SYSTEMS ENGINEERING — THE RELIABLE METHOD OF RAIL SYSTEM DELIVERY

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Abstract—*This paper discusses the common issues and problems many rail system delivery projects face and provides insight into the way in which a systems engineering approach to rail system delivery would address them.*

Keywords—*collaboration, integration, rail system, requirements, systems engineering*

INTRODUCTION

Many rail system delivery projects suffer with similar, if not the same, issues and problems, which usually result in increased cost and/or schedule delays.

Within a highly commercial and competitive environment, rail projects are rarely able to deliver required long-term operational performance benefits while satisfying short-term project delivery objectives. In some cases, requirements related to a railway's long-term operational performance are compromised to fulfill short-term project delivery objectives, and overall performance is adversely affected. When the impact of such a compromise is understood, significant efforts are made to ensure that the project delivers what is required, but these efforts increase the project's cost and/or delay its schedule, to the detriment of the business case.

After a brief background discussion, this paper defines 10 key areas of a rail system delivery project in which issues and problems commonly occur. Then, in the next section, it describes how a systems engineering approach, especially when applied from the outset, provides a project team with a reliable method of managing a complex rail system delivery project effectively in a commercial and competitive environment.

Samuel Daw

srdaw@bechtel.com

BACKGROUND

Objectives of Rail System Delivery Projects

The primary objective for most, if not all, rail system delivery projects is to deliver the defined system within the financial targets and time constraints agreed upon between the customer and supplier, with minimal disruption to existing operations. The rail system's definition should accurately reflect the needs of its users, customers, and operations and maintenance personnel, and specify requisite features and functions, operational safety and performance requirements, and other requirements related to support over its life cycle.

Market Forces

The financial authority to undertake a rail system delivery project is usually based on the strength of the related business case, one which demonstrates that the perceived benefits to be delivered by the project will exceed anticipated costs and a reasonable return will be made over a reasonable period. Once a case has been made and the financial authority has been granted, the next step is to select a suitable supplier (prime contractor), usually through a competitive bidding process, the rigor of which will be aligned to the scale and complexity of the project. The procurement agent will be seeking a supplier that can fully satisfy the technical and commercial requirements, usually at lowest cost.

The successful supplier will most likely be the one that develops confidence in its ability to deliver what is required within the financial targets and time constraints set by the business case. In some cases, the procurement agent will work with the preferred supplier to further reduce cost and schedule associated with the project as a part of contract negotiation. Due to an environment where market forces prevail and similarly capable suppliers compete for the same work, cost and schedule can be driven down to unrealistic levels. It is not unusual for suppliers to accept very challenging and potentially

ABBREVIATIONS, ACRONYMS, AND TERMS

EN50126:1999	European Standard entitled "Railway Applications – The Specification and Demonstration of Reliability, Availability, Maintainability, and Safety (RAMS)"
EU	European Union
QA/QC	quality assurance/ quality control
RIA	Regulatory Impact Analysis
SDS	system design specification
SRS	system requirements specification
SSDS	subsystem design specification
SSRS	subsystem requirements specification

A supplier development process seeks to better understand the cost buildup of supply, encourages openness and innovation, and identifies improved and leaner ways of working as a means of reducing costs over the longer term.

unrealistic financial targets and schedules to secure competitive contracts to supply railway systems and subsystems.

Unfortunately, overly zealous attempts to drive down cost and shorten schedules to safeguard the business case can actually end up threatening it. The need for a supplier to make a reasonable return for its efforts may be overlooked. The competitive bidding approach sometimes aims at short-term cost reductions with little or no understanding of the challenges and cost buildup of supply, making long-term results very costly. In contrast, a supplier development process would seek to better understand the cost buildup of supply, encourage openness and innovation, and identify improved and leaner ways of working as a means of reducing costs over the longer term.

