Systems Engineering in Construction (Cont'd.)

Another characteristic of construction projects is increased the complexity and number of stakeholders. Unlike other types of projects, large construction projects are often at least partially funded by government agencies. In many cases, there are multiple funding agencies at different levels of government (city, county, state, and federal). Add to this the many groups affected by the project, from local communities to utilities and transit systems that must be crossed or relocated, along with potential land use restrictions and environmental impacts, and the requirements list grows exponentially.

The codes and standards that form part of the requirements add another layer of complexity to construction projects. Unlike aerospace or other types of projects, construction projects can cross into different jurisdictions, leading to varying and sometimes conflicting requirements for the different physical locations of packages of work.

Systems Engineering for Design-Build Projects

Design-Build projects have some unique characteristics of their own that have the potential to increase project risk. On design-build projects, there is a shift in responsibility for the quality of the work, including the development of final requirements and specifications, away from the agency and towards the contractor. The design is initiated by one firm, but completed by another: this handoff increases the potential for misinterpreted requirements or incomplete incorporation of requirements. Internal integration is much more complex, as the work is broken down into much smaller packages to enable a more continuous construction effort.

Status of Systems Engineering in Construction

Systems engineering can help address all of the issues previously described. However, the application of systems engineering in construction lags behind that of some other sectors, such as aerospace. Progress has been made on applying systems engineering to construction projects in the EU and Australia. While there has been no clear mandate for SE historically, the US High Speed Rail projects create an opportunity for future large-scale infrastructure projects to follow the same path.

The California High Speed Rail Project is an example of a large construction project requiring its contractors to use an SE approach. This project is perfect situation for an early application of systems engineering in the USA.

Useful References

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This Leaflet

This leaflet is part of a series intended as brief introductions to the application of systems engineering approaches to infrastructure projects. It was developed by the International Council On Systems Engineering (INCOSE) Infrastructure Working Group in the interest of aiding industry.

For further information about the application of systems engineering in large infrastructure projects, including a Guide applicable to the Construction project stage, go to www.incose.org and look for publications.

INCOSE is a not-for-profit membership organization founded to develop and disseminate the interdisciplinary principles and practices that enable the realization of successful systems.

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INFRASTRUCTURE
WORKING GROUP

Applying Systems Engineering to Industrial & Infrastructure Projects

Applying Systems Engineering to Infrastructure Design

The Need

Large infrastructure projects include those for the construction of public works and private structures, including industrial plants, energy and other utilities, airports, sea ports, canals, dams, rail, highways, tunnels, and bridges, among others.

Nuclear plant construction projects and projects constructed for the government (e.g., DOE, DoD) tend to require a more rigorous application of systems engineering methods. Other infrastructure projects typically involve organizations and industries that have not traditionally utilized a systems engineering approach. There is a significant advantage to be gained by the adoption of systems engineering methods within the remainder of the infrastructure sectors.

Large infrastructure projects involve complex design activities. Managing the documentation and incorporation of a multitude of requirements, preparing a design to meet those requirements, integrating the components of the design, and verifying and validating that the design has met requirements are all facilitated by the application of systems engineering principles.

Design efforts can suffer several types of problems caused by the inadequate application of systems engineering methods. For example, if the requirements aren't properly documented and managed, the design may not include elements critical to meeting the needs of stakeholders or applicable codes or standards. Often, the various components of the design are not well integrated, leading to design conflicts. Changes in requirements or stakeholder needs lead to scope creep, late design changes, and cost and schedule overruns. Solving these and other issues drives the need for a more formal approach to managing engineering design on infrastructure projects. Systems engineering helps address these issues in an increasingly complex environment.

What is Different About Systems Engineering?

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, and conducting design synthesis and system validation. SE considers both the business and technical needs of customers with the goal of providing a quality product that meets user needs (http://www.incose.org/AboutSE/WhatIsSE).

