groups who were responsible for delivering separate aspects of the same project; the civil engineering works team and the Intelligent Transport Systems (ITS) team. Both groups applied different project delivery methods; civil engineers used a straight construction approach on the civil works and the ITS team used SE on their more complex and highly technical ITS systems. However, both groups remained committed to and flexible to achieving the collective outcome in an integrated and functional form, which ended up occurring with the benefits of this project being achieved within the first 12 months of operation, namely reduced traffic incidents and less congestion. SE was the approach which was recognised as the project delivery method on M4SM, this was agreed to and applied consistently throughout the project, including into the Operations and Maintenance Phase of the MMS. Had this not occurred, the potential for the highly integrated approach and solution that was delivered as a result, would have been unlikely to happen.

Cross Case Analysis – Early Findings

Noting that a full cross case analysis is about to occur, the collective indications that come out of these four cases at this early stage are that SE is not applied across NSW Transport comprehensively and consistently. This is largely because it is instead seen as something that is time consuming, a lot of effort and not really delivering any more than the current project delivery methods that are already used in NSW Transport.

Whilst there are some instances and examples of where very effective application of SE has occurred on single instance transport projects, these remain isolated examples which are seen as a category of projects that due to their highly complex, heavily integrated and technically detailed solutions, require an approach to project delivery which warrants clear requirements specificity throughout the project which are progressively verified and validated, where integration and interfaces are critical to developing an aggregated system that works and fit in seamlessly to the existing transport network, which has a reasonable level of confidence that it will continue to work for its anticipated useful life.

The examples of the three projects used provide two instances of the benefits SE are able to bring to problems and issues, with one other example which highlights that where SE is not applied fully throughout projects, outcomes may be achieved, but not to the maximum extent that may have been possible. Consequently, SE is not utilised as widely and, in some instances, as fully as it could be within NSW Transport. More should be done to showcase the examples of where it is able to work effectively when applied correctly, to encourage further uptake of the practice.

The feedback obtained during interviews across the three project-level case studies revealed a recurring pattern: while Systems Engineering (SE) practices were recognised as valuable, particularly in technically complex or safety-critical contexts, there remained persistent institutional and cultural resistance to their full and consistent implementation. This feedback was used to inform the refinement of the initial Elementary SE Framework and supported the development of a more streamlined, dual-pathway model that could better account for the challenges of operationalising SE in a transport asset and infrastructure setting.

As the framework evolved through iterative analysis, the evolution of 'SE adoption' and 'SE application' methods that represented two distinct, but interdependent systems of activity, highlighted the need for a dual-pathway approach that addresses both the social readiness for SE and the technical execution of SE processes within project environments, as illustrated in the following section.

Emerging Systems Engineering Framework

Figure 4 illustrates the architecture of the Emerging Systems Engineering Framework. On the left, the SE Adoption Model outlines a context-dependent pathway for generating willingness, understanding, and alignment among stakeholders. On the right, the SE Application Model reflects a tailored implementation of ISO 15288-based processes, modified to the specific needs and complexity profile of the project. The input sources (highlighted in blue) represent key enablers, artefacts, and governance structures that inform both models. Importantly, the adoption process is not merely a precursor to application, but a dynamic feedback system that shapes how SE processes are scaled, sequenced, and communicated throughout the lifecycle. This integrated framework responds to the institutional realities of the NSW transport sector, where program heterogeneity, procurement fragmentation, and legacy delivery cultures have historically impeded the uptake of SE. The Emerging SE Framework offers a structured, yet adaptable, model for embedding systems thinking into transport infrastructure practice, and is currently the subject of ongoing research and validation to assess its generalisability across other sectors and jurisdictions.