> "It's unwise to pay too much, but it is worse to pay too little. When you pay too much, you lose a little money, that is all. When you pay too little, you sometimes lose everything, because the thing you bought was incapable of doing the thing it was bought to do. The common law of business balance prohibits paying a little and getting a lot—it can't be done. If you deal with the lowest bidder, it is well to add something for the risk you run. And if you do that, you will have enough to pay for something better."
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> *—John Ruskin, English philosopher (1819–1900)*

When the business case is cost and/or schedule sensitive, the project needs to be managed particularly carefully to ensure that a financial return is actually delivered. In this respect, the sponsor will carefully monitor the progress of the project as a means of ensuring the investment.

Economies of Scale

Product sales volumes in the railway industry are significantly lower than product sales volumes in many other industries and markets. In addition, many railway administrations operate their railways differently and apply variants of products in different applications. Hence, the market size for rail products can be relatively small.

Unfortunately, this can lead suppliers to focus on their home markets and develop specific products for specific railway administrations, reducing the size of the overall market through which development costs can be recovered—in effect, increasing project costs. A number of global suppliers have begun developing generic products that can be used by multiple railway administrations, which allows development costs to be recovered over a wider market. However, these generic products usually require some form of adaptation before they can be used by a particular administration. In common with product development risk, product adaptation can also represent risk to project delivery.

Many rail projects seek to reduce technology risks by applying only "proven" technologies. However, unless the equipment has been previously applied, operated, and maintained in a very similar specific application environment, each new specific application represents some application risk.

Progress Measurement

Normally, project progress is measured by the achievement of planned deliverables. In other words, the supplier must deliver documentation, construction materials, equipment, and infrastructure, and other requirements, on an agreed upon schedule.

In many cases, measurements that quantify deliverables but do not take into account their quality—determine whether or not they truly fulfill project requirements—create a false sense of progress. This can result in the project moving from one phase in its life cycle to the next prematurely, and, like building on a foundation of sand, it is almost certain to introduce difficulties during later phases of the project life cycle.

Collaboration

It is worth noting that complex projects are delivered through the collaboration of people and organizations. Most project organizations, however, are based on vertical structures and organized into the engineering disciplines and functions that are required to deliver the project. Unfortunately, this type of structure does not encourage collaboration among various disciplines and functions—or even among individuals within these groups—in pursuit of a common goal.

To the contrary, verticality actually encourages the engineering disciplines and functions to work in isolation from one another toward their own objectives. This problem can be further exacerbated on major projects where these groups are geographically separated. Organizational problems can lead to rework, schedule delays, and increased cost.

Operational Concept

For many rail system projects, insufficient consideration is given up front to the definition of the operational concept. The operational concept defines how a system is intended to operate within the application environment, taking into account how it interacts with and influences adjacent systems, and the roles of its operators and maintainers. The operational concept should also define how operations are to be recovered in the event of a failure or disturbance, and the provisions that are required to facilitate preventative and reactive maintenance activities.

In most cases, operational principles having to do with safety are clearly set out, and rightly so. But operational principles related to performance and availability may be neglected. Without a well understood and clearly defined operational concept, it is difficult to develop an accurate and complete set of system requirements and to convey those requirements between customer and supplier.

Crucially, the system's inability to support an effective operational concept is only discovered during system validation, or worse, later.

Standards

In many cases, projects are required to demonstrate compliance not only with customer and/or contract requirements, but also with a range of related standards, such as legislative and industry requirements and local custom and practice.

The process of identifying relevant standards and eliminating those that are not relevant can be time consuming, as is the subsequent capture, apportionment, and tracking of requirements.

When the hierarchy of industry and legislative standards has been aligned, compliance to high-level requirements can be proven simply by demonstrating compliance with the low-level requirements, as they are derived from the high-level requirements.

However, in some cases the hierarchy of industry and legislative standards may not be aligned. Furthermore, many standards are based on the solutions already in use on the railway, and while it may be possible to extrapolate the underlying requirements for the existing solutions, it can be difficult to achieve agreement of these underlying requirements.

