Guide for the Application of Systems Engineering in Large Infrastructure Projects

Developed by the INCOSE Infrastructure Working Group

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Notices

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Preface

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Table of Contents

1 INTRODUCTION

1.1 FOREWORD

This Guide is intended for an international audience. For the sake of consistency with other publications produced by INCOSE, such as the Systems Engineering Handbook, this Guide was written following the US English Standard.

1.2 SCOPE

This Guide covers the application of Systems Engineering (SE) practices to Large Infrastructure Projects (LIPs). Such projects include the construction of infrastructure (e.g., highways, railways, electricity generation and distribution, water collection, storage, and distribution, and waste water collection and transfer), and the construction of major industrial plants, such as oil & gas platforms, refineries, mines, smelters, water and wastewater treatment and steel works.

These projects may include a design stage, if this has not been completed prior to going to construction, but the emphasis of this Guide is on how to use SE practices to better perform the construction stage of a project. The focus is on the realization of the designed (or engineered) solution during construction and the transition into service of the resulting built product, and as a consequence, the application of SE practices is concentrated more on the construction process than on the design of the product [1] or on the continuing operation and maintenance stage.

1.3 PURPOSE

The purpose of this Guide is to reposition traditional SE practices, as it has been successfully developed and applied in the defense, aerospace, manufacturing and telecommunications industries, into the context of the construction industry and thereby provide professionals engaged on LIPs a convenient and comprehensive access to the relevant parts of the system engineer's toolkit.

The Guide is not an introduction to, or textbook on, SE and it is assumed that the user will have either some understanding of good engineering practices or take the time to access the references highlighted throughout the Guide. However, for completeness, Appendix C gives a brief introduction to SE.

1.4 STRUCTURE OF THE GUIDE

To achieve this purpose, the Guide presents the case for applying SE practices to LIPs and, particularly, to the planning and management of the construction process (Section 2) and then describes a LIP from a systems viewpoint to establish concepts (Section 3) that are then used to explain how the application of SE practices can be beneficially used to better execute the construction process (Section 4). The Guide concludes with Section 5 which summarizes the recommendations for applying SE practices to LIPs. The appendices provide additional reading for those interested in gaining further background and contextual information.

Readers who want to understand how the authors arrived at the guidance and therefore its formulation should read the entire Guide; those wishing to just understand and apply the guidance should first read Section 5 and then Section 4.

2 THE CASE FOR APPLYING SE PRACTICES TO LIPS

2.1 CHARACTERISTICS OF A LIP

A LIP normally starts as a high level problem statement (e.g. more power needs to be supplied to area X or more people need to get from A to B in a shorter time) by a major stakeholder (e.g. a Government Agency). The definition of the solution to the problem emerges from the consideration of options and the development of a conceptual design. Thus the project starts to specify a particular solution (e.g. a new nuclear power station, a wider highway or a high speed railway) and the way to achieve it (see Appendix C3 for various implementation strategies). Throughout this stage the LIP depends on a large number of uncertain and optional factors for which the estimated costs can vary substantially. In new and unique fields the lack of sufficiently similar reference cases creates a major headache for cost estimators.

A LIP often does not become a sustainable project until funding is allocated against a solution that has been assessed for its constructability. From that point onwards, the design concept is developed in more and more detail and this elicits additional requirements from stakeholders and clarification of the design choices until a detailed specification of the design solution, the Product System, is established. At this stage the cost for the Product System, assuming a specific implementation process, can be estimated relatively accurately. However LIPs generally take a long time to complete (often years rather than months) and the project environment (economical, political, legislative, technological, etc.), and hence the stakeholders' expectations and design solution, can change significantly over this extended period.

2.2 RELATIONSHIP BETWEEN LIPS AND SE PROJECTS

We can consider the LIP to consist of two main stages; the development of an engineering solution in the form of a detailed design and, the delivery of the design solution through procuring contractors to build or construct the solution, as indicated in Fig. 2.1.

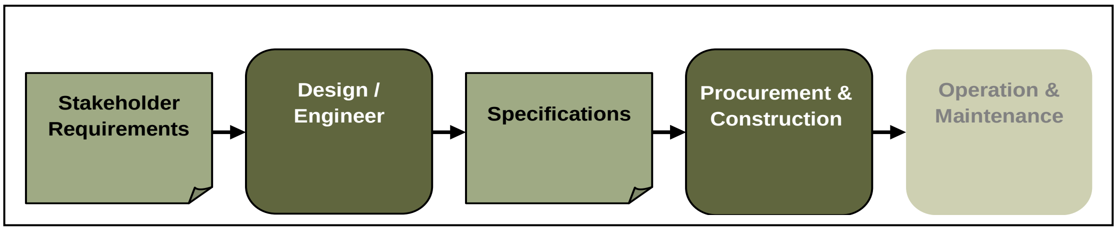


Figure 2.1 High-Level View of a Traditional LIP Lifecycle

It is by comparing the nature and relative extent of these stages in the case of a project in the aerospace and defense industries, or, more generally, the manufacturing industry, with the case of a LIP, that we realize the challenges that have to be faced when applying the existing SE body of knowledge [2] to LIPs.

In the case of the manufacturing industry, the deliverable is most often numerous items of the same product, such as the same airplane, car, radar, or mobile phone, and the effort that goes into developing and testing the detailed design before entering mass production is usually many times the cost of a single item. Design is also a technically complex stage, with leading edge technology from different disciplines required to meet very challenging specifications, intense interaction with multiple users, and so on. Consequently, many of the SE processes are either directly concerned with this design stage, or relate to the management of the technical complexity when addressing other project aspects.

In the case of a LIP, such as a major highway or railway, it is not always possible to develop or test a prototype; the first item is the only item. The technology involved may not develop as quickly as, for example, in electronics; the design is, to a large extent, circumscribed by standards and codes; the technical solutions will be similar to those of recent projects, and the cost of the design will be a fraction of that of the implementation, which in this case is the construction stage. Due to these factors, the design processes for LIPs tend to be relatively well established and reasonably optimized and any complexity to be addressed lies more in issues of interfaces, procurement and constructability, given the specific political, commercial and local conditions, than in the design of a certain type of bridge, the particular alignment of a railway or highway or the type of power generation plant.

The procurement and construction stage, on the other hand, is usually rather unique and quite specific; each project faces new ‘on-the-ground’ conditions and a host of challenging decisions relating to temporary works, enabling works, land use for equipment and material storage, site and service access without disturbing existing operations, allocation of heavy equipment, access to utility services, management of multiple work sites, workforce accommodation at remote work sites, sequencing of work, the interaction of numerous contractors on the same site, and many more.

2.3 ADDRESSING COMPLEXITY

In LIPs there are many complexities. There may be a number of outcomes required by a variety of stakeholders, some seemingly contrary to each other, and many alternative ways to satisfy the requirements all competing for priority and for the same resources and finances.

For projects that have a long time span, construction will often begin before engineering is complete. Situations such as these require a systematic approach in order to keep the project aligned. These circumstances add significant complexity to otherwise straightforward processes. For example, design change analysis will require not just consideration of the affected system/sub-system designs but also of the procurement and construction status of all interacting systems and facilities. Careful analysis to identify all the potentially affected organizations, structures, systems, people and processes is required to ensure proposed changes will not adversely impact other areas and, will lead to the required outcome.

It has been found that, in general, the brain’s ability to work with (e.g. to remember or to change) concepts declines rapidly once they are described by more than about seven parameters. It can be useful therefore to reduce the complexity of any object by taking a ‘systems view’ of the whole project and breaking it down into smaller, simpler, interacting parts which can be organized and managed more easily.

The application of the system view is used to demonstrate how we control the design solution of our LIP so that we then address the complexities associated with how we manage the delivery of it during the construction stage.

2.4 ADDRESSING UNIQUENESS

For many types of infrastructure project, such as high-rise office blocks and residential buildings, the construction process is relatively efficient as a result of having been performed many, many times; such that we can consider each project being an incremental step in a long, continuously improving development process. However, because LIPs have a degree of uniqueness it is difficult to standardize and therefore to optimize the construction process itself.

A structured, systems approach to managing the project's three critical factors (cost, time and quality) which can be applied on any LIP is therefore proposed. Also, by modeling the particular characteristics of the LIP using SE practices it is proposed that an appropriate contracting strategy can be formulated.

2.5 ADDRESSING UNCERTAINTY

One characteristic of LIPs is the lack of scope and cost certainty. This has led to the development of a number of procurement approaches that allocate the risk of this uncertainty in different ways e.g. Engineer Procure Construct (EPC), Design and Build (D&B), Private Finance Initiative (PFI), Public Private Partnership (PPP), Alliancing and Build Own Operate (BOO) (see Appendix C3).

This Guide uses a LIP lifecycle based on the Engineer Procure Construct (EPC) approach so as to focus on the particular challenges faced during the construction stage by the Procurers and the Contractors. However alternative contracting strategies and their consequences are described in Appendix C3 for information. In general, the alternative strategies affect how the various risks associated with cost uncertainty are apportioned and do not fundamentally affect the Construction Process itself.

2.6 MOTIVATION

The motivation for introducing SE processes on LIPs is a desire to better manage the risks associated with the likely significant degree of change in the environment and associated scope of the project over the extended timescales. Also, the construction process on LIPs can be complex and therefore would benefit from being carefully planned and controlled through implementation using a structured, systematic approach.

The business case for this Guide, therefore, is the generally accepted view (see Appendix C.1) that the industry could benefit from better organization and integration of activities leading into and during the construction stage of the project lifecycle. This would help manage the uncertainty associated with the cost estimation and changing scope and could improve construction productivity hence making the industry more cost effective and therefore possibly more beneficial (profitable) for constructors.

3 THE SYSTEMS VIEW OF A LARGE INFRASTRUCTURE PROJECT

3.1 THE PRODUCT OF THE PROJECT

For the purposes of this Guide we start the definition of the System to be produced by the LIP, the Product System, at the stage where it is a proposed solution, a conceptual design, to a set of stakeholder requirements. At this stage the System Architecture[1] is a graphical description of the System (often supported by text and data) that shows the complete System at the highest level and, as a minimum, includes:

- The total System;
- External interfaces;
- Next lower level systems/sub-systems and their interfaces.

Once the System Architecture defining the design solution is sufficiently developed, the lower level systems, sub-systems and components can be progressively developed. The logical decomposition of the System is called the System Breakdown Structure (SBS) and needs to consider:

- How the System is going to be procured i.e. the elements to be packaged into separate contracts and agreements.
- How the System will be designed, built and integrated - the disciplines involved (e.g. Process, Civil, Mechanical, Electrical and Software Engineering) and the order of manufacture or construction and proving and bringing into service.
- The arrangement of the functions and management of critical interfaces.

3.2 THE LIFECYCLE OF THE PROJECT

The LIP has a lifecycle with discrete phases (separate delivery and introduction into service of a version of the System) and stages (separate increments of the lifecycle for each phase).

The work to be done for each phase of the System is defined as a high level activity chart that clearly identifies and relates to the stages of the lifecycle. For the purposes of this Guide a simplified version of the traditional SE Lifecycle [3] is used (see Figure 2.1) which identifies the Engineering or Design Stage, the Procurement and Construction Stage and the Transfer into Operation and Maintenance Stage).

[1] LIPs often engage an Architect at the concept design stage and so there is a need to avoid confusion that might arise in both the stakeholder community and the project team by careful use of the term ‘architecture’. However, there is a close relationship between the product of the Architect of a building and that of the SE, so it is recommended that the System Architecture references the Architect’s drawings to show where they fit into the SE Framework for our LIP.

This high level lifecycle is decomposed in a Work Breakdown Structure (WBS) that must relate to both the SBS and the way the work is to be divided between different organizations, the Organizational Breakdown Structure (OBS), as it will define who and how each part of the System is going to be successfully completed.