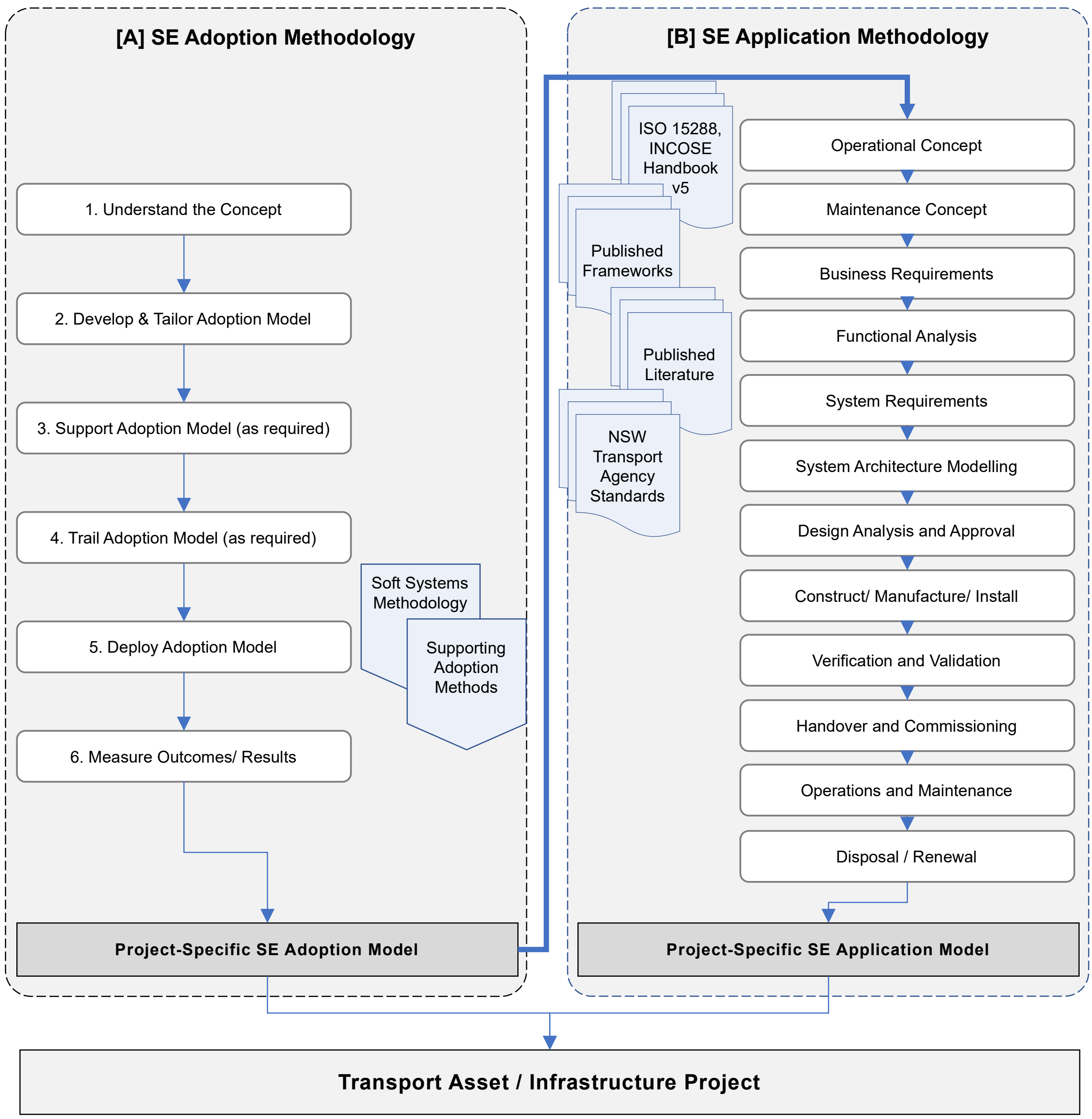

Figure 4. Systems Engineering Emerging Framework

The Emerging SE Framework integrates two distinct but interdependent methodologies: SE Adoption and SE Application to address both the socio-organisational and technical dimensions of implementing SE on transport asset and infrastructure projects.