For the supplier of modern products and systems, this can significantly increase overheads associated with the management of standards and noncompliances, and, in some cases, it can lead to delays in the acceptance of new products when the underlying requirements are unclear.

Complex projects are delivered through the collaboration of people and organizations.

Definition and Apportionment of Requirements

For many projects, system and subsystem requirements are poorly defined, if they are defined at all. While it is an objective of many projects to make use of existing products and systems in new applications, and rightly so, the purpose of tracking requirements is to ensure that customer, contract, legislative, and industry requirements are all satisfied. One of the main reasons for defining, apportioning, and tracking the requirements through design and verification is to demonstrate this compliance. As such, it is an important means of determining to what degree requirements can be fulfilled using standard products and systems, allowing potential gaps to be identified so that appropriate action can be taken.

In some cases, customer requirements are used as the basis of apportionment to the subsystems, leading to difficulties in subsystem delivery and systems integration. Customer requirements usually contain:

- Actual customer requirements
- System requirements
- Useful information
- Constraints

System requirements should define "what" is required of the system in order to fulfill the customer requirements and to deliver the operational concept. Quite often, the definition of system requirements is missed altogether, and the project concentrates on the definition and fulfillment of subsystem requirements, in some cases defined around product specifications, rather than through the definition and top-down apportionment of system requirements.

All in all, the definition of "what" the project is required to deliver can be quite poor. While the system may demonstrably fulfill the requirements that have been defined, missing features and functions are normally identified at a very late stage of the project, usually during validation, with significant impacts on project delivery.

Systems integration actually takes place when the scope of the subsystems is defined.

Project Life Cycle

Another common feature of rail projects appears to be the desire to "get on with the job," and move into detailed design and construction as soon as possible. Enthusiasm for progress sometimes causes a project to move from one phase to the next before it is ready to do so. Even when deliverables and content from a previous phase are found to be missing, and attempts to complete them are prioritized during the current phase, enthusiasm for progress may lead the project to advance prematurely yet again to the next phase. But in such cases, it is usually only a matter of time before the project arrives at a point where incorrect assumptions have been made and rework becomes the order of the day.

Project Processes and Procedures

A related project deficiency is the lack of suitable project processes, which should be rolled out to those that are required to implement them from the outset. A manual of project processes and procedures should be developed that documents the way in which members of the project team have agreed to collaborate and work together.

In some cases, the task of defining project processes and procedures is allocated to the quality assurance/quality control (QA/QC) function. While members of the QA/QC function are capable of writing project processes and procedures, these documents may not necessarily reflect the way in which the project team members intend to work together.

In other cases, there is a belief that the project team knows what it is doing because it has delivered similar projects before. While this may be true, it is almost certain that the project team has not delivered a rail system with the identical group of people, or with the identical conditions of this particular application.

Ironically, with experienced and competent individuals, project processes and procedures should be easily agreed on and defined; but it's not the experienced and competent individuals who will need to refer to and rely on them most—it's those who are less experienced and competent.

On many projects, processes and procedures are treated in isolation from one another and are not integrated, with the catchall statement "to be read in conjunction with …."

If the way in which processes and procedures relate to one another is left open to interpretation, there is room for error. This has an impact on a project's ability to deliver the system effectively. It can lead to an alarming audit trail and further burden the project with corrective actions, some of which may be valid, but many of which are not, distracting the project's attention from the delivery of the system.

Project Schedule

Another common weakness in many projects is the way in which the project schedule is developed and managed. In many cases, each project discipline and function defines its own sub-schedules, and attempts are then made to join the sub-programs together at the master program level.

Due to the level of complexity of integrating the sub-schedules, as a compromise the sub-schedules are sometimes rolled up a level and integrated into the master program at a higher level only. Obviously, this means that any necessary integration at the detailed level can be missed, resulting in inputs that are not always made available when required, and information that is not exchanged as needed.

Systems Integration

In many projects, systems integration is perceived as the stage in the project where the black boxes are connected together and where validated subsystems are integrated with one another to form the system.