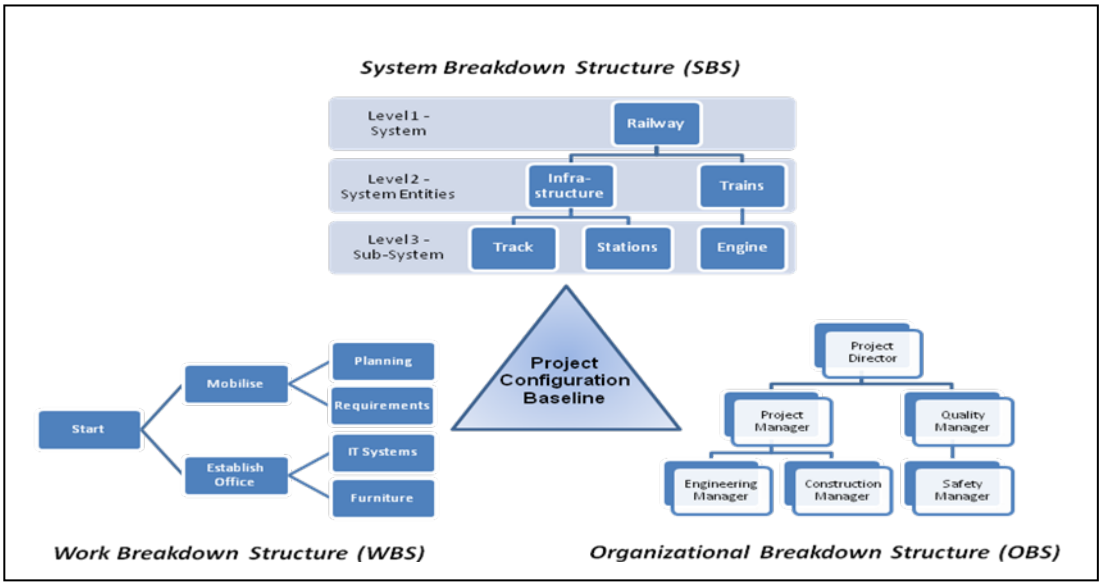


Figure 3.1 Relationship between System, Work & Organizational Breakdown Structures

3.3 CONTROLLING THE PROJECT DYNAMICS

For our LIP we tend to get the main funding approval, the approval to commit funds to construction contractors, once we have a definition of the Product System in sufficient detail to accurately estimate the project cost and schedule and to understand and quantify the areas of risk that may affect the project. We have the definition of a Product System that is expected to achieve specific functions which have certain performance, reliability, availability, maintainability and safety (PRAMS) characteristics. At the start of the construction stage, as well as the specification of the Product System, we also have a defined budget (the estimated cost) and timescale (program or schedule). This defines each side of the LIP's Project Management Triangle for Cost, Time & Quality, as illustrated in Fig. 3.2.

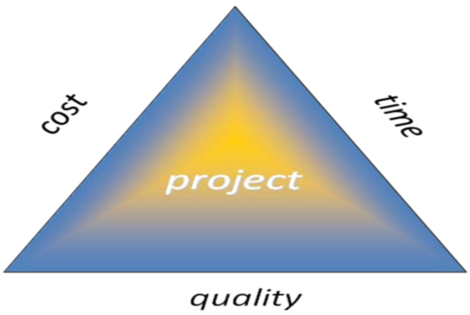


Figure 3.2 The Project Management Triangle.

The objective of our LIP is to deliver the System (achieve the agreed solution and meet all requirements (as progressively changed under control through the project lifecycle)) while maintaining a ‘balanced PM triangle’, in the sense of balancing the weights assigned to the three sides of the triangle as agreed between all the parties involved.

Using a framework based on an interrelated WBS, OBS and SBS the time and cost of each work package, each contributing organization and each element of the System can be seen, hence making it relatively straightforward to monitor and, if necessary, make adjustments so as to maintain a balanced PM Triangle. The project should be baselined (captured) using the WBS, OBS and SBS at appropriate milestones (e.g. at the end of each lifecycle stage) so that the LIP’s time, cost and quality is synchronized to a consistently defined scope. Changes to the project from one baseline to the next are controlled using the Configuration Management SE practice (see Section 4.4.2 and 4.4.3).

3.4 MEASURING SUCCESSFUL DELIVERY

To measure our success, we need to start out with an agreed definition of the System with both the stakeholders that are to accept the product of the LIP and the parties responsible for its delivery. This definition is called the Required System Build Configuration (RSBC). The success of the LIP will, in part, be measured by demonstrating achievement of (validating) each item of the RSBC (i.e. each configuration item). The extent to which the RSBC is delivered in compliance with specifications (such as regulations, design codes and standards) and how well the resulting System is verified, validated and documented will determine the quality of the LIP.

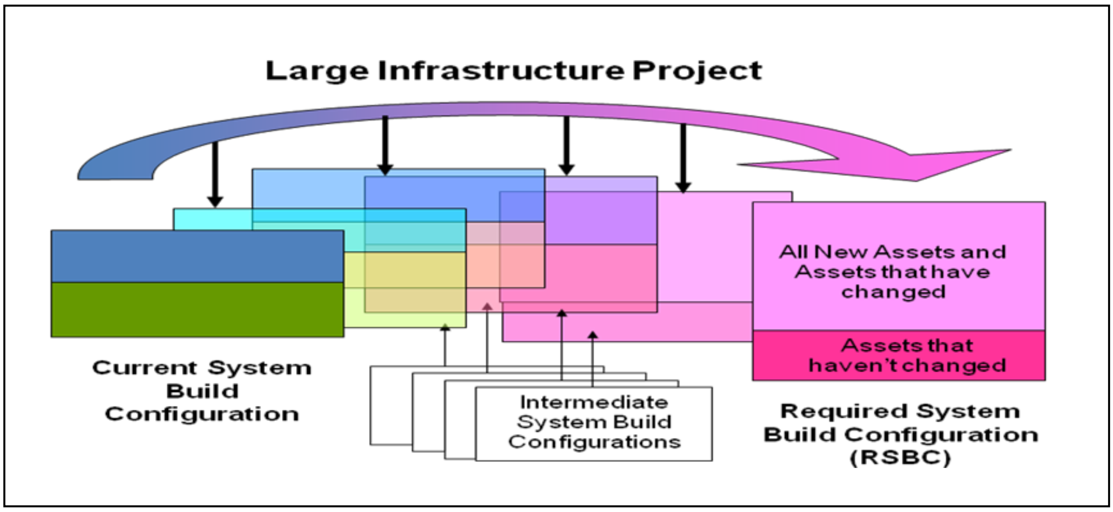


Figure 3.3 How the SBC evolves through the Project Lifecycle.

Other measures of success will be associated with the balance of the Project Management Triangle; how much it cost and how long it took. If we control what is actually being built, in the form of the System Build Configuration (SBC), throughout the project lifecycle, then the metrics associated with changes to the System, its cost and its timescales should be captured in the process so as to provide the relevant metrics against which the successful balance of the Project Management Triangle is judged.

Thus the SBC needs to be closely monitored and managed. Designs often change, for instance due to unknown field conditions which become apparent during the construction stage. In addition, stakeholders often change their requirements as their expectations vary over time, they better understand the detail of the solution or some significant external factors emerge. These changes will result in an update of the RSBC. The actual definition of the SBC therefore needs to be a living document, with progress and modifications captured throughout the project lifecycle. The final SBC will be validated against the revised RSBC, and the project as a whole against the stakeholders' goals and objectives.

3.5 CONSIDERING THE PROJECT AND POST –PROJECT CONDITIONS

3.5.1 THE PROJECT ENVIRONMENT

LIPs usually have a long lifecycle from problem definition to solution delivery. Their cost is high and the impact on the physical environment is often significant. There are also usually a lot of stakeholders involved and often there are many different interests with different views on the balance between cost and benefit. Therefore LIPs tend to be subject to influences that are political, social, environmental and economic. Changes are often associated with a need to reduce cost (or get more for the money being spent), meet additional or changed (more rigorous) regulations or to achieve more demanding timescales. Changes also 'emerge' as the SBS, WBS and OBS develop and contracts are negotiated. It is not surprising therefore that many LIPs change substantially in scope, quality, time and cost over the life of the project.

It is important therefore to have a method for managing the change that itself does not consume an inordinate amount of time and cost; rather one that is a natural and continuous part of the project process. The structured System definition (SBS), systematic work breakdown (WBS) and structured allocation of responsibilities or contracts (OBS) described above facilitates strong management, and hence control, of the SBC, including all internal and external interfaces, throughout the project lifecycle.

The complexity of the external environment in which LIPs are usually embedded has led to the development of various approaches for understanding this environment. Prominent among these is a methodology called PESTLE analysis (acronym for Political, Economic, Social, Technological, Legal, and Environmental) [4].

3.5.2 THE POST-PROJECT ENVIRONMENT

Using the SBC as the way the System is defined during the project allows us to continue to have a coherent view of the System once it has been delivered, so long as the SBC is maintained by the Operations and Maintenance (O&M) organizations. Later phases of the LIP then extend, modify, update, refurbish or replace the existing SBC; all of which can be controlled in a systematic way using Configuration Management practices (see Section 4.4.2 and 4.4.3).

The LIP delivers the constructed System (its Product) into the O&M stage of its lifecycle, which may end with the replacement and/or decommissioning of the System. In the O&M stage different parties often take responsibility for ownership, operation, maintenance and development of the System. The transfer of the System into this stage needs to consider the same issues regardless of the procurement model used, albeit the transition stage will cross different organizational and contractual boundaries depending on the model in place.

Even if the System handover is from one party (e.g. the Engineer, Project or Construction Manager) to only one other (e.g. the Owner) there are likely to be a number of parties (including contractors, regulators, asset owners, infrastructure managers, operators, maintainers, financiers, and developers) who provide and receive the information defining what has been handed over and how it is to be managed. No doubt each party will have a different view of the System and a different way it wants to provide and receive information about the System and the way it has been produced and is to be managed in the future.

It is good practice to consider the requirements for an effective transition from the LIP into the O&M stage early in the LIP lifecycle so that the SBS can be structured according to the packaging for handover as well as for construction. It is possible then that the SBC on handover can be maintained into the O&M stage, hence facilitating continuing Configuration Management and supporting the effective implementation of future phases of the LIP and further development (extension, modification, update or refurbishment) of the System. If the SBC is maintained through its life then replacement or decommissioning (a project in its own right) can benefit from a clearly defined starting position where the Build Configuration of the System to be replaced or decommissioned is known and under control.

4 APPLYING SE PRACTICES TO THE CONSTRUCTION PROCESS

4.1 PROCUREMENT AND CONSTRUCTION PROCESS OVERVIEW

If we view procurement and construction as a process in the same manner as the INCOSE Systems Engineering Handbook [5] analyses an engineering process then that view would look something like Fig. 4.1. The inputs, the detailed design solution and contract strategy, are converted using technical and project processes to the outputs required by the stakeholders. These outputs typically include the accepted constructed items, as-built drawings, asset data records, operation and maintenance manuals, trained users, assurance evidence and on-schedule and on-cost delivery.

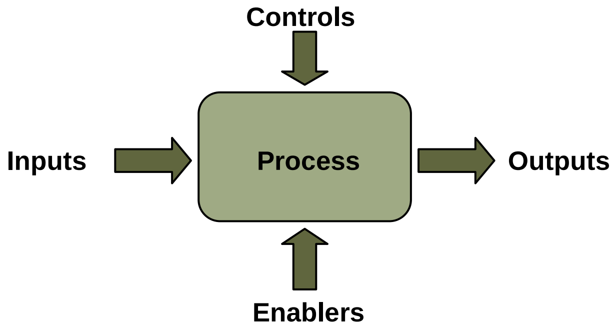


Figure 4.1 Structure of the Description of a Process.

This process is constrained by the controls and supported by the enablers. Controls include agreements with external organizations such as regulators and utility providers, established contractor processes and procedures, laws, regulations, and industry codes and standards. The construction process must recognize these controls to ensure successful completion without having to relearn the lessons of the past, to incur delays, or to incur penalties. The enablers are items that support the effort by providing necessary management systems and technical tools that are needed to facilitate the effective progress of the processes.

The following sub-sections consider each aspect (inputs, outputs, controls and enablers) in turn.

4.2 PROCESS INPUTS

4.2.1 CONTRACTING STRATEGY

Due to their complexities and scale LIPs are often decomposed into, and procured in, a number of smaller, more manageable projects and systems called ‘contract packages’. Contract packaging facilitates the handling of such things as technical complexity, phasing, expertise allocation, sharing of resources, legal and regulatory constraints, procurement options and cash flow. Since the ultimate cost of a project is determined largely by early technical decisions, it is paramount that a process be in place early to deal with the complexity and potential ambiguity resulting from packaging.

Having too many packages can be a nightmare for those in charge of managing the construction process. Having too few packages may not result in optimum project delivery or cost. This concern creates an opportunity for Systems Engineers to determine the optimum construction packaging plan which renders value to the Constructor as well as the Procurer and Project Manager. Although the literature search does not lead to a known mature model, modeling can be used as a means for determining the contract packaging process. A suitable model would be based on the numerous, inter-related requirements and constraints that are inherent in LIPs, including:

- Logical sequence of construction
- Access to site for construction
- Geographic boundaries
- Local contracting practices
- Project funding constraints
- Economic considerations including competition and procurement rules
- Union and workforce practices
- Integrated project schedule

Project schedules are often represented in two dimensions: activities and time. To deal with the complexity required by LIPs, another dimension needs to be added to the schedule, to allow a comprehensive look which includes access and geographic boundaries. A three dimensional integrated project schedule can be developed that looks at project activities from a geographical standpoint (location where each individual package is built) and from a time standpoint (when each individual asset/package is built).

The more complex the project, the more the Procurer will be subject to contract packaging risk. Using a sole Contractor may pose the risk that the contractor may default. Conversely, selecting too many Contractors may complicate the construction management process and division of responsibilities and liabilities. The selection of a Project Management Contractor (aka Project Delivery Partner) that provides oversight of the cost, schedule and quality assurance processes is strongly recommended as it is good practice to have an independent perspective and view on progress.

