Chapter 1

Introduction to Transportation Systems Engineering

1.1 Introduction to Systems Engineering

1.1.1 A Few Definitions

Everyone uses the term “System” and has an intuitive notion of what a system is, but there is a formal definition. INCOSE defines a systems as: A combination of interaction elements organized to achieve one or more stated purposes. This general definition covers almost everything you can think of – household appliances, transportation management systems, the latest weapon system – all of these are systems.

Then what is systems engineering? Since the term was coined in the 1950s, systems engineering has evolved from a process focused primarily on large-scale defense systems to a broader discipline that is used in all kinds of project development. Systems engineering can be applied to any system development, so whether you are developing a household appliance, building a house, or implementing a sophisticated transportation management system, systems engineering can be used. INCOSE defines systems engineering like this:

Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem.

Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to *production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.*

Note that this definition is very broad – it covers the project life cycle from needs definition to system disposal. It includes technical activities like requirements and design, as well as project activities like risk management and configuration management. Systems engineering provides a systematic process and tools that directly support project management.

1.1.2 Systems Engineering Principles

Start with Your Eye on the Finish Line

You should reach consensus at the very beginning of the project on what will constitute success at the end. This means that the stakeholders should start with an agreement of what the project should accomplish and the metrics that will be used to measure the success of the project. This initial focus on the finish line must be sustained by project management as project development progresses and competing interests and project complexities begin to dominate the day-to-day work.

Stakeholder Involvement is Key

Successful projects involve the customer, users, operators, and other stakeholders in the project development. Systems engineering is a systematic process that includes reviews and decision points intended to provide visibility into the process and encourage stakeholder involvement. The systems engineering process includes stakeholders through all stages of the project, from initial needs definition through system verification and acceptance. The stakeholders who are involved in any particular step will vary, providing managers, operators, and technical personnel with an opportunity to contribute to the steps in the process where their input is needed.

Define the Problem Before Implementing the Solution

Very often, you'll have a solution already in mind at the start of a project and may even find yourself "backing into" requirements to match your solution. Resist this temptation and instead use the systems engineering process to first define the problem. You'll find that there are actually multiple ways to solve the problem, and a good trade study will help you to determine the best solution on the basis of a clear understanding of the requirements.

Delay Technology Choices

Technology is constantly changing. The choices available when a project is initially conceived may well be replaced by better technology by the time the project is implemented. Specifying technology too early will result in outdated technology or constant baseline changes as you try to keep up with technology advancements. It's best to follow the systems engineering process by defining the needs, requirements, and high-level design without specifying technology. You'll have a stable baseline, and you'll be able to make the most appropriate technology choices when it is time to implement. *Baseline* is a frequently used term in systems engineering. A baseline is a reference point against which everyone on the project team works, so you want to control the changes that are made to the baseline.

Divide and Conquer

Many systems are large and complex. A key systems engineering strategy is the decomposition of such a system into smaller subsystems and then of the subsystems into more manageable hardware and software components. These simpler components are easier to understand and define, and ultimately are easier to build. Much of the systems engineering process is built around this approach – breaking down a big problem into many smaller components that can be individually solved and then recombined.

Connecting the Dots – Traceability

As you move from one step to the next in the systems engineering process, it is important to be able to relate the items in one step with those in another. The relationship between items is called traceability. For example, you use traceability to relate a requirement to the subsystem that will implement the requirement. Traceability connects many items together. The requirement will be related to a user need as well as to a test that will be used to verify the requirement. Traceability is a powerful concept that allows you to be certain whether the system implemented at the end of the project is directly connected with the user's needs that were identified at the beginning.

1.1.3 The “V” Systems Engineering Model

Overview of the “V” Model

Since it was first developed in the 1980s, the “V” model has been refined and applied in many different industries, see figure 1.1. Wings have been recently added to the “V” as part of its adaptation for ITS to show how project development fits within the broader ITS project life cycle. The left wing shows the regional ITS architecture, feasibility studies, and concept exploration that support initial identification and scoping of an ITS project based on regional needs. A gap follows the regional architecture(s) step because the regional architecture is a broader product of the planning process that covers all ITS projects in the region. The following steps in the “V” are for a specific ITS project. The central core of the “V” shows the project definition, implementation, and verification processes. The right wing shows the operations and maintenance, changes and upgrades, and ultimate retirement of the system.