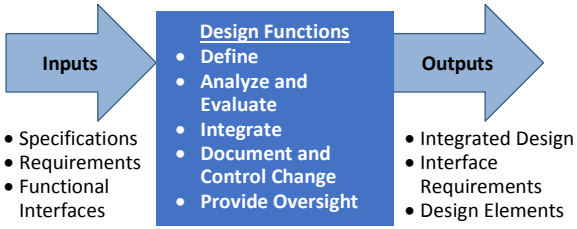
Systems engineering involves multidisciplinary teams working together to define project requirements, identify alternative designs, select the optimal solution, build the product, conduct testing to ensure the product meets stakeholder needs and requirements, and operate and maintain the product through its lifecycle.

Many of these steps are undertaken on traditional design projects. The systems engineering approach differs in a few fundamental aspects:

- Requirements are thoroughly defined, refined and allocated to lower-level system elements, assigned to suppliers and subcontractors, and tracked, through the testing and verification phase of the work.
- The product is viewed from a system perspective: links between requirements are identified so that changes to any one area can be analyzed for impacts to the requirements for the system as a whole.
- The entire product lifecycle is considered from the start of the project, including disposal of the final product.

Design Engineering as a Process

This figure provides a simple context diagram showing design engineering as a process.



The design engineering process gathers inputs from the specifications and system requirements, identifies and specifies all systems, structures and major components to be designed and produces an integrated design with interface requirements and descriptions of the system elements.

Systems Engineering in Design

From a systems engineering perspective, effective design management requires the following activities to be well executed:

Define

Describe a high-level system consistent with stakeholder requirements and specifications. Refine and allocate the system requirements to lower-level system elements as appropriate. Identify interfaces between system elements, and between the system and other external systems.

Analyze and Evaluate

Analyze the system as a whole to determine how best to achieve user and client requirements. Establish criteria for selecting from among the design alternatives. Evaluate design alternatives and decide on the best option.

Integrate

Define and manage interfaces with external systems. Define the strategy for integrating system elements. Ensure the design elements are integrated throughout the effort, from preliminary engineering through final design. Resolve interface issues.

Document and Control Change

Document the preliminary engineering phases and the baseline design. Establish traceability between requirements and system elements.

Analyze design changes for their full impact on the integrated design and the requirements. Approve changes through a prescribed process and appropriate levels of authority. Understand the impact on the rest of the system ***before*** committing to the change. Ensure approved changes are propagated to all affected items.

Provide Oversight

Manage the resulting information and the processes being implemented. Develop metrics useful to show the quality of the design management activities.

Benefits of Systems Engineering

As infrastructure projects become more complex with regard to the size of the systems, the number of requirements and stakeholders involved, and the sophistication of the associated technology, the risks of project failure increase. The application of systems engineering can help ensure these projects are delivered on time and budget, and that they meet requirements.

Systems engineering improves project outcomes by:

Improving system quality

Systems engineering involves an increased focus on thorough planning at the start of the project, including identifying stakeholder needs, documenting how the desired system will operate, and establishing system requirements, including tracing all requirements to their source documents. It also provides a detailed approach for ensuring those requirements are tracked through the testing stage and verified in a disciplined manner, through the use of a requirements verification traceability matrix (RVTM).

Gaining increased stakeholder participation

Systems engineering requires the involvement of all stakeholders throughout the project to ensure the project continues to meet stakeholder needs. This continuous involvement helps the project team identify and document any changes to the requirements as early in the project as possible. The use of a standard systems engineering project process helps stakeholders actively participate in the development of the system, and facilitates the involvement of new stakeholders by reducing the learning curve.

Ensuring design integration

The thorough and detailed documentation of requirements in a requirements matrix provides a good foundation for design integration. The matrix documents the connections from the source files, such as contract documents, down to very detailed requirements for smaller system elements. It also documents interfaces and traceability between requirements, both internal and external. It also helps document changes in requirements, and enables the team to identify impacts of the changes on the requirements for other parts of the system.

Reducing cost and schedule overruns

Combined with the disciplined project controls that form part of the systems engineering approach, the rigorous tracking of requirements helps reduce the risk of schedule delays and cost overruns.

Systems Engineering in Construction

There are several unique aspects of systems engineering on large infrastructure construction projects. One difference is that the system elements are often completed by different firms under separate contracts, and often at different times. This makes it even more difficult to integrate the work (as it's done across projects), and to successfully complete the verification and validation that all of the requirements have been met (as each contract is only a part of a larger system).