Appendix C.3 presents further information on the development of a model of the Contracting Strategy.

4.2.2 Design Solution

The design solution is represented by the System Build Configuration (SBC) as decomposed in the System Breakdown Structure (SBS) and allocated according to the Work Breakdown Structure (WBS) to each contracted party as defined in the Organizational Breakdown Structure (OBS) as explained in Section 3 and shown in Figure 3.1. Figure 4.2 gives an example of the relationship between the SBC, SBS and WBS on a railway project.

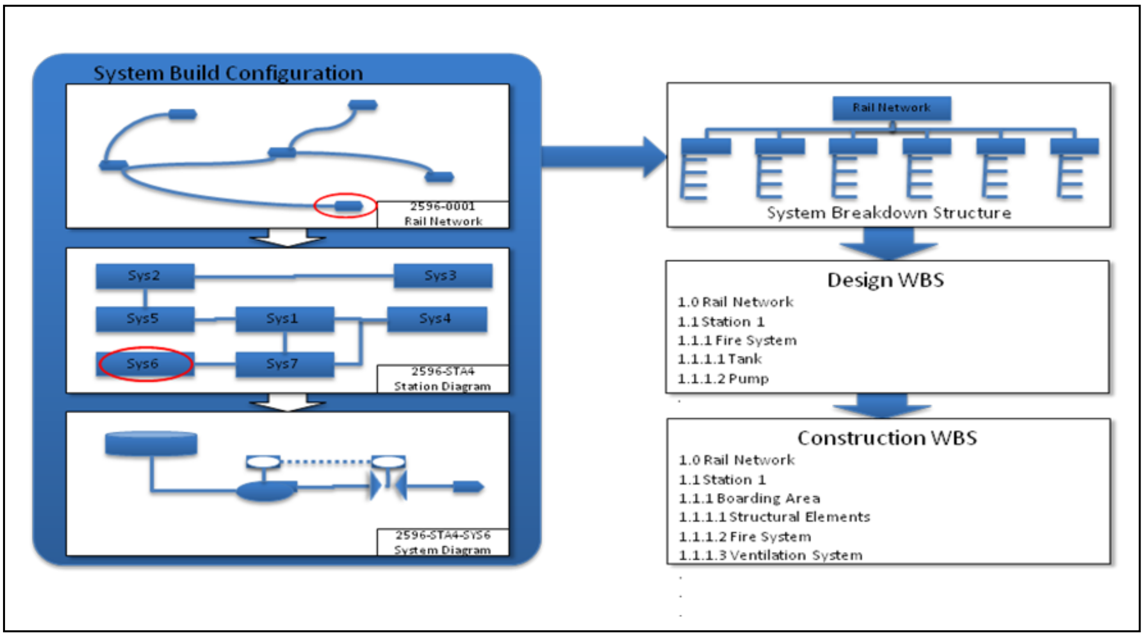


Figure 4.2 Example of the Relationship between the SBC, SBS and WBS

4.3 PROCESS OUTPUTS

4.3.1 HANDOVER AND TAKEOVER OF THE SYSTEM

The term ‘system handover’ implies the delivery of the System (by the Contractor) whereas the term ‘takeover’ implies the acceptance of the System (by the Procurer or Operator). However these terms are not always used consistently and care must be taken to ensure it is clear which party is responsible for what. If the Procurer takes the System over from a Contractor and cannot hand it over to the Operator then this can cause a major problem. SE helps mitigate any risk associated with this area of uncertainty by providing verification and validation processes for assuring the delivered System meets the stakeholders’ expectations at each stage in the project lifecycle. This approach helps the transition of the System from the Construction stage into the Operation & Maintenance (O&M) stage to proceed more smoothly.

4.3.2 TRANSITION INTO SERVICE

Transitioning from Construction to O&M in a LIP can be a complex process. To achieve a smooth transition into service the requirements for transfer must be captured early and considered through every stage of the project. The SE approach provides a structure that helps manage the complexities as described below.

4.3.2.1 THE TRANSITION IS A SYSTEM IN ITSELF

During the transfer from the construction project into O&M the LIP is in a transitional stage. This stage may have various states. Each of these states will have a unique build configuration that represents a unique system and must be defined. The SE process provides the tools to capture the required interim SBCs so that the system design (as defined in the SBS) is able to account for these transitional states.

4.3.2.2 TRANSITION TO O&M TAKES TIME

In a LIP, the transition from Construction to O&M will not be an instantaneous process. This transition will occur over many weeks or even months. The transition will most probably occur using an incremental approach. Many different groups of people will contribute to the transition. Many different groups of people will be affected by the transition. Many activities, unique to the transition stage, should be considered during the planning stages. All these factors represent an extensive list of process requirements that must be considered at all stages of the LIP leading up to this transition stage.

4.3.2.3 MANY TASKS OCCUR DURING THE TRANSITION TO O&M

During the transition many tasks interact in close space and time proximity. Tasks include:

- Validation of the System to ensure that it meets the needs of the stakeholders.
- Recording all deficiencies.
- Perform day-to-day operation and maintenance.
- Document and repair any defects.
- Maintain consistency of the system build configuration (SBC) with its documentation.
- Train O&M personnel.

Without planning for these interactions (interfaces) some tasks may be delayed or extended. The requirement decomposition process used in SE will help to capture these interactions (interfaces) and adequately prepare for them.

4.3.2.4 INVOLVE PROJECT STAKEHOLDERS AT THE BEGINNING

During the transition LIPs have many project stakeholders involved (operators, maintainers, trainers, contractors fixing up minor defects and omissions, sales people pushing for action, etc.). The needs of some of the stakeholders will have an impact on the project transition to O&M. SE gives a structure for capturing each stakeholder's requirements and classifying them appropriately. In this way it is less likely that incorrect assumptions will be made, that stakeholder requirements will not be met, and that significant project issues will occur during the transition stage. Without a structured (systems) approach success can be compromised.

4.3.2.5 TRANSITION PROCESS NEEDS TO BE DESIGNED

Since the transition to O&M can be represented by a unique set of *systems*, these will need to be catered for in the design, or planning, of the project. If there are any special stakeholder needs, requirements or constraints that would impact the design of the transition *systems*, then these would need to be captured in the earlier project stages involving needs assessment, concept selection, project planning and concept of operation. Typically the transition will include a staged or phased transition approach so as to minimize any disruption to operations.

4.3.2.6 TRANSITION NEEDS TO START EARLY

The later in the project that a need is identified, the more impact that need has on the project budget, timeline and feasibility. Mistakes and omissions are costly and can have a serious impact on project success. Due to the uniqueness of LIPs, a proof of concept is not normally developed, therefore it is more difficult to identify missed requirements and design issues. Because of this it is much more important to have the correct and complete requirements identified early in the project. SE provides the framework and the tools to help identify both Product and Process requirements and to develop the design right first time to achieve the project's complete objectives.

4.4 PROCESS CONTROLS AND ENABLERS

4.4.1 RISK MANAGEMENT

In the traditional approach to contracting, risks are defined and mitigated by the Procurer. Mitigation activities and technical solutions are thereby defined and placed into the various contracts. In today's contracting environment, more and more Procurers (mostly bodies governed by public law) in the construction industry are moving from the traditional contracts to more complex contracts (see Appendix C3). Risk management in these contracts is increasingly based on the project goals derived from the main stakeholders. It is very important that the Procurer and Contractors are committed to an agreed allocation of these risks and that they are aware of their responsibilities related to the identification and mitigation of the risks.

Therefore, it is important that both the Procurer and the Contractors are working from the same risk management strategy (as set out, for instance, in a Risk Management Plan) and working with a common risk repository (e.g. a Risk Register). Where more and more contracts are being done by non-national parties it is advisable to use recognized international standards so that the different parties can have the same mutual understanding on what risk management is within the project.

4.4.2 MANAGING CHANGE / CONFIGURATION CONTROL

The Constructor will start with a design, but inevitably changes will be required due to constructability, efficiency, fit, unforeseen circumstances, or a number of other reasons. Controlling change is one of the most important processes during construction. A poorly run change management process can cause significant cost overruns and schedule delays.

Configuration control of the process design is essential and critical. Standards such as ISO 10007 [6] and ANSI/EIA-649 [7] define Configuration Management processes. However, these standards were established for common industrial circumstances and sometimes need to be tailored to meet the needs of large, complex infrastructure projects; an example is given in [8]. Many infrastructure processes include development of control systems or other systems containing significant software. Processes that address the particular characteristics of software should not be overlooked.

Change management requirements will vary with the Procurer and the selected project approach. For example, highly regulated projects (e.g. in the nuclear industry) may require design documents to accurately reflect the facility as construction progresses. Other projects may allow the design documents to be updated to reflect the as-built facility after construction completes. In addition, deciding what must be maintained under configuration control will also greatly influence the cost of any change.

A fundamental concept of change control is that the design, facility and support documentation (e.g. operations, maintenance and training manuals) must be fully aligned not later than the time that the System is transitioned into service. Thus, change processes for the Procurer, Project Manager, Engineer, Constructor and O&M organizations must align at this point of integration. Coordination between all affected parties is essential to success, especially to prevent this process from becoming a bottleneck restricting progress. The structure and nature of these processes will depend upon contract strategies, and upon where the technical authority lies.

A change management process will have the following characteristics:

- A set of documented processes for configuration identification, control, status accounting and audit. Ad hoc methods should not be used.
- Identifies items and documentation that are required to be maintained under configuration control.
- Requires identification of all affected configuration-controlled items, requirements and supporting assurance evidence (e.g. calculations), associated design and procurement documents, and support documentation. (Items and documentation that are not required to be controlled need not be identified.)
- Requires change documentation to be packaged and reviewed for completeness and for impact to the project baselines.
- Requires a sequence for implementation and integration with other change packages.
- Requires clear approval authorities to be established.
- Ensures alignment among design, facility and support documentation.
- Identifies and records construction evidence required to document as-built conditions.

Refer to the configuration management standards [6] & [7] for a more complete list.

Tightly coupled design and construction processes require more rigid configuration management processes to ensure changes are correctly and fully implemented. In such circumstances, construction is often accomplished at risk that something completed may have to be changed. For example, when developing a large complex of integrated facilities, design and construction might be coincident. If a change is necessary, the impact to previously acquired and constructed items needs to be determined and carefully managed to ensure configuration control is not lost. Thus, the risk for change needs to be considered when sequencing and scheduling construction activities.

4.4.3 Controlling the System Build Configuration

The Contractor is responsible for managing the part of the SBC allocated under their contract. The configuration management process of the Contractor is normally controlled by the enterprise policy and standards required by the Procurer and defined in a Configuration Management Strategy. The Contractor has to define a Configuration Management Plan based on this strategy.

During the construction process the Contractor needs to report on the status of the SBC on a regular basis and has to verify that the plan and activities are in line with the chosen configuration management strategy.

Where the Contractor has a long term responsibility for maintaining a compliant SBC it is important to consider the different technology lifecycles. Infrastructures like tunnels, water barriers, etc., are designed and built for a long asset life (mostly 80-100 years) whereas modern technology used within these infrastructures (e.g. tunnel ventilation systems) have a shorter lifespan and are often affected by changes to safety legislation and environmental compliance. Such issues need to be considered during the project lifecycle to ensure the appropriate product control and support is integrated with the enterprise. The consequences of not adequately planning for the management of changes to the SBC can be significant. An example of this is from the Netherlands where all the road tunnels have to meet the new safety requirements in 2014, if not the tunnels will be closed to traffic.

4.4.4 PROCESS VERIFICATION AND VALIDATION

SE practice dictates that criteria for validating that requirements are met are specified early in the project lifecycle and, where practical, at the same time as the requirements themselves are defined. Assurance (by verification) that the processes are being followed, and that the intention of each stage has been achieved in the subsequent stage of the lifecycle, is also important.

Processes are measured to ensure they are producing the expected results within time and cost constraints. There are a number of tools used for this purpose, including assessments, audits, and measuring process factors that provide leading indicators of performance.

Assessments are self-performed investigations designed to examine compliance against requirements, or to determine how well a process meets the intended objectives. Results identify areas for improvement. These are effective tools to discover where process designs or personnel are not performing as intended, and provide warning of potential non-compliance and other project issues.

Audits are performed by those independent of doing the work (e.g. by Quality Assurance staff, the Procurer or the Regulator) for the purpose of checking process results against requirements. These audits are not controlled by the Contractor but need to be included in their budgets. Like assessments, audits reveal process or implementation weaknesses or non-compliances that need to be addressed to ensure project success.

The most important approach to process verification is the measurement of factors contributing to success. Each process can be considered an equation where the final result is based on the contributing factors. These factors can be supplier quality, weather, specific construction methods, tooling arrangements, process controls, or other factors that influence output quality. Each process could have hundreds of such factors, but not all factors are important. Identifying these factors will require collecting data. Six Sigma methods [9] may be useful in assessing these factors. Once found, these factors will provide leading indicators useful to point to problems that can be addressed before they adversely affect quality.