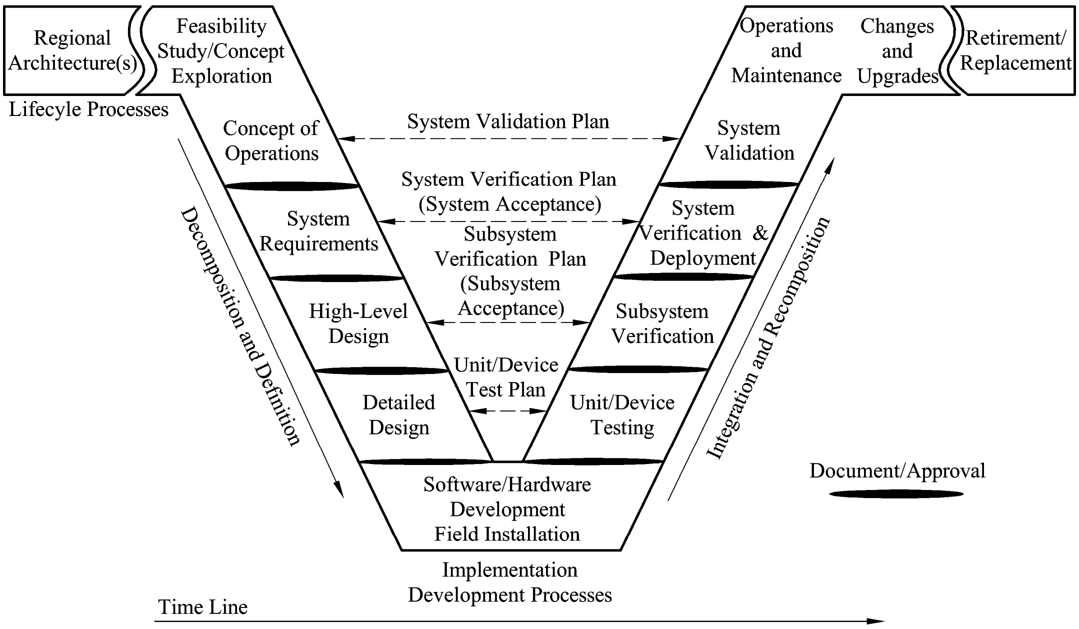

Figure 1.1 Systems engineering “V” diagram.

The wings are a key addition to the model since it is important to consider the entire life cycle during project development. As shown in the “V”, the systems engineering approach defines project requirements before technology choices are made and the system is implemented. On the left side of the “V”, the system definition progresses from a general user view of the system to a detailed specification of the system design. The system is decomposed into subsystems, and the subsystems are decomposed into components – a large system may be broken into smaller and smaller pieces through many layers of decomposition. As the system is decomposed, the requirements are also decomposed into more specific requirements that are allocated to the system components.

As development progresses, a series of documented baselines are established that support the steps that follow. For example, a consensus Concept of Operations supports system requirements development. A baseline set of system requirements then supports system design. The hardware and software are implemented at the bottom of the “V”, and the components of the system are then integrated and verified in iterative fashion on the right.

Ultimately, the completed system is validated to measure how well it meets the user’s needs.

Connecting the Left and Right Sides of the “V”

One of the first things that strikes you about the “V” is the symmetry between the left and right sides of the model. This symmetry reflects the relationship between the steps on the left and the steps on the right. The system definition that is generated on the left is ultimately used to verify the system on the right. For example, the user’s needs and performance measures that are identified in the Concept of Operations are the basis for the System Validation Plan that is used to validate the system at the end of project development. Similarly, a System Verification Plan is developed with the System Requirements so that the engineers consider how to verify each requirement as the requirements are written.

The connections between the left and right are indicated by the arrows that cross the “V”, showing how plans developed on the left drive the process on the right. These connections provide continuity between the beginning and end of project development and ensure that the engineers are focused on the completion of the project from the beginning. The connections between the left and right sides of the model reflect one of the systems engineering principles — start with your eye on the finish line.