Systems integration actually takes place when the scope of the subsystems is defined, i.e., when system requirements are apportioned to the subsystems. At this stage, the system has essentially been disintegrated in such a way that parts of the system can be delivered in a manageable way and effectively integrated with one another at a later stage. Hence, the system is designed for integration.

Due to this misconception, systems integration is not always properly considered during early project phases. Also, a systematic approach to systems integration is sometimes lacking, and projects fail to identify the integration risks they face at an early enough stage. As a result, they fail to take positive action to eliminate integration risks at an early stage of the project.

Competence Management

One issue that is faced on almost every project is the effective management of competence. Staff are sometimes appointed to roles based upon their capability rather than their competence. A capable person is someone who can recognize the competencies required to undertake a role, develop those competencies, and then undertake the role.

Hence, if we appoint capable individuals, they will get the job done, but much of their time in the early stages will be spent learning rather than doing. If this learning period is not recognized and carefully managed, perhaps through mentoring, it can lead to inappropriate decisions and inappropriate direction for the project during early stages, decisions and direction that must be maintained to save face.

Role of the System Authority

In many systems projects, the need to establish a system authority from the outset is not identified. In complex, multidisciplinary projects, it is not usual to identify a single person who understands all of the technical issues and challenges faced by the project and who is able to take all of the significant decisions and set the project direction in the interests of the project.

Normally, a system authority would be constituted, usually someone with diverse expertise, to provide strong direction, make good decisions, and manage and coordinate the activities of the subsystem delivery teams. Without the system authority, it is possible that a suboptimal solution will be delivered that will adversely impact operations during initial operations, at least until problems and shortcomings are resolved.

SYSTEMS ENGINEERING APPROACH

Collaboration

A systems engineering approach clearly recognizes that projects are delivered through the collaboration of people and organizations. For example, the approach toward the definition and integration of project processes and procedures, as described in later sections of this paper, encourages collaboration from the outset, with project staff working together to agree on the way in which they will deliver the project.

The organization of the project, taking into account the various constituent engineering disciplines and functions and their geographical locations, is a key element of the project design as the vehicle to deliver the system. While a vertical organizational structure is valuable from the outset, allowing like-minded individuals to work together as they develop and refine their thinking, it can constrain the overall collaboration. Groups in such organizations often end up at cross purposes when issues, challenges, and problems arise.

In some instances, changing from a vertical organizational structure (based on various engineering disciplines and functions) to a horizontal organizational structure with multidisciplinary and multifunctional teams (based on tasks to be undertaken and deliverables to be produced) can greatly improve collaboration. However, the timing of the change is important and, as with any organizational change, requires sensitive management.

The organization of a project is a key element of project design as the vehicle for delivering a system.

Operational Concept

The systems engineering approach embraces defining the operational concept from the outset, and uses modeling to check and confirm understanding with all affected stakeholders, and to demonstrate the operational benefits to them, when possible, to secure their buy-in.

By using modeling, as appropriate, the operational concept can be validated from the outset, providing a graphical definition of the way in which the system is to operate, including the various modes of operation and human-system collaboration. This approach also fosters a common understanding between customer and supplier at an early stage.

Baselines of Standards and Stakeholders

A systems engineering approach establishes clear baselines of relevant standards and key stakeholders from the outset, including a record of decisions and justifications relating to the selection of standards and stakeholder input.

The baselines are subject to rigorous change control, such that the implications of any changes in inputs arising through changes in either related standards or related stakeholder input can be readily identified and considered prior to acceptance or implementation.

Definition and Apportionment of Requirements

Systems engineering takes a systematic approach to the development and definition of customer requirements, and to defining acceptance criteria for each requirement—i.e., what the project is required to do to demonstrate that customer requirements have been fully satisfied.

Similarly, a systematic approach is taken toward defining system requirements and the associated verification criteria—i.e., what the project is required to do to verify that system requirements have been fully satisfied.

A systems engineering approach encourages collaboration on a project from the outset.