It is important to also validate that we are achieving the results expected (or required) from the construction process. Evidence of requirements satisfaction tends to be associated with the measurement of how well the Product of the project is meeting the defined Quality, Time & Cost targets assuming an optimized construction process. The Quality target for the Product will be measured using established SE methods (e.g. analysis, inspection, demonstration, factory and on-site testing).

For a LIP many systems will be integrated on-site during the construction stage as the Product System of the project is progressively built. It is important that all the systems are proved prior to integration (some off-site) and then again as part of the integrated System.

A recent approach to verification and validation that is particularly applicable to LIPs is that of Progressive Assurance, as used on railway projects [10].

4.4.5 REGULATORY PERMITS AND CERTIFICATION

Planning Authorities often issue permits and consents based on the proposed System design and the construction methods to be used. The project must prove that the Product System and *Process System* have met the conditions in the permits and consents in order to gain approval. Failure to do so could result in significant penalties, rework and, on occasions, demolition and rebuild. It is important therefore to base the permits and consents on robust Product and Process design intentions, something that a SE approach will facilitate.

Regulators often require certification that a system performs the permitted functions, particularly in a safe manner (i.e. meets the safety requirements), and is accurately represented by design and construction records. Demonstration of compliance is often provided by a argument supported by evidence, much as in a court of law, for example by the presentation of a Case for Safety or Safety Case. SE practices such as Progressive Assurance [10] facilitates the construction of the argument and provision of evidence.

5 SUMMARY

Large Infrastructure Projects (LIPs) are characterized by their scale (over $1billion), duration (lifecycle of years rather than months), uniqueness (every project has a significant difference in its solution and/or execution), complexity (number of interacting parts, stakeholders and/or activities) and cost uncertainty (due to unpredictable construction conditions and other economic, political and technical factors), and by the substantial proportion of cost, time and effort dedicated to the construction stage of the project lifecycle.

Systems Engineering (SE) is a discipline which has evolved to help manage complexity and improve the technical quality of engineered products. Traditionally it has focused on high technology applications and manufactured products and so has developed many good practices relating to the specification and satisfaction of requirements and making sure the design process is optimized so as to mitigate risks associated change, which will have cost, time and quality consequences, in the later stages of the project lifecycle.

This Guide has been produced by System Engineers involved in LIPs who see the benefit of applying SE thinking and practices to the Construction Stage of the project lifecycle.

Taking a ‘systems view’ of the LIP from a project management perspective provides a structured framework, the Project Management Triangle, which balances time, cost and quality through the project lifecycle as the uncertain scope changes. By linking the definitions (breakdown structures) of the System (the ultimate product of project) with the Work (the activities to be undertaken) and the Organization (the parties involved) and creating a Project Baseline comprising a know state of all three we have a fixed starting position for the Construction Stage which can then be controlled using SE processes, such as Configuration Management, through the Construction Process and thereafter as the required solution (the System) is transferred into service to the Operation and Maintenance (O&M) organizations. The Guide pays particular attention to the ‘transfer into service’ stage as the authors recognize that it can be a complex and time consuming step in itself and, if not given sufficient early attention, could compromise the success of the entire project.

The success of the project can be measured using SE practices to show how well the outcome met the intention (as defined in the initial project baseline) at the outset of the Construction Stage. It is important to take due consideration of the changes and the risks mitigated through the extended period of construction that SE practices have helped to effectively control when judging success.

An important factor in the success of any LIP is selecting the optimum strategy for implementing the selected design solution through the Construction Stage. SE practices can assist this selection by ‘designing’ a contracting, or procurement, strategy having considered a number of variables. This contracting strategy should be chosen on a balanced risk profile and appropriate allocation of risks between the Procurer and the Contractors and it is important that all parties have the same understanding of where the responsibilities lie for managing the identified risks.

An emerging SE practice, model-based systems engineering (MBSE), would appear to have a role in the development of the processes used in LIPs and, particularly, those relevant to the Construction Stage due to the uniqueness of each project. This Guide advocates following the same path used on contemporary SE projects but to build models of the construction process instead of models of the design solution.

APPENDIX A - GLOSSARY OF SYSTEMS ENGINEERING TERMS AND ABBREVIATIONS

A1 DEFINITIONS

Large Infrastructure Project (LIP). A project concerned with constructing infrastructure (motorways, railways, power stations, ports, water supply, wastewater treatment, etc.), and with construction costs exceeding 1 billion US dollars.

Project Lifecycle. The view of the project as consisting of discrete **phases** (separate delivery of a version of the System) and **stages** (separate increments of the lifecycle for each phase). A common partitioning into lifecycle stages is the following (adapted from ISO/IEC 15288):

Exploratory research	Identify stakeholders' needs and explore ideas and technologies.
Concept	Refine stakeholders' needs, explore feasible concepts, propose viable solutions.
Development	Refine system requirements, create solution description, design System, verify and validate System design.
Construction	Construct System, inspect and verify.
Utilization	Operate System to satisfy users' needs.
Support	Provide sustained System capability.
Retirement	Decommission System and restore its environment.

System. Capitalized, i.e. 'System', means the whole System (the complete Product of the LIP). Without capitalization, 'system' applies to any part of the Product, and italicized *system* means a process management system (a system of processes). Note: Construction contracts often use the term 'the Works' to define the system (the product) as related to the scope of that contract and 'the Work' to define the processes to be followed (including lifecycle stages and working practices).

Strategy. The framework (or process system architecture) within which the LIP will be carried out, for example an **Implementation Strategy, Contracting Strategy, Procurement Strategy or Delivery Strategy**.

NETLIPSE: A Network for the dissemination of **knowledge** on the management and organization of Large Infrastructure Projects in Europe. The main goal is to **exchange knowledge** on the management and organization of Large Infrastructure Projects (LIPs). http://www.netlipse.eu – see also Appendix B.

A2 ABBREVIATIONS AND ACRONYMS

BOO	Build Own Operate
BOOT	Build Own Operate Transfer
D&B	Design & Build
D&C	Design & Construct
E&C	Engineering & Construct
EPC	Engineer Procure Construct
INCOSE	International Council on Systems Engineering
IWG	Infrastructure Working Group
LIP	Large Infrastructure Project
MBSE	Model Based Systems Engineering
NETLIPSE	See A1
OBS	Organizational Breakdown Structure
OH&S	Occupational Health & Safety
O&M	Operation & Maintenance
PFI	Public Financing Initiative
PPP	Public Private Partnership
PRAMS	Performance, Reliability, Availability, Maintainability, and Safety
RSBC	Required System Build Configuration
SBC	System Build Configuration
SBS	System Breakdown Structure
SE	Systems Engineering
WBS	Work Breakdown Structure

APPENDIX B – ORGANIZATIONS ASSOCIATED WITH SYSTEMS ENGINEERING IN LARGE INFRASTRUCTURE PROJECTS

B1 INCOSE AND THE INFRASTRUCTURE WORKING GROUP

As the leading international organization dedicated to Systems Engineering (SE), the International Council on Systems Engineering (INCOSE) has for some time been interested about extending the knowledge and use of SE beyond its traditional domain of defense, aerospace, and telecommunications. A reflection of this is a number of working groups focusing on specific industry segments, and one of these is the Infrastructure Working Group (IWG). Infrastructure represents the largest portion of capital investment in any country [11], and when one considers that on a typical infrastructure project, the construction costs represent about 85 % of the total cost, it is reasonable to put some effort into extending the benefits that SE has brought in its traditional domain to the construction industry and, in particular, to Large Infrastructure Projects (LIPs). This Guide is the outcome of this effort by the IWG, and it is presented to the construction industry as a first step on the way to establishing SE as a valuable component of the construction process.

As a framework for SE activities, INCOSE has generally adopted the international standard ISO 15288 [12], and this is also reflected in the SE Handbook published by INCOSE [13]. For further discussion on the framework and how it relates to the construction process see Appendix C2.

B2 NETLIPSE

The book *Managing Large Infrastructure Projects*, published by A.T. Osborne BV, 2008 [14], is a most interesting and valuable documentation of the lessons learned on 15 major infrastructure products in Europe, with the findings clearly grouped into eight categories. The study specifically addresses Project Management, but because these are large and very complex projects, many of the problems encountered are those that arise in complex systems in general, and it is therefore interesting to see to what extent the lessons learned are covered by the SE processes. In the Table below, the findings are mapped against the applicable clause in ISO 15288:2008 [12], where the shaded items signify only partial overlap.

NETLIPSE BOOK [14]		ISO 15288: 2008 [12]	
Sec.	**Category Title / Description**	**Clause**	**Title / Description**
6.2	**Objectives and Scope**		
6.2.1	Define the objectives in interaction with the stakeholders	6.4.1.3 a.2)	*Elicit stakeholder requirements.*
6.2.2	Formulate a vision		
6.2.3	Translate objectives into scope, work packages and milestones	6.3.1	Project Planning Process
6.2.4	Assess and authorize scope changes	6.3.2.3 b.1)	*Manage project requirements and changes to requirements in accordance with the project plans.*
6.2.5	Use configuration management to assess the impact of scope changes	6.3.5	Configuration Management Process
6.2.6	Implement a variation procedure	6.3.2.3 b.6)	*Initiate change actions when there is a contractual change to cost, time, or*

NETLIPSE BOOK [14]		ISO 15288: 2008 [12]	
Sec.	**Category Title / Description**	**Clause**	**Title / Description**
			quality due to the impact of an acquirer or supplier request.
6.2.7	Organize adequate expertise to be able to deal with scope changes	6.3.1.3 b.4)	*Establish the structure of authorities and responsibilities for project work.*
6.3	**Stakeholders**		
6.3.1	Involve operators and industry	6.4.1.3 a.1)	*Identify the individual stakeholders or stakeholder classes who have a legitimate interest in the system throughout its lifecycle.*
6.3.2	Facilitate liaison with local stakeholders and critics		
6.3.3	Avoid mixed messages	6.4.1.3 b.4)	Establish with stakeholders that their requirements are expressed correctly
6.3.4	Reach consensus with stakeholders before tendering	6.4.1.3 a.4) 5.4.1.3 a.2	*Establish with stakeholders that their requirements are expressed correctly. Resolve requirements problems*
6.3.5	Enable the political branch to supervise the project		
6.3.6	Formalize responsibilities with client/sponsors	6.1.2.3 c.1)	*Negotiate an agreement with the acquirer.*
6.3.7	Brand the project		
6.4	**Financial Management**		
6.4.1	Use proper calculations to support decision-making	6.3.3	Decision-making Process
6.4.2	Search for financing and funding possibilities	6.2.3 6.2.4	Investment Management Process Resource Management Process
6.4.3	Control cost and budgets in relation to scope	6.3.2.3 b.5)	*Evolve with time the scope, definition and the related breakdown of the work to be carried out by the project in response to the corrective action decisions taken and the estimated changes they introduce.*
6.5	**Organization and Management**		
6.5.1	Address roles and responsibilities clearly: client/sponsor, project delivery organization, contractors	6.3.1.3 b.4)	*Establish the structure of authorities and responsibilities for project work.*
6.5.2	Design and implement a structure for reporting and decision-making	6.3.6 6.3.7 6.3.3	Information management process Measurement Process Decision-making Process
6.5.3	Communicate a project management policy	6.2.1.3 6.3.1.3	Lifecycle Management Process Project Planning Process
6.5.4	Address and manage checks and balances within the project organization	6.3.2.3 a.1)	*Assess the effectiveness of project team structure, roles and responsibilities.*
6.5.5	Stay in control in a decentralized project organization: quality management systems.	6.2.5	Quality Management Process
6.5.6	Work where work is. Adapt the organization to changing circumstances		
6.5.7	Invest in human resources and internal knowledge management	6.2.4 6.3.6	Resource Management Process Information Management Process