Decision Points

Projects have been managed for years using Gantt charts that identify tasks and major milestones. You don’t start the next task until you have completed the previous supporting tasks and passed the intervening milestone. The “V” diagram is similarly punctuated by a series of major milestones (labeled Document/Approval in the figure) where the output of the previous step is reviewed and the customer and project team determine whether the project is ready to move to the next step in the process. The project moves forward only if the criteria for the decision point have been satisfied. Decision points are important milestones that provide visibility into the project development and allow for issue identification and course correction during development.

1.1.4 Value of Systems Engineering

Although ITS projects come in many shapes and sizes, they all use technology (computers, communications, sensors, etc.) and frequently include the exchange of information, either within a system or between systems. The technology and integration that sets ITS projects apart also creates challenges for the ITS project manager. What every ITS project manager wants is a successful result at the end of the project, with “success” measured by:

- How well the implementation satisfies the needs of the people who use it
- How closely the project stayed within the budgeted cost and schedule.

Systems engineering reduces the risk of schedule and costs overruns and increases the likelihood that the implementation will meet the user’s needs. Other benefits include:

- Improved stakeholder participation
- More adaptable, resilient systems
- Verified functionality and fewer defects
- Higher level of reuse from one project to the next
- Better documentation.

These assertions have been supported by several studies that have shown that good systems engineering results in better cost and schedule performance. Studies have been performed by the *International Council of Systems Engineering* (INCOSE)1, Boeing2, and IBM3 among others. Figure 1.2 shows the results of an INCOSE study that collected both planned and actual project and systems engineering cost data for 44 projects. The survey indicated that investing in systems engineering did improve project cost performance. The responses indicated a 50% overrun on average without systems engineering and a clear trend toward better cost performance results with systems engineering.

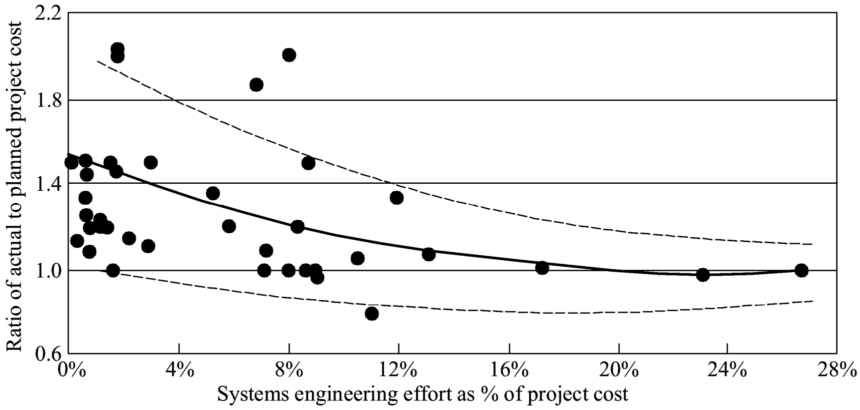

Figure 1.2 Systems engineering improves project cost performance.

1.2 Applying Systems Engineering

1.2.1 The Traditional Project Life Cycle and Systems Engineering

The systems engineering approach discussed in previous chapters may be viewed as an extension to the traditional project development process that is already established in transportation agencies. As transportation organizations gain experience with ITS projects and the systems engineering approach, they typically find that they can weave the systems engineering processes and best practices into their overall project development process.

Traditional Transportation Project Development

Transportation projects are identified and funded through transportation planning and programming /budgeting phases. Funded projects are then implemented using a process similar to the traditional capital project development process in which including Project Initiation, Preliminary Engineering, Plans/Spec & Estimates, Construction, Project Closeout. But the exact process used for transportation systems projects will vary with the type of project.

For example, ITS projects that install only field equipment (e.g., variable message signs) would use a process that is very close to the traditional. ITS projects that involve hardware and software development and integration would require additional systems engineering analyses that would be significant extensions to the traditional process.

While project development processes vary from where to where and from organization to organization in each area, the transportation project development process tends to have the same major steps.

- **Project initiation —** In this step, the project manager is identified, the project team is assembled, and the project development is planned. A high-level definition of the project is developed, costs are estimated, and the required forms and checklists are completed to garner approval for the project from the sponsoring and funding agency(ies). For FHWA and FTA, this is a critical point in the process where approval to proceed is given and federal funds are obligated.