System requirements and the design outline are then refined through analyses and assessments from different perspectives, such as operability, safety, performance, human-factors integration, constructability, maintainability, etc., in an iterative manner. Also, system requirements are apportioned to the subsystems according to the outline system design.

Importantly, the systems engineering approach aims to determine the minimal set of system and subsystem requirements necessary for full coverage. Getting that balance right from the beginning is essential, because establishing too many requirements will overburden the project, while establishing too few can lead to deficiencies in the system's design and operability.

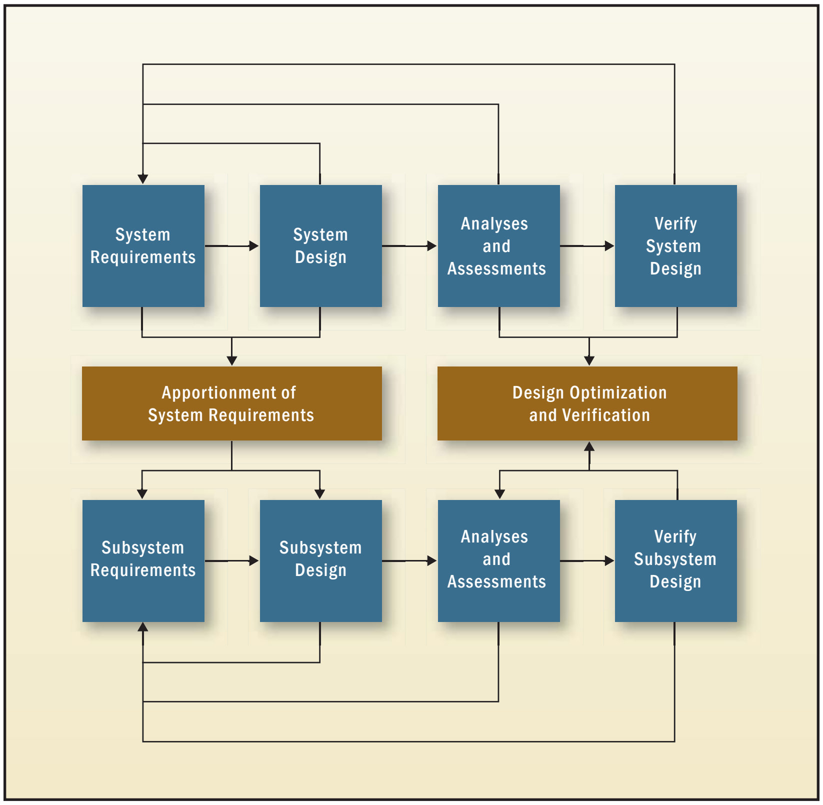

Figure 1. Iterative Refinement of Requirements and Design

Figures 1 and 2 provide illustrations of the iterative approach to the refinement of system requirements and system design, to the apportionment of system requirements to subsystem requirements, and to the refinement of subsystem requirements and design. They also show how the system design is updated to reflect each decision made during the detailed design of the subsystems.

Project Life Cycle

A systems engineering approach defines an appropriate project life cycle model at the outset, one that takes into account the profile of technical and commercial risks over the project life cycle. The life cycle may be based on an industry standard life cycle, e.g., EN50126:1999, but it is tailored to ensure its applicability to the project, taking into account the nature and context of the system to be delivered, its constituent subsystems, and their relationships to the system and to one another. By this means, the system management task is clearly defined.

Objectives, inputs, requirements, outputs, and phase verification criteria are clearly defined for each phase of the project life cycle, and it is only possible to move from one phase to the next when all requirements of the current phase have been demonstrably fulfilled.

Figure 3 provides an illustration of a project life cycle for a typical railway system delivery project, based on EN50126:1999 and organized as a "V" representation.

Project Processes and Procedures

A systems engineering approach seeks to define and harmonize the processes and procedures to be implemented by the project through a collaboration of the personnel who are required to implement them—effectively defining "how" they intend to work together to deliver the project, and encouraging a collaborative approach from the outset. Inputs, tasks, and outputs are clearly identified for each process, and processes are integrated with one another to ensure that all inputs can be satisfied and that owners of shared information take into account the needs of users.