NETLIPSE BOOK [14]		ISO 15288: 2008 [12]	
Sec.	**Category Title / Description**	**Clause**	**Title / Description**
6.6	**Risk (and opportunities)**		
6.6.1	Position the responsibility for risk analysis within an independent group		
6.6.2	Do not forget to identify opportunities		
6.6.3	Share risk analyses with contractors and before tendering	6.3.4.3 a.3) 6.3.4.3 a.4)	*Identify the responsible parties and roles and responsibilities* *Provide the responsible stakeholders with adequate resources to perform risk management.*
6.6.4	Include risks and risk reservations in cost estimates		
6.6.5	Use a risk database	6.3.4.3	Risk Management Process
6.6.6	Rank and prioritize risks	6.3.4.3 c.2)	*Estimate the probability of occurrence and consequences of each identified risk.*
6.6.7	Make risk management part of regular management routines	6.3.4.3 d.1) 6.3.4.3 d.1) 6.3.4.3 f)	*Continuously monitor all risks and risks management context for changes and evaluate the risks when their state has changed* *Continuously monitor for new risks and sources throughout the life-cycle.* *Evaluate the Risk Management Process*
6.7	**Contracting**		
6.7.1	Customize the contracting philosophy to the characteristics of the project and the country	6.1.1.3 a.1)	*Establish a strategy for how the acquisition will be conducted*
6.7.2	Consider criteria other than price		
6.7.3	Allocate risk to the party best suited to carrying it	6.3.4.3 a.3)	*Identify the responsible parties and roles and responsibilities*
6.7.4	Use incentives in the contract		
6.7.5	Equip contract managers with adequate expertise	6.2.4	Human Resource Management Process
6.7.6	Cooperation is essential in a good contract		
6.8	**Legal Consents**		
6.8.1	Link legal procedures and stakeholder management		
6.8.2	Map procedures and keep them updated		
6.8.3	Ensure legal expertise is available		
6.8.4	Communicate with authorities proactively		
6.8.5	Coordinate the consents and tenders planning		
6.9	**Knowledge and Technology**		
6.9.1	Be careful with experiments		
6.9.2	If new technology is applied, organize the management of innovation		
6.9.3	Organize expertise and knowledge exchange within the project organization	6.3.6.3 b.3)	*Retrieve and distribute information to designated parties as required by agreed schedules or defined*

NETLIPSE BOOK [14]		ISO 15288: 2008 [12]	
Sec.	**Category Title / Description**	**Clause**	**Title / Description**
			circumstances.
6.9.4	Connect with other organizations		
	Other		
		6.4.8.3 a.1)	Define the strategy for validating the services in the operational environment and achieving stakeholder satisfaction
		6.4.8.4 a.1)	Prepare a strategy for operation
		6.4.8.5 a.1)	The corrective and preventive maintenance strategy to sustain service in the operational environment in order to achieve customer satisfaction

The outcome of this (quite cursory) analysis illustrates some of the issues that are under discussion in the IWG:

a. ISO 15288 assumes that projects are carried out within an *enterprise*; in these LIPs each project is an enterprise. That is, many of the enterprise processes become project processes.
b. The study highlights the importance of the *contracting strategy* and its influence on almost all the other processes in the project; this is completely missing from ISO 15288.
c. The study and the findings focus on cost and schedule issues (risks) arising from causes within the *environment* (political, economic. societal) of the project; this important aspect is only indirectly (and vaguely) addressed in ISO 15288.
d. The legal aspects, and their influence on the project in the form of obtaining *consents*, are highlighted in the study, but are ignored in ISO 15288.
e. The study also emphasizes the importance of developing and managing knowledge within the project; again, this is not addressed by ISO 15288.

B3 ORGANIZATIONS CONCERNED WITH THE CONSTRUCTION PROCESS

Throughout the world there are numerous organizations concerned with various aspects of the construction industry, ranging from education and professional recognition to specialized design codes. A few are listed below (by country):

Australia:

The Australian Institute of Building, www.aib.org.au
Australian Building Coded Board, www.abcb.gov.au

Canada:

Canadian Construction Association (CCA) www.cca-acc.com
Construction Specifications Canada (CSC) www.csc-dcc.ca

UK:

Construction Industry Research and Information Association, www.ciria.org
Institution of Civil Engineers (ICE). www.ice.org.uk

USA:

The Construction Specifications Institute, www.csinet.org
Construction Industry Institute, www.construction-institute.org
National Institute of Building Sciences, www.nibs.org
American Underground-Construction Association, www.auca.org
American Society of Civil Engineers (ASCE). www.asce.org

Netherlands:

NLengineers is the Dutch association of consulting engineers ('NLingenieurs' in Dutch).
www.onri.nl/english

International:

International Council for Research and Innovation in Building and Construction,
www.cibworld.nl/site/home/index.html

APPENDIX C - ADDITIONAL SUPPORTING MATERIAL

C1 THE RELATIONSHIP BETWEEN SYSTEMS ENGINEERING AND LARGE INFRASTRUCTURE PROJECTS

C1.1 A BRIEF INTRODUCTION TO SYSTEMS ENGINEERING

A system is a set of interacting elements, and this concept can be used in one of two ways; either to describe the features of the set as a whole, aggregating information hiding, or to *describe* a complex entity in terms of a set of less complex, but interacting component entities. Systems Engineering (SE) is the application of this concept to the engineering of a system; and it is a methodology for handling complex projects. As such, it is one of the processes within engineering, but it is of a somewhat different nature than other technical processes SE does not participate directly in the conversion of a need into a service that meets that need, but only indirectly through structuring those processes and their artifacts into a hierarchy of systems and subsystems. SE is also different from the traditional engineering disciplines, such as civil, mechanical, electrical, and chemical engineering, in that it is not grounded in an area of natural science; it sits above all the engineering disciplines as a meta-discipline.

Central to any application of the system concept is the choice of how to describe an entity as a system; that is, how to choose the elements and their interactions in such a way as to benefit the task at hand to the greatest extent possible. This activity, the *architecting* of the system, is the most creative and potentially innovative activity within SE, and while there are many general rules and heuristics [15] to assist in performing it, it is ultimately dependent on experience. Once a particular system has been chosen, SE has standards for documenting the elements and the interfaces, and processes for how to manage these as the project progresses [16].

The two ways of using the system concept are reflected in SE as follows:-

1. the complexity is managed by considering all the factors interacting with the project throughout its life time (holistic view) and describing these factors as elements of a system, structured through time by means of a lifecycle with distinct stages, and over the breadth of factors by means of such identifiers as disciplines, contracts and special interests.

2. when faced with a complex entity, such as a very large set of requirements, SE applies a process of analysis to structure these requirements into a system of groups of requirements, such that there are strong dependencies between the requirements within each group, but weaker (yet well defined) dependencies between the groups. One can then look for solutions that meet the requirements within each group before considering them as a whole; overall system optimization will then generally require adjustments to these solutions rather than having to look for new ones.

3. when faced with the potential for change and managing complexity driven by size, SE applies methods for capturing and linking information useful for the control of change and ensuring all the ripples caused by that change can be identified and addressed.

C1.2 Complexity as the Common Factor

Construction projects are traditionally viewed as highly mechanistic, deterministic endeavors. Successful construction practice revolves around tightly controlling labor, materials, equipment, and processes. Construction management processes focus on controlling scope, cost, and schedule, and there is an extensive and mature body of knowledge dealing with this [17]. However, as in other areas of engineering, the issue is the efficiency of these traditional processes as the complexity of the projects increases; there is ample evidence that LIPs struggle with the increase in complexity due to such factors as the public funding and budgeting process, political considerations, complex relationships between numerous project participants, community concerns, special interest groups, heterogeneous user groups, long lifecycle, etc. [18].

A complex system can be defined as "a system with numerous components and interconnections, interactions, or interdependencies that are difficult to describe, understand, predict, manage, design, and/or change" [19]. Not all LIPs would qualify as complex systems; well established project types, ranging from straightforward commercial activities such as big box stores to large but well-understood process plants, do not fit within the definition. However, many LIPs do fall within the definition, and as such need to be viewed as complex systems that might benefit from tools and techniques that are being developed to deal with a variety of complex systems.

LIPs that are also complex systems cannot be neatly lumped into categories; rather, the whole concept of complexity typically suggests unique challenges. What can be done, however, is to adopt structured approaches to dealing with issues like interfaces and interdependencies. SE provides a suite of time-tested structured processes that have been used to overcome some of the largest technological challenges of the past few decades. Unfortunately, the construction community has not generally adopted SE as part of its toolkit; this Guide has made the case for making SE a common practice within the construction world.

C1.3 Cost-Effectiveness as the Common Driver

The main driver for introducing and developing SE was the need to improve the delivery of major aerospace and defense projects in the decades following World War Two. This improvement was achieved by, on the one hand, developing the designs in a top-down fashion, so that the complexity resulting from demanding requirements and multidisciplinary, leading-edge technology could be handled in steps of increasing detail, and on the other hand by managing the extremely complex acquisition process itself, with its multitude of contractors and compressed timeframe, by treating it, from the earliest planning stage to operation, as a system of interacting work-packages. The first ensured the effectiveness of the systems in operation, the second reduced rework and waste through inadequate planning and organization. In short, the aim was to increase cost-effectiveness, and numerous successful programs, such as the atomic submarine program and the Apollo program, indicated that this goal was indeed attained [20].

Large infrastructure projects (LIPs) are now facing the same need to improve delivery and increase cost-effectiveness, and the issues that must be addressed to achieve this objective are similar to those faced by the aerospace and defense industry [21]. It is only the language and the environment in which they are embedded that are different, as the following brief discussion shows.

On the effectiveness side, the top-level task is to satisfy stakeholder needs, which subdivides into the two tasks of correctly identifying the stakeholders, and then determining their needs. The next step is to determine and understand the issues that stand in the way of satisfying these needs or, in other words, the problems that have to be overcome in order to be able to satisfy these needs; what Warfield called the "problematique" [22]. The process of arriving at a set of agreed stakeholder needs that at the same time keeps the associated problems within realistic limits is in itself very complex. Besides such factors as conflicting user needs with regard to the features and performance of the product and to purely physical factors, such as geology or flooding, LIPs are characterized by the fact that they are generally quite intrusive. As a result, the stakeholders include a large and diverse collection of special interest groups, often well organized and highly vocal, and their influence on a project can outweigh any other factor, not least as a result of their political significance. As an example, in the case of a high voltage transmission line, the engineering may require six months, the construction work itself eighteen months, but the public consultation may take five years. The effective and successful execution of the stakeholder management process is a major component of any construction project, and the handling of the numerous elements and their interactions as a system rather than individually offers significant advantages.

There then follows the search for the best solution to this set of problems through a process of concept design, feasibility studies, and detailed design. Because of the size of the projects, the time required for this process is often many years, during which time both the stakeholders and their needs will change. Besides adding to the complexity and the cost, this can delay the projects very considerable, even by decades, which constitutes a decrease in their effectiveness in meeting the original stakeholders' needs.

On the cost side, the cost of each of the projects stages - needs determination, solution development, and implementation – can very easily get out of hand unless the complexity is managed through well-developed and structured processes. The motivation for introducing SE is therefore the same as in the aerospace and defense industries it is only that the sources of the complexity are partly different, as was discussed in the previous section. However, to the overall cost must be added the cost of implementing the SE processes, so this cost should be small compared to the resulting savings and the value of the improved effectiveness. Consequently, keeping the overall driver of increased cost-effectiveness in mind, applying the established body of SE knowledge successfully to large infrastructure projects requires that both the processes themselves and the manner in which they are implemented within the projects need to be tailored to the environment in which these projects exist, and that is the challenge addressed by this Guide.

C1.4 THE RELATIONSHIP BETWEEN SYSTEMS ENGINEERING, PROJECT MANAGEMENT AND ASSET MANAGEMENT

Eisner [23] summarizes by stating that "A typical scenario is that a company might set up a project whose basic purpose is to systems engineer some type of system. Thus, there is always a strong connection between project management and systems engineering".

Eisner [23] also states that "Effective design and construction of any system involves both an effective systems engineering process and a deep understanding of the domain knowledge implicit in the system. The best systems engineers have both the systems engineering and the domain knowledge expertise. It is not really possible to function with excellence as a systems engineer on a given program without having the appropriate domain knowledge understanding."

Deep understanding of the domain knowledge implicit in a LIP is often derived from those with expertise in Asset Management. Asset Management is about having a full appreciation of the full lifecycle implications of the LIP, and as such, has a strong connection with both SE and project management in this context.

Hudson, Hass and Uddin [24] describe infrastructure or asset management approach as a process of life-cycle cost integration and, as such, treats them in this context. The life-cycle model is the traditional view of design, construction, maintenance, rehabilitation and renovation and the cost model is the balance between performance and cost, in terms of the users and the owners.

These authors also refer to SE in the context of what this engineering approach can contribute to infrastructure or asset management, which can also be applied to LIPs. Since SE involves the development of new systems and understanding and modeling of its operations, the lessons learnt from applying systems concepts need to be translated to LIPs. In particular, the systems methodologies associated with modeling and systems analysis. This is in acknowledgement that infrastructure consists of a set of interacting components that are affected by external influences.

Since LIPs are a part of an infrastructure system (e.g. rail systems, electricity distribution network and highway system) the interrelationships between SE, project management and asset management are key factors for the successful implementation of LIPs.

The debate is often when setting up a LIP, how do you get these three fundamental disciplines to work together to produce successful outcomes.

C2 UNDERSTANDING THE CONSTRUCTION PROCESS

C2.1 AS A COMPLEX PRODUCT

The primary drivers for introducing SE are to improve cost-effectiveness, maximize quality and minimize rework and to achieve this in the case of LIPs we need to focus on improving the construction process. The shift in emphasis from the design process to the construction process is the main reason why the established SE practices need a reformulation, or tailoring, in order to apply to LIPs. Instead of the product being the System, as stated in ISO 15288 [25], the product we wish to re-engineer is the construction process itself.