On the left, the SE Adoption Methodology derives directly from the SSM workshop findings, which revealed that willingness, understanding, and stakeholder alignment must be established prior to formal SE implementation. This six-stage process begins with developing a shared understanding of SE, followed by tailoring and supporting an adoption model, piloting its use, deploying it at scale, and measuring outcomes. Supporting adoption methods, including Soft Systems Methodology, provide iterative feedback to ensure contextual fit.

On the right, the SE Application Methodology reflects a formal, lifecycle-oriented process consistent with ISO/IEC 15288 and the INCOSE SE Handbook 5th edn, supplemented by published frameworks, literature, and NSW Transport agency standards. It progresses from concept definition and requirements capture through system architecture modelling, design analysis, construction and installation, verification and validation, commissioning, operations, and eventual disposal or renewal. The application of SE as supported by agency standards provides a well-structured and process-oriented foundation for delivering complex systems. However, this formal application pathway often presupposes a level of stakeholder readiness and organisational maturity that does not consistently exist across transport programs requiring the SE Adoption Methodology to establish the pre-conditions necessary for effective application – specifically, the socio-organisational dynamics that influence whether SE is translated, understood, accepted, adopted and applied on project practices. Drawing on insights from the SSM workshops, case studies, and change management theory (e.g., Kotter's 8-Step Change Model; Normalisation Process Theory), the adoption model is designed to cultivate stakeholder commitment, overcome misconceptions, and progressively build confidence in SE as a value-generating discipline.

The two methodologies operate sequentially, with the Adoption Model preparing the organisational and cultural environment for SE, and the Application Model executing the technical processes in a project-specific, standards-compliant manner. This dual-pathway approach, grounded in participatory problem structuring and best-practice SE literature, ensures that both the human and procedural conditions for SE success are met, thereby addressing the systemic barriers identified in the Discovery Phase and elaborated on in the Development Phase case studies, and by consequence, builds on the rationale established for the initial and emerging SE framework. This dual-model approach represents a departure from traditional assumptions in the field, where SE is often introduced as a technical solution in isolation, without first addressing organisational readiness. As case study participants reported, attempts to apply SE without preparatory engagement often resulted in superficial compliance, procedural fatigue, or outright resistance. By contrast, sequencing the Adoption Model prior to the Application Model enables projects to surface latent concerns, align objectives across disciplines, and embed SE practices in a manner that is context-sensitive, staged, and socially legitimate.

Discussion

The Emerging SE Framework advances established project delivery applications of SE (e.g., Locatelli et al., 2013; Faulconbridge & Ryan, 2020) and lifecycle management approaches as defined in ISO/IEC 15288, while incorporating a dedicated SE Adoption Model that explicitly promotes the use and value of SE. This dual-pathway approach addresses both the socio-organisational and technical dimensions of SE implementation, and is designed to improve the effectiveness and efficiency of SE deployment in the transport sector, which has typically experienced fragmented and inconsistent uptake, despite clear evidence of SE's value in managing complexity, assuring integration, and delivering lifecycle performance in large-scale asset and infrastructure projects. By sequencing adoption activities ahead of technical application, the framework establishes the cultural readiness, shared understanding, and stakeholder alignment necessary for sustained implementation. It is anticipated that this approach will support SE practitioners and non-practitioners alike, enabling all project stakeholders to effectively collaborate to achieve verifiable, integrated, and whole-of-life outcomes on transport asset and infrastructure projects, while reinforcing established and validated SE application methods.

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Biography

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Roger Hadgraft is a civil engineer with more than 30 years of experience in improving engineering education. He has published many papers on problem- and project-based learning (PBL), and the use of online technology to support student-centred learning to meet the needs of engineering employers.

He was instrumental in introducing a project-based curriculum in civil engineering at Monash University and in several disciplines at RMIT. He established the Master of Sustainable Practice and Bachelor of Sustainable Systems Engineering, both at RMIT.

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