The processes may be integrated through the use of a matrix, providing visibility of owners and users of shared information. This approach allows interactions between the various processes to be clearly identified, and aims to establish a dialogue between owners and users as to the format and content of information to

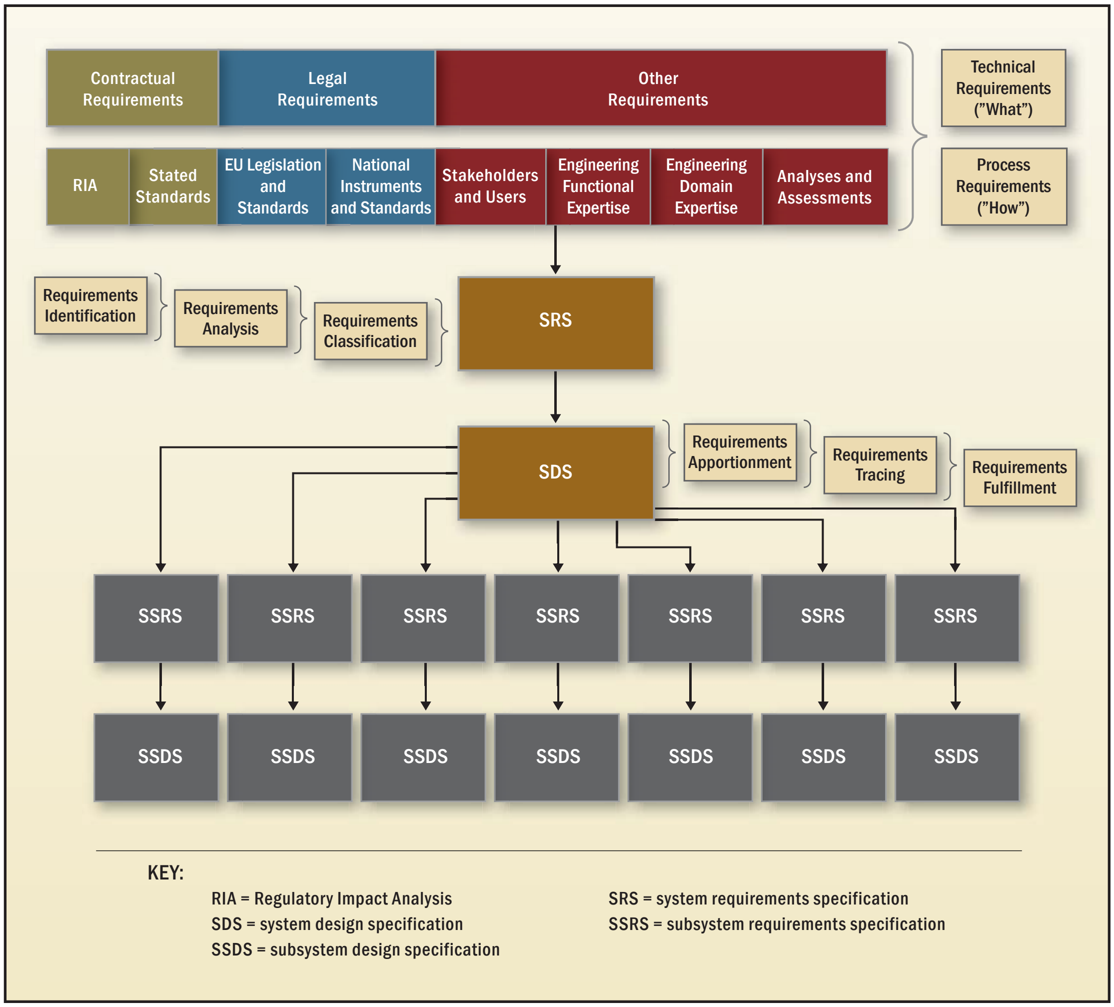

Figure 2. Apportionment of System Requirements

A systematic approach is taken toward defining system requirements.