The sources of complexity remain the same; they are technical (e.g. geotechnical and structural), behavioral (both within the organizations involved in construction and with their interfaces to external parties) and dynamic (due to the long lifecycle). The application of SE also remains the same as for any other complex entity; a description of both the problem space and the solution space as systems of interacting elements, and then the means of working with such systems in the form of a number of processes, ranging from definition through control to verification and validation.

The first consequence of applying SE to the construction process as a complex product is that it is viewed as going through a number of *lifecycle stages*, as defined in the Systems Engineering

Handbook [26]. Although these stages are listed in sequential order, they are often run as overlapping activities.

Table C.1 SE Lifecycle Stages as applied to the Construction Process

LIFECYCLE STAGE	PURPOSE IN THE CONSTRUCTION PROCESS	DECISION GATE
Concept	• Identify the stakeholders and their needs (disruptions during construction, noise, damage to the environment, local community benefits, financing requirements, etc.). • Identify the problems associated with satisfying these needs. • Identify the issues impacting the contracting strategy (contractor capability and availability, material supply (quarries, batching plants, steel, etc.), long-term relationships). • Explore viable solutions and select the optimal one.	Approval to proceed to binding negotiations or to submit bid.
Development	• Subcontract development and negotiations. • Detailed planning (access, transport costs, temporary infrastructure, etc.). • Community consultation and information. • Obtain statutory approvals and planning consents.	All statutory approvals and planning consents obtained.
Production	• Finalize all documentation (plans, induction procedures, safe work method statements, etc.) • Complete workforce • Award subcontracts • Purchase materials	Approval from all contract partners.
Utilization	• Execute the process as designed.	Hold points, as per the WBS
Support	• Configuration, change and risk management.	Variations approved
Warranty and Retirement	• Settle all claims and any warranty issues	Sign-off by all parties, as required.

Within the SE process, the first three of these stages are commonly illustrated in terms of the Vee model [27], but there are now two left-hand legs, one concerned with developing and designing the product, and one concerned with developing and designing the construction process. The bottom of the Vee is concerned with supply and fabrication, in accordance with the procurement strategy contained in the construction process and the technical requirements contained in the design. There are also two right-hand legs, one concerned with implementation through progressive construction by means of the execution of Works (see Appendix A), and the other concerned with progressive integration and testing in accordance with the technical requirements of the subsystem specifications, as illustrated in Fig. C.1. It is with the two additional legs that this Guide is primarily concerned.

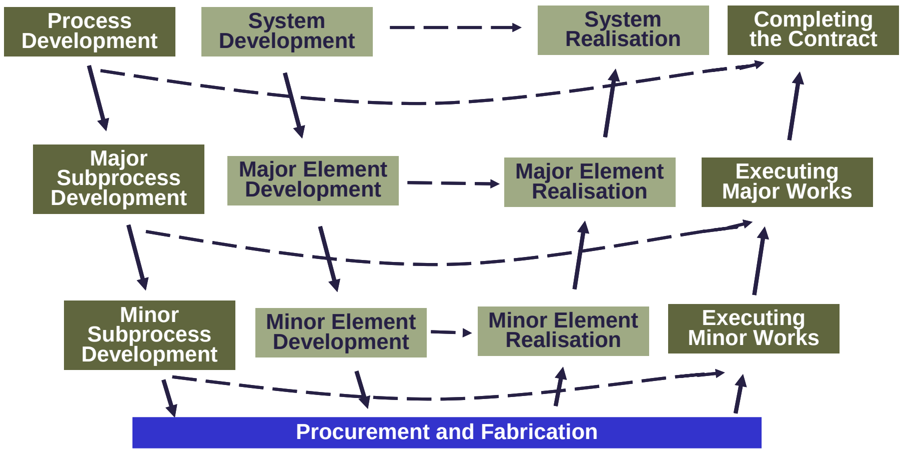


Figure C.1 The Modified Vee Model

The modified Vee model in Figure C.1 shows the duplication of the legs to explicitly show the simultaneous development of the product and the process. The direction of the arrows indicates the idealized flow of information and/or material, in reality there will always be some corrective feedback between stages.

C2.2 As the Outcome of a Set of Processes

In ISO 15288 [28] and in the INCOSE Handbook [29], systems engineering is structured into a number of processes, grouped as two Agreement Processes, five Organizational Project-Enabling Processes, seven Project Processes, and eleven Technical Processes. These are listed in Table C.2, together with an assessment as to their relevance to developing the construction process. That is, what value could these processes add to what is already employed in the construction industry. Processes shaded in grey are considered of no or minor relevance in that context.

Table C.2 Relevance of the ISO 15288 Processes to Construction

ISO 15288 Process	Relevance to the Construction Process Development
Acquisition Supply	These two Agreement Processes are not relevant to engineering the construction process, as acquirer and supplier is one and the same organizational entity.
Lifecycle Model Management	The lifecycle model of the construction process was described above. (Perhaps less well understood is the integration of various aspects of the project, such as legal, acquisition, technology, etc.)
Infrastructure Management	The physical infrastructure required for developing the construction process, such as computers and computer-based tools, is generally available in large construction companies. However, as with all large-scale applications of IT, interoperability of different systems is always an issue.
Project Portfolio Management	This is not particularly relevant to LIPs, as their size makes each one an enterprise in itself.

Human Resource Management	The development and availability of systems engineering skills is obviously a major issue, but the process for managing those resources is no different from the process of managing other human resources, and this process is generally well developed in major construction companies.
Quality Management	This needs to be extended to encompass the activity of designing the construction process, but this is closely related to the verification process. Key questions: Are the processes capable of producing the products needed by all stakeholders? Are the processes used compliant with regulatory or customer requirements?
Project Planning	Planning the design of the construction process is an activity where the SE process, as set out e.g. in sect. 5.1 of the Handbook and also in ISO15288, can make a significant contribution. Unless the development of the construction process is explicitly defined in a plan, its outcome will be very variable, and Measurement and Verification are meaningless.
Project Assessment and Control	Not a major issue, and closely related to Verification and Measurement. The outcome of assessment should be captured in Lessons Learnt.
Decision Management	A greater degree of sophistication than is found normally on construction projects would be beneficial. For example, greater use of models.
Risk Management	The process is normally well established; it is the allocation (and thereby the effectiveness of the control) of risk that is an issue, as discussed in sect. 5.2 of the Handbook.
Configuration Management	Controlling the configuration of the construction process (i.e. the realization of the contracting strategy) and of the SBC. SE has something to offer here, and this is treated in Section. 4.4.2 and Section 4.4.3.
Information Management	The dissemination of information to a large set of subcontractors within the project and to numerous stakeholders, both internal and external, requires a structured approach.
Measurement	The measurement of how well the construction process was developed can, in the end, only be the evaluation of the project outcome in terms of cost, schedule, and product performance. However, the current work on Leading Indicators is of relevance here [30].
Requirements Definition	This process of establishing the requirements on the construction process is generally handled quite well, what is often less satisfactory is the documentation of the outcome. A formal, consolidated Requirements Definition Document is required.
Requirements Analysis	This is perhaps the process that is most in need of a system engineering approach. The problems associated with satisfying the requirements are not developed in enough detail, and so features of the construction process that would be important are overlooked.

Architectural Design	In the context of the construction process, this becomes contracting strategy development, a very important activity to which a system approach can provide a significant contribution, as discussed in Appendix C3.
Implementation	This includes producing all the construction process documentation, such as WBS, subcontracts and purchase orders, method statements, site induction procedures, etc. Normally this is handled quite well.
Integration	Co-ordination of subcontracts, site access and possession management, etc. This is normally handled quite well.
Verification	This is a small additional process, verifying that the activities in the plan are executed as required and the associated documentation produced. This takes the form of surveillances and audits; the most common problem is that the outcome is not acted upon. In addition, this activity examines whether the processes perform consistently as expected. Are they producing quality results the first time?
Transition	This is mobilization is normally well handled.
Validation	Validation of the process becomes a quality assurance issue, and the SE methodology has nothing to add here.
Operation	These three processes are contained in construction management, and if the construction process is well designed, there is nothing for SE to add here.
Maintenance	
Disposal	

C2.3 As a Process in Response to a Complex Set of Requirements

Requirements placed on the construction process as a whole are, in principle, contained in a statement of the form "Construct and put into service the product specified in the detailed design documentation while satisfying a set of constraints". The detailed design specification may contain specifications for hundreds, or even thousands, of individual elements of the product. The set of constraints specific to the project include such factors as cost, completion time and, environmental and community consent conditions, as well as constraints of a non-project specific nature, such as general legislative requirements (e.g. OH&S, local preference, etc.).

A further set of constraints and factors influencing the construction process include climatic factors (e.g. winter, rainy season), transport infrastructure, local resources (manpower, know-how, power, water), and political stability. To develop an optimal construction process, i.e. one that will provide an acceptable product and satisfy all the requirements while at the same time provide the best outcome for the construction contractor (profit on this project, long-term development and standing in the industry, etc.) is clearly an extremely complex undertaking. It is in handling this complexity through a top-down design approach that SE can add significant value.

C2.4 AS A PROCESS TAKING PLACE IN A SPECIAL PHYSICAL ENVIRONMENT

Much of the existing SE literature implicitly (and sometimes explicitly) assumes that it is concerned with the manufacturing industry. That is, that the activities take place within a factory environment that has a degree of permanence and reflects a continuous development and investment, and within a product development process that involves technology development, prototyping, and serial manufacturing of a given product. The construction process is very different, it does not take place in a factory, but on a construction site that is unique to each project, and for a one-of product that does not allow any prototyping or beta-testing. A particularly important consequence of this is that the safety aspects of both the construction process and of the product have to be considered and worked through for each project "from scratch". This does not mean that the processes and procedures have to be developed for each project; on the contrary, they evolve slowly from project to project and represent an accumulation of experience. But their application through hazard identification, analysis, and elimination or mitigation, and their documentation in the form of project-specific procedures, instructions, and safe working method statements, has to be carried out for each project and constitutes a very considerable cost element [31].

Again, a structured approach that views construction as a system of interlinked processes and the integrated safety artifacts as a product system subjected to the normal SE processes, ranging from definition through control to verification and validation, can result in a significant increase in cost-effectiveness [32].

C3 DEVELOPING A PROCUREMENT AND IMPLEMENTATION STRATEGY

C3.1 OVERVIEW

LIPs take place within a framework of *contracts* between the project participants; the structure of this framework is variously called the *contracting*, *implementation*, or *procurement strategy*. Taking a SE approach and viewing the project as a system, the contracting strategy is part of the arrangement of the system and, just as with the System, there are several views of this 'architecture' [33]. In one view, which we might call the *implementation view*, the participants are the elements, and contracts and agreements are the interactions between them. The participants are legal entities of one sort or another, but in a particular project they are identified by the role they play in that project. Some of the main roles are:

- *Sponsor*, the entity that initiates the project and proposes a first, high-level implementation strategy.
- *Owner*, the entity that will have the System as an asset on its balance sheet.
- *Equity Provider*, either a single legal entity or a group of shareholders.
- *Debt Provider*, usually financial institutions.
- *Engineer* (or Consultant), the entity that designs the System, but may also take on management roles.

- *Contractor*, the entity that will build and create the System.

- *Operator*; this may be the Owner, but may be an entity that is engaged by the Owner or that leases the System from the Owner.

- *Maintainer*; this may be the Owner, the Operator, or a separate entity engaged by either the Owner or the Operator.

For smaller construction projects, the classical structure has been that Proponent, Owner, Equity Provider, Operator, and Maintainer are the same entity, which then deals directly with the Debt Provider, the Engineer, and the Contractor, while the management of the project is shared some way between these three (e.g. Managing Contractor or EPCM). However, for LIPs, as was already indicated in Section 2, the scale of investment, the body of work, and the associated financial risks are so large that such a simple structure is not practical. Of the many possible relationships between the participants in LIPs, some occur frequently enough to be given a separate identity:

- *Public Private Partnership* (PPP). The public body (local, state, or federal government body), as Proponent, forms a partnership with private companies that take on various roles, such as Equity Provider, Debt Provider, Operator, and Maintainer, and this new entity, as Owner, then forms relationships (contracts) with Contractors and Engineers. In some cases the Contractors and Engineers may be required to take a stake in the new entity as shareholders.

- *Build Own Operate* (BOO). In this case the role of the Proponent (usually a government body) is limited to providing the legal framework for the project (access to land, regulation of tolls, etc).

- *Build Own Operate Transfer* (BOOT). This is a variation on the BOO structure, in that ownership of the System reverts to the Proponent after a defined period (typically 25 years).

- *Alliancing.* This is an attempt to overcome the adversarial aspects of the classical contracting format and may, in principle, be applied to any contract within a wider contracting strategy, although the most common application is between the Owner and a group of Non-Owner Participants (NOPs), often the main construction contractor and the principal consultant.