- **Preliminary engineering —** In the traditional capital project development process, environmental, right-of-way, and other studies are performed depending on the type of project. These studies result in better understanding of the project requirements and constraints. ITS projects that include a construction component will require these same studies as well as additional engineering analyses to fully specify the project requirements for the ITS portion of the project. Note that from a federal aid perspective, preliminary engineering also includes plans, specifications, and estimates (PS&E). PS&E is split out separately here to differentiate between requirements-oriented and design-oriented steps in the traditional project development process.

- **Plans, specifications, and estimates (PS&E) —** The detailed design for the project, including detailed project specifications, estimates of material needs, and associated costs, is documented. In a traditional construction project, this step provides companies with all the information they need to develop an accurate bid. Construction elements in an ITS project will also require traditional design documentation (e.g., layout sheets, plan and elevation views, and cross-section details). Design documentation is required for the hardware and software components in an ITS project, but it takes the form of high-level design, interface specification, and detailed hardware and software specifications.

- **Construction —** The project is built. In a traditional transportation project, this is construction of the actual physical improvement. In an ITS project, this includes the procurement and implementation of the hardware, software, and enabling products (e.g., manuals, operating procedures, and training). This step also includes both the inspection of the physical improvement and integration and the testing of the implemented system.

- **Project closeout —** After final inspection, the completed project is accepted, as-built plans are created, a project history file is completed, and final project documentation is submitted for audit prior to final payment.

Mapping Systems Engineering into the Project Life Cycle

As it has evolved through a century of building roads and public transit systems, the transportation project delivery process used by most agencies today already includes many important features of the systems engineering process. In both processes, the system is specified in increasing detail, beginning with needs, moving to requirements, and then into design. Multidisciplinary project teams and systematic stakeholder outreach and communications are hallmarks of a good transportation project development process and sound systems engineering practice. By taking advantage of this similarity in concepts and processes, the systems engineering process can be integrated as an extension to the agency's existing project development process.

Making these types of linkages and mainstreaming ITS development into the agencies' project development process makes it easier to incorporate systems engineering into each agency's process.

Although there are similarities, there are also key differences between the traditional process and the systems engineering approach that should be considered when planning your next ITS project. For example, in the traditional transportation project development process, there is clear contractual separation between the consultant that prepares the PS&E and the contractor that builds the project. This is a risky approach for many ITS projects, in which it is important to have more continuity across the project development life cycle so that the contractor who ultimately implements the ITS system clearly understands the underlying user's needs and requirements and has the latitude to implement the most cost-effective solution. For example, the contractor that implements custom software for an ITS project should also participate in the detailed software design. You would not want to impose a contractual barrier between the software designer and the software implementer. Differences like these have led to use of innovative procurement practices for ITS projects that are discussed in the next section.

1.2.2 Applying Systems Engineering in Project

Procurement and Systems Engineering

The project development process is strongly influenced by the selected procurement strategy. ITS projects have been procured through traditional low-id, systems manager, design-build, and other innovative procurement approaches. The procurement strategy will influence who (i.e. agency, consultant, or contractor) takes the lead for each process step, but the fundamental systems engineering process steps (Concept of Operations, Requirements, and Design) should still be accomplished for all types of transportation system development projects. An important thing to remember is that the agency is never completely off the hook, regardless of the procurement approach. With any approach, there is always a need for the agency to be involved in the process.

A poorly chosen procurement strategy can adversely impact a project just as much as the lack of a sound systems engineering approach. It is important to tailor the procurement strategy based on the type of ITS project and not to assume that it always has to be done the same way. The traditional approach of putting a specification on the street and awarding the implementation to the low-bid contractor may work well for projects with extremely well understood requirements. However, the complications of inexperienced personnel, new requirements and technologies, changing environments, and shifting priorities lead to the need for newer approaches for many ITS system acquisitions. This is particularly true when a project includes custom software development.

Selecting a Development Strategy

There are several different ways that a system can be developed and delivered using the “V” systems engineering model. The best development strategy depends on how much you know about the system that you want to implement, whether you have all the funds that you need to implement the system in one fell swoop, your agency and contractor capabilities, and your assessment of the project risks. Three basic development strategies can be used:

- **Once-through –** Plan, specify, and implement the complete system in one pass