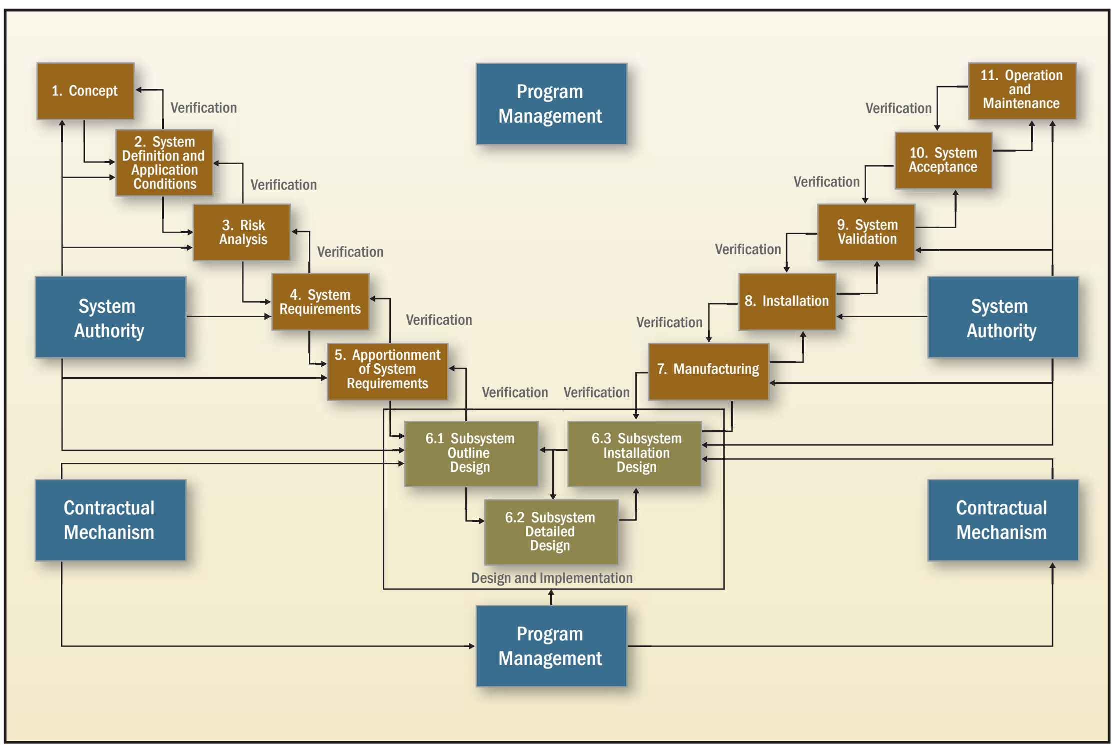

Figure 3. Typical Project Life Cycle

be shared and exchanged. Hence, it encourages collaboration among the various engineering disciplines and functions within the project.

Project Schedule

Following a systems engineering approach, the project schedule is based on the project life cycle and processes, and includes detailed information relating to task ownership and task durations, etc. By this means, the schedule reinforces project processes and procedures and vice versa.

The schedule is carefully checked to ensure that all inputs will be made available as they are needed, and that all outputs required of the project will be delivered. If a required input is not clearly identified in the schedule, it is doubtful that it will somehow materialize on time. Therefore, it is crucial that all inputs and outputs are included in the schedule.

The systems engineering approach was deliberately conceived to ensure that the long-term objectives of a project are fulfilled in an ever-changing external environment.

Systems Integration

A systems engineering approach will aim to ensure that the system is specifically designed to enable integration, recognizing that system integration actually takes place during the apportionment of system requirements to subsystem requirements.

Integration risks are clearly identified and ranked at an early stage of the project life cycle, and specific activities are defined to mitigate potential risks at the earliest opportunity, making use of modeling, simulation, and testing as appropriate. As with all other project-related activities, it is essential that systems integration risk identification and mitigation activities be included in the project schedule.