C3.2 A SYSTEM APPROACH TO DEVELOPING THE STRATEGY

From a SE perspective, the task of developing the contracting strategy is no different, in principle, to that of developing the System, and the first step is therefore to determine the *requirements*; what must the strategy achieve, what are the constraints, how is performance to be measured? With numerous and diverse participants, the requirements are correspondingly drivers and should be documented in a clearly structured manner.

The second step is to obtain an in-depth understanding of the *problem space*; what are the issues that influence the performance or effectiveness of the contracting strategy? How are these issues linked? How can they be ranked? The answers to these questions depend both on the details of the particular project and on the state of the environment in which the project is going to exist, and finding the correct answers is a complex activity that requires a methodical approach in order to be successful [34].

The third step is then the documentation of the chosen strategy in the form of a set of contracts; a task that is carried out by a legal firm. And here lies the kernel of why contracting strategies are often less than successful. The legal firm is most often not financially involved, and therefore has no direct stake in the project. This arms-length position can be seen as appropriate in terms of impartiality and disinterest, but it leads to a focus on the purely legal aspects of the contracting strategy and to a reduction or even complete elimination of the two first steps. Each member of a project team is focused on doing what it is good at doing and to start doing it as soon as possible; the role of the systems engineer is to sit above the specialized members and provide the overall "best-for-project" view, and this is no less true when it comes to developing the contracting strategy.

C3.3 Creating a Packaging Model

Creating the packaging model requires the determination of the relationships among the different variables that need to be considered for contract packaging. For most LIPs, the variables include the following:

- Overall risk (Ri)
- Cash Flow (Cf)
- Phasing (Ph)
- Ease of Design (Ed)
- Ease of Construction (Ec)
- Ease of procurement/competition (Ep)
- Access to site (As)
- Other external factors (Ef)
- Environment risk (Ee)

With these variables, the model can be represented as follows:

Packaging = function (Ri, Cf, Ph, Ed, Ec, Ep, As, Ef, Ee)

Further studies need to be performed to determine the weight that each variable has in the packaging process. Such studies are expected to be performed in the future to address the challenges that packaging creates. It is expected that this Guide will be updated to reflect the findings of these studies.

Upon creation of the model, the value of each of the variables included in the model will be determined. Recognizing that "hard" values may not always be available, intangibles must be quantified to the full extent, in order to graphically draw model results and determine the "optimum" packaging plan.

C3.4 Subcontracting Strategy and the Allocation and Control of Risk

C3.4.1 Overview

Turning now to the focus of this Guide, the construction process, this process again takes place within a framework of contracts that may be considered to form the next level down in the hierarchy of contracts from the contracts between the major Participants discussed earlier in this section, and are therefore referred to as subcontracts.

Subcontracting strategies depends on the different acquisition strategies. Within the construction domain there are 3 major contract types:

- D&C (Design and Construct)
- E&C (Engineering and Construction)
- C (Construction)

According to the philosophy of ISO15288, contracts are closed between enterprises and not between project teams (see Fig. C.2). The main contract is based on a requirements specification that contains System (product) requirements and process requirements. The System requirements specify the physical system, whereas the process requirements specify the way the system should be realized, maintained, and operated (depending on strategies mentioned in Section C3.1) under general and specific legal considerations.

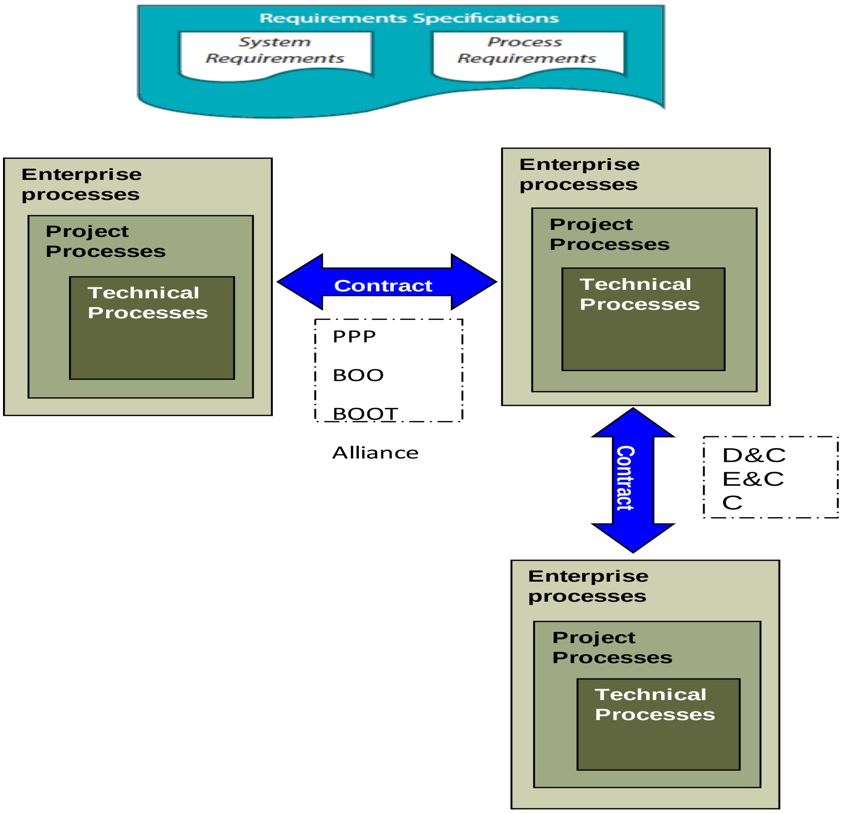


Figure C.2 The Contract as an Interface between Enterprises

Within the construction industry, contractors should apply the same process as the acquirer (contracting authority). First of all, they set up a strategy for procurement and implementation. Based on this strategy, the contractor sets up contracts for different parts (subsystems) of the System to be delivered.

Subcontracting strategies are related to the different acquisition strategies on which the main contract is based; possible combinations of main contracting and subcontracting are:

Contract	Subcontract
PPP, BOO, BOOT, Alliance	D&C
	E&C
	C
D&C	E&C
	C
E&C	C

Within all of these contracting types we look at different so called "systems of interest". This is illustrated in Figure C.3.

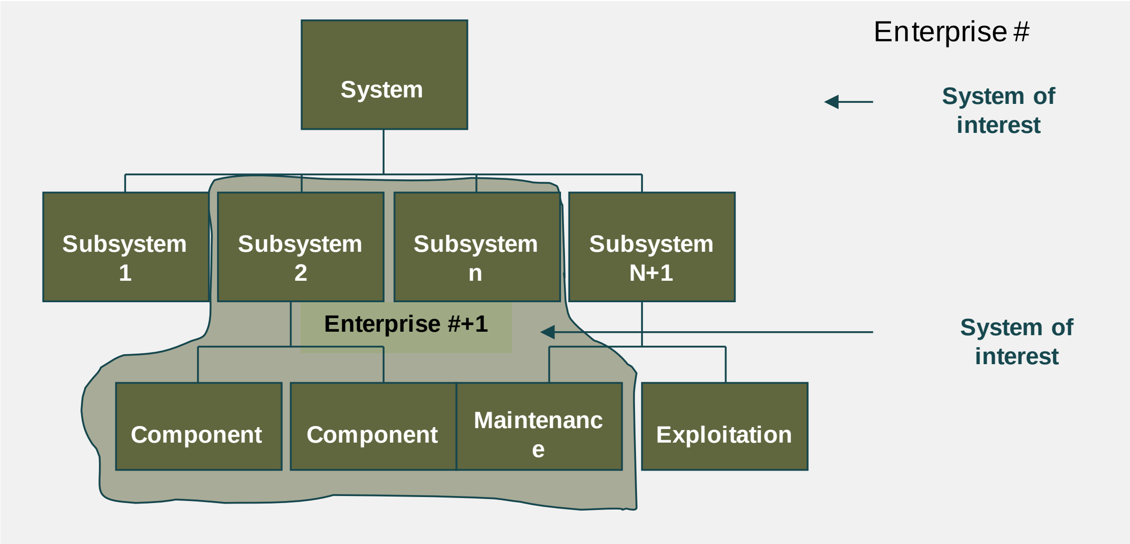


Figure C.3 The Systems of Interest is Relative to the Enterprise

<u>Design and Construct (D&C)</u>

The contract is based on functions and processes the "system of interest' has to fulfill. Based on these functions and processes, the contractor has to carry out the design and decide what kind of processes they, as a company, have to employ; thereby the contractor is responsible for the realization of the "system of interest". Within D&C contracts the acquirer asks the contractors to make a proposition based on a problem definition. After an agreement on the proposed solution the contractor is responsible for the design and build of the agreed solution.

<u>Engineering and Construct (E&C)</u>

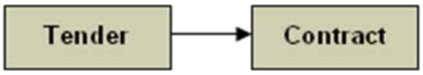
The contract is based on functions and processes the "system of interest' has to fulfill. On the basis of these functions and processes, the contractor has to carry out the design and decide what kind of processes they, as a company, have to employ, and again, the contractor is responsible for the realization of the "system of interest". The constraint is that the shape and dimensions are fixed. Within E&C contracts the contractor will design the solution given by the acquirer.

Construct

The contract is based on the (complete) design which has been done by the acquirer. The contractor has no design responsibility. These contracts normally do not involve any work or discipline outside construction.

C3.4.2 Processes and Activities

Processes and activities are different in the different stages of the project lifecycle. Within this project lifecycle there are two main stages. The "Tender" (or "Procurement") stage, where a contractor is to obtain a contract; and the "Contract" stage, where the system itself is developed and built within its operational environment.



Within the "Tender" stage, the contractor has to obtain confidence of the acquirer that they are the right party to do the job. This means that the contractor will be the best performing party, based on the award criteria (lowest price or most economically advantageous tender). Mostly this stage is split up into parts: first the acquirer may limit the number of suitable candidates to be invited to tender, to negotiate or to conduct a dialogue with, by a qualitative selection. In the restricted procedure the minimum will normally be five. In the negotiated procedure with publication of a contract notice and the competitive dialogue procedure the minimum will normally be three. In any event the number of candidates invited will be sufficient to ensure genuine competition. These parties have to prove to the acquirer that they fulfill selection criteria: minimum criteria and the criteria for qualitative selection, such as economical and financial standing, technical and professional knowledge or ability.

In the tender stage both of the parties (acquirer and contractor) have to come to a mutual understanding of the requirements, so that both parties have the same knowledge level relating to needs and goals and the derived requirements. The tender stage can be seen as a tool for a successful hand-over (transfer of responsibility) of the LIP from the acquirer to the contractors.

In the contract stage, the contractor has to prove that the proposal is compliant to the contract on a regular basis. The acquirer will evaluate the proposals against the requirements in the draft contract or the request for proposal. In the case that the proposals are compliant, the acquirer will complete the contract or agreement in accordance with the award criteria specified in the request for proposal. These award criteria will be either:

(a) when the award is made to the tender most economically advantageous from the point of view of the acquirer, various criteria linked to the subject-matter of the public contract in question, for example, quality, price, technical merit, aesthetic and functional characteristics, environmental characteristics, running costs, cost-effectiveness, after-sales service and technical assistance, delivery date and delivery period or period of completion; or

(b) the lowest price only.

Because of the nature of infrastructure systems (in complexity and scale), it is important for the acquirer and the contractor to work from the same basic principles. These basic principles are not only the use of a common definition and acronym list, but also the use of a common process framework (for example ISO15288).

C3.5 DEFINING AND ALLOCATING THE HAND-OVER RESPONSIBILITIES

A common model used within infrastructure projects is the 'V' Model. A version updated by the Dutch Ministry of Public Works [35] as illustrated in Figure C.4.

The situation today is that there is frequently a misunderstanding of the responsibilities within the model. Acquirers often underestimate their responsibilities vis-a-vis Stakeholders and the interfaces with them at system level. The Contractors are often thought to be doing a good job for the Acquirer. On the other hand, Contractors often have a poor understanding about the goals of the Acquirer on a political and environmental level.