Competence Management

A systems engineering approach seeks to identify the competencies that are required for each of the roles to be undertaken within the project. The aim is to employ both competent (with significant relevant experience) and capable individuals (with the ability to become competent with experience), and ensure that early decisions are made by those who are competent to make them while capable individuals are being developed and mentored in their project roles.

The mix of personal characteristics required to contribute to project definition, development, and delivery requires careful consideration. Most projects attempt to retain technically competent staff from start to finish, mainly for consistency and familiarity reasons. However, this may not be in the best interests of the staff or project for a number of reasons. During the project's initial phases, personnel who are "shapers" are needed to conceive and establish the project structure, as the vehicle for delivering the system, although they must be kept within the bounds of reality by well-grounded individuals. As the project progresses, "completer finishers" are needed to focus on delivery. Getting the balance of personality characteristics wrong in personnel who are assigned to each phase can adversely impact a supplier's project delivery performance.

Role of the System Authority

Depending on the nature and complexity of the system to be delivered, a systems engineering approach will implement a properly constituted system authority, whose role and responsibilities will be clearly defined, with decision-making authority to provide:

- Guidance and direction, based on highly relevant, broad experience
- System management, including oversight and coordination of subsystem delivery projects, interfaces, systems integration, and change management
- Long-term thinking

CONCLUSIONS

Systems engineering is an effective means of addressing many of the problems that we predictably experience in rail systems delivery projects. It ensures that customer requirements are actually delivered by the supplier in the most effective and efficient manner.

The systems engineering approach was deliberately conceived to ensure that the long-term objectives of a project are fulfilled in an ever-changing external environment by the most efficient route possible, focusing the minds of customers and their suppliers on a common goal based on a common understanding.

Ideally, systems engineering starts at the outset of project definition and continues as the facilitator for effective rail system delivery throughout the project life cycle. Although systems engineering is unable to prevent false expectations from being agreed upon at the outset, it represents the most reliable method available for successful rail system delivery.

Unfortunately, it seems that systems engineering is not well understood in the railway industry, and its half-hearted implementation on many projects has resulted in easily preventable project delivery difficulties. Managers of rail system delivery projects often don't recognize the need to adopt a systems engineering approach until their projects experience difficulties. Fortunately, even when systems engineering is not applied until the middle stage of a project, it can be used to minimize the impact of difficulties on the outcome—although in some cases the approach may be applied too late to fully recover and satisfy all of the project objectives.

To reap its maximum benefits, a systems engineering approach should always be implemented at the start of a rail systems delivery project and applied throughout its life cycle, until successful system completion and turnover is accomplished. ■

BIOGRAPHY

Samuel Daw's 24 years of experience in the railway industry includes 2 years with Lloyd's Register Rail Limited as head of systems integration, 4 years with Siemens Transportation Systems as principal engineer for products and systems engineer, and 3 years with Bechtel Civil as a rail systems engineer. Sam began his career as an electronic technician apprentice with ABB Signal Limited, in Plymouth, England, where he advanced to the position of electronic design engineer before joining Adtranz Limited (ABB Daimler-Benz Transporation/Signal), in Plymouth as product manager.

Sam's extensive technical experience in rail systems covers systems integration and systems integration management, including operational concept definition, modeling, and validation; requirements engineering; project life cycle definition and integrated process definition and implementation; and system architecture and interface control.

Sam is a chartered engineer and registered European engineer. He is also a member of the Institution of Engineering and Technology (IET), the Institution of Railway Signalling Engineers (IRSE), the Institute of Electrical and Electronic Engineers (IEEE), and the International Council on Systems Engineering (INCOSE).

Sam earned a Diploma in Management Studies with distinction and a Certificate in Management from the Plymouth Business School, University of Plymouth, Drake Circus, Plymouth, England. He also holds a BE in Electrical and Electronic Engineering with honors from Polytechnic South West, Drake Circus, Plymouth, England.