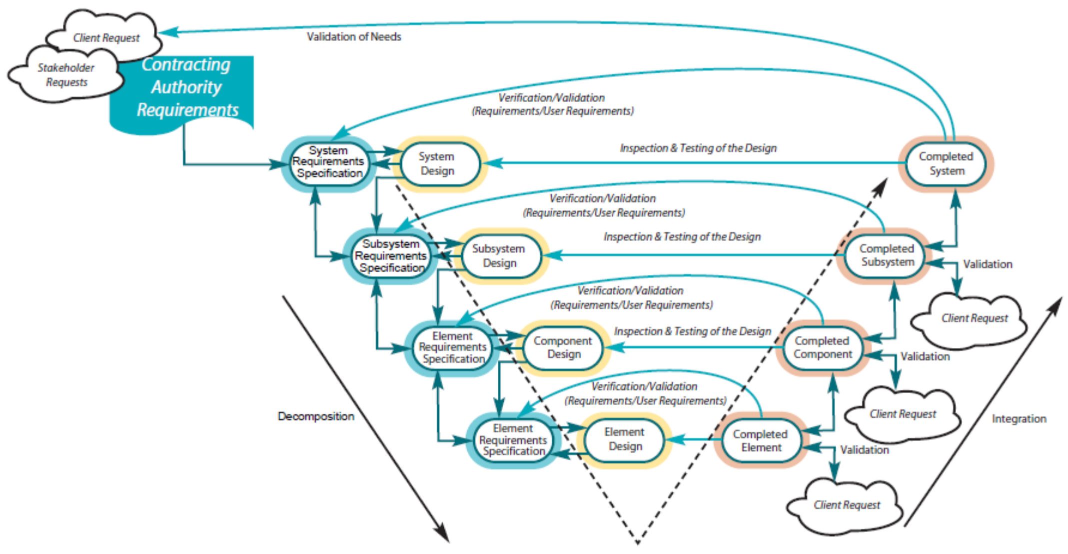


Figure C.4 The V-Model

The handover responsibilities defined by the V-model are bi-directional. At each system level, the hand-over responsibilities are shifting from the Acquirer to the Contractor. The Acquirer is always the main party related to system responsibilities. Within LIPs the political and environmental impact can be very significant. The Acquirer must ensure that the contract is complete and clear. In other words, the acquirer has to verify that the contract will deliver an operational system that will meet the requirements and will meet the needs and goals of all stakeholders, which were the basis for starting the project in the first place. The Acquirer is, for example, responsible for the stakeholder analysis at the system level, and from that point of view the acquirer must set up a system assurance strategy. This is extremely important with stakeholders in the area of state and local politics.

When contracting at a certain system level, the Acquirer is responsible for delivering a system specification(s), system assurance strategy and verification & validation management plan at that system level. The contractor is responsible for delivering the design (starting at system level), verification & validation plans based on the system assurance strategy, a compliant System and support for the final validation of the System itself.

Contracting at a lower system level will give the Acquirer more responsibilities on design, implementation, integration, verification and validation, and Figure C.5 shows a case where the Acquirer provides the system design and contracts out individual subsystem D&C packages.

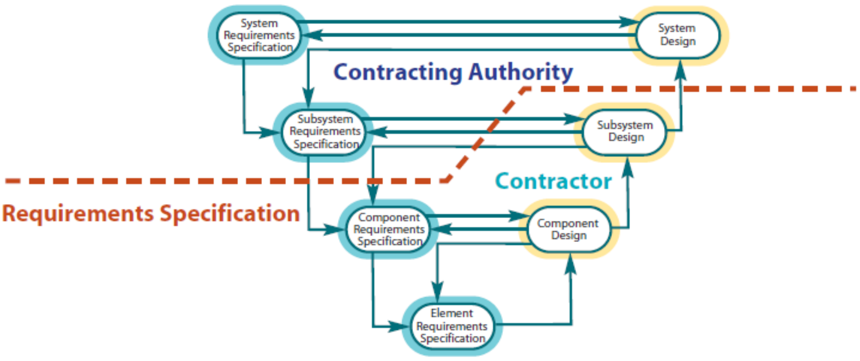


Figure C.5 Allocation of Responsibilities

Figure C.5 shows the allocation of responsibilities in a case where the Acquirer (contracting authority) has developed the system design and is contracting out D&C packages for individual subsystems (only one shown).

APPENDIX D - NOTES AND REFERENCES

References [n]

1. This is by no means the first time a systems approach, or systems thinking, has been applied to construction, but it appears to have been mainly applied to the management of the construction process rather that to the design of the process. For example, Newcombe, R., D. Langford, and R. Fellows, *Construction Management*, Mitchell, London, 1990, present a system model of the building organization that draws heavily on the work of Katz, D. and R.L. Kahn, *The Social Psychology of Organizations*, Wiley, New York, 1978. They view the organization as a system from a number of different *views*; strategic, information, organization, social, and, centrally, management. Each of these is a conversion process with inputs and outputs, and feedback from the environment (as influenced by the outputs). The management system has a number of subsystems (or sub-processes); manpower, building materials, construction plant, finance, and production.

   Another very useful reference is the recent publication *Managing Design and Construction Using Systems Engineering (for Use with DOE O 413.3A)*, doc. no. DOE G 413.3-1, published by the US Dept. of Energy, 23 September 2008.

2. Joan Woodward, in *Industrial Organisation: Theory and Practice*, Oxford Uni. Press, 1965, (quoted in *The Practice of Construction Management*, 2nd ed., by B. Fryer, BSP Professional, 1990) was one of the first to point out the significant differences in the management of different technologies. In particular, the management of mass and process production was found to be more structured and formal than that of one-off or small batch production. Many of the accepted "management principles" were developed for the former grouping and are not necessarily applicable to the latter.

3. *Systems Engineering Handbook – A Guide for System Lifecycle Processes and Activities*, v. 3.2, INCOSE-TP-2003-002-03.2, C. Haskins (Ed.), January 2010.

4. A number of organizations provide explanations and tools for performing PESTLE analysis, some of these are:

   Renewal Associates, www.renewal.eu.com/resources/Renewal_Pestle_Analysis.pdf;
   RapidBI, http://rapidbi.com/created/the-PESTLE-analysis-tool.html

   Chartered Institute of Personnel and Development,
   www.cipd.co.uk/subjects/corpstrtgy/general/pestle-analysis.htm

5. *Systems Engineering Handbook – A Guide for System Lifecycle Processes and Activities*, v. 3.2, INCOSE-TP-2003-002-03.2, C. Haskins (Ed.), January 2010.

6. *Quality Management - Guidelines for configuration management*, BS EN ISO 10007:2003 ISBN 0 580 42169 4.

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8. Knott, A., *Applying Configuration Management Principles on a Large Scale Operational Railway Infrastructure*, Railway Engineering 2004 Conference, 6-7 July 2004, Commonwealth Institute, London.

9 Pyzdek, T, *The Six Sigma Handbook*, Quality America Inc www.qualityamerica.com .

Pande, P.S., R.P. Neuman, and R.R. Cavanaugh, *The Six sigma Way, How GE, Motorola and Other Top Companies ARE Honing Their Performances*, McGraw-Hill, ISBN0-07-135806-4

10. Knott, A. and Stubbs, M, *Innovative Systems Engineering Practices that help manage the Organisational and Technical Complexity of a Modern Railway Project*, Int'l Conf. on Railway Engineering (ICRE), Hong Kong, 25-27 March 2008. (see also Ref 32)

11. Hillebrandt, P.M., *Economic Theory and Construction Industry*, Macmillan, 2000, states that construction makes up 10 % of GDP world wide and, for example, is the largest industry in the United Kingdom and the second largest, after public health, in Sweden.

12. ISO 15288:2008, *Systems and software engineering – System lifecycle processes*.

13. *Systems Engineering Handbook – A Guide for System Lifecycle Processes and Activities*, v. 3.2, INCOSE-TP-2003-002-03.2, C. Haskins (Ed.), January 2010.

14. A recent report on best practices and lessons learnt in large infrastructure projects in Europe, *Managing Large Infrastructure Projects*, M. Hertogh, S. Baker, P.L. Staal-Ong, and E. Westerveld, produced by NETLIPSE, a research programme of the Sixth European Framework Programme (FP 6) of the European Commission and published by A.T. Osborne BV, 2008. The correspondence of the issues identified in that report with the processes of ISO 15288 was examined by the INCOSE IWG and is attached to this Guide as Appendix C.

15. Rechtin, E., *Systems Architecting – Creating and Building Complex Systems*, Prentice Hall, 1991; and

M.W. Maire and E. Rechtin, *Systems Architecting*, 3rd ed., CRC Press, 2000

16. A standard reference work is *Systems Engineering and Analysis*, by B.S. Blanchard and W.J. Fabrycky, 5th ed., Prentice Hall, 2010.

17. The publications concerned with construction management are too numerous to be listed, as a perusal of any library catalogue will demonstrate. A (random) selection would not be useful, as some are concerned with construction management in general, others with certain aspects, such as quality, safety, contract management, and data management. A few books relevant to particular topics in this Guide are referenced in the following; a journal dedicated to the subject is *Journal of construction engineering and management*. American Society of Civil Engineers, New York, NY.

18. Numerous reports and publications have documented the relatively poor state of the construction industry. *Building Innovation: Complex constructs in a changing world*, by D.M. Gann (Thomas Telford, London, 2000) states: "Construction in a number of

countries, including in the United States, experienced negative productivity growth in the period 1970 – 93, compared with the 3-4 % positive growth in high and medium-high technology industries". And a 2001 FIDIC Position Paper, *Quality of Construction*, identifies the decreasing quality of construction. Also *ASCE Guiding Principles for Critical Infrastructure.pdf*, dated 2009

19. Magee & deWeck, *Complex System Classification*, INCOSE 14th Annual International Symposium, 2004

20. The development of systems engineering is documented in various publications, a good overview of the early years, and successes, is given in the report by Hans Bode, "The Systems Approach", in *Applied Science – Technological Progress*, report to Committee on Science and Astronautics, US House of Representatives, 1967.

21. A recent report on best practices and lessons learnt in large infrastructure projects in Europe, *Managing Large Infrastructure Projects*, M. Hertogh, S. Baker, P.L. Staal-Ong, and E. Westerveld, produced by NETLIPSE, a research programme of the Sixth European Framework Programme (FP 6) of the European Commission and published by A.T. Osborne BV, 2008. The correspondence of the issues identified in that report with the processes of ISO 15288 was examined by the INCOSE IWG and is attached to this Guide as Appendix C.

22. Warfield, J. N, *An Introduction to Systems Science*, World Scientific Publishing, 2006.

23. Eisner, H., *Essentials of Project and Systems Engineering Management*, New York, John Wiley & Sons, 1997.

24. Hudson, W. R., R. C. G. Haas, et al., *Infrastructure Management: Integrating Design, Construction, Maintenance, Rehabilitation, and Renovation*, New York, McGraw-Hill, 1997.

25. "The systems considered in this International Standard are man-made, created and utilized to provide products and/or services in defined environments for the benefit of users and other stakeholders", ISO 15288, clause 5.1.2.

26. *Systems Engineering Handbook – A Guide for System Lifecycle Processes and Activities*, v. 3.2, INCOSE-TP-2003-002-03.2, C. Haskins (Ed.), January 2010.

27. The 'V' model has been presented and discussed in numerous publications; one is *Visualizing Project Management*, by K. Forsber, H. Hooz, and H. Cotterman, 3rd Ed., J. Wiley and Cons, 2005.

28. ISO 15288:2008, *Systems and software engineering – System lifecycle processes*.

29. *Systems Engineering Handbook – A Guide for System Lifecycle Processes and Activities*, v. 3.2, INCOSE-TP-2003-002-03.2, C. Haskins (Ed.), January 2010.

30. The 'V' model has been presented and discussed in numerous publications; one is *Visualizing Project Management*, by K. Forsber, H. Hooz, and H. Cotterman, 3rd Ed., J. Wiley and Cons, 2005.

31. Safety in the construction industry in treated by various organizations and documented in many publications. Some pertinent organizations and websites are: US Dept. of Labor, Occupational Safety and Health Administration, www.osha.gov/, European Agency for Safety and Health at Work, http://osha.europa.eu/en, National Safety Council of Australia, www.nsca.org.au/.

32. Knott, A. and Hodges, B, *A Case for System Acceptance - Progressive Assurance Practices on the East London Line Project*, International Council of Systems Engineering (INCOSE) International Symposium 2008, Utrecht, Holland, 15-19 June 2008.

33. Architecting and the views of a system architecture are the subject of a significant portion of the systems engineering literature, and some standard references include;

    Rechtin, E, *The art of systems architecting*, Prentice Hall, 1991.

    Maier, M. and E. Rechtin, *The art of systems architecting*, 2nd edition, CRC Press, 2000.

34. The importance of the early stages of the systems engineering process is emphasized in most books on systems engineering; it is in taking a holistic view of the project and developing an optimal framework for its execution before any discipline-specific work is carried out that systems engineering makes its major contribution. A methodology particularly suited to LIPs was developed by John Warfield, as referenced in sec. C2.

35. *Leidraad voor Systems Engineering binnen de GWW-sector*, (in Dutch), produced by Rijkswaterstaat and ProRail, 2008. An English version of Issue1 was distributed at the INCOSE Int'l Symposium 2008 in Utrecht. Issue 2 is currently only available in Dutch at www.leidraadse.nl .

APPENDIX E - FEEDBACK FORM

Title of Technical Report:

Guide for the Application of Systems Engineering in Large Infrastructure Projects

Paper number/Technical Report No:

INCOSE-TP-2010-007-01 – Draft 2C dated 3rd Jan 2012

Authors/WG:

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Comment Resolution Matrix dd mmm 2012

Location of Comment (Para, Section, Page)	**Description of Issue, comment and rationale**	**Importance Rating** (R=Required, I=Important, T=Think about for future version)

Page n of m (add pages as necessary)

(Back cover)

End