Systems Engineering in Major Capital Projects

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INTRODUCTION

Abstracts were requested regarding any of the following: applying systems engineering to rail applications; aspects of the systems engineering lifecycle applicable to the risk profile of rail projects; priorities in systems engineering processes; technical challenges to projects, e.g., managing legacy interfaces, controlling software development, and delivering systems acceptable to rail operations staff.

Scope of this Document

This paper discusses how STV applies Systems Engineering (SE) in Major Capital Projects, specifically Underground Projects, where space constrains present additional challenges. The paper will address the following topics:

- Applying Systems Engineering / Defining Priorities: The paper will address how the Systems Engineering process is scaled and tailored to address the specific needs of Major Capital Projects.
- Requirements Management: Major Capital Projects have literally hundreds if not thousands of requirements to adhere to. The paper will address how operational and system requirements are identified, captured, managed, allocated, refined, assigned and traced to the design, implementation and testing phase.
- System Integration, Verification and Validation Testing: The paper will describe how STV applies Systems Engineering in Major Capital Projects to prepare for successful testing during integration, startup and pre-revenue testing.
- Safety Certification: The paper will describe how the Systems Engineering and Requirements Management process is used to provide for successful Safety Certification.

Document Structure and Content

This paper is subdivided into the following subsections and discusses the following content.

- Value of Systems Engineering
- Challenges in Civil Projects
- Systems Engineering Tailoring
- Requirements Management
- Systems Testing
- Safety Certification
- Summary

OVERVIEW

Value of Systems Engineering[1]

The International Council of Systems Engineering[2] (INCOSE) defines Systems Engineering (SE) as follows:

> *"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 ..."*

Major civil projects include a variety of complex systems, including but not limited to:

- Electric Traction System,
- Signaling System,
- Communication and SCADA systems,
- Mechanical Systems,
- Electrical Systems,
- Plumbing Systems, and
- Ventilation Systems.

Systems Engineering reduces the risk of schedule and cost overruns and increases the likelihood that the implementation will meet the operator's needs. Other benefits include:

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[1] Source: Systems Engineering for Intelligent Transportation Projects – An Introduction for Transportation Professionals – January 2007

[2] http://www.incose.org/practice/whatissystemseng.aspx

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

Studies performed by INCOSE, Boeing, IBM and others on 44 projects indicated that investing in systems engineering did improve project cost performance. The responses indicated a 50% cost overrun on average without systems engineering and a clear trend toward better cost performance results with systems engineering.

Challenges in Civil Projects

Civil projects typically follow the traditional plans, specifications and estimates (PS&E) approach.

Plans: provide drawings that present the civil elements in their final arrangement on civil backgrounds. The focus is on construction. Details of the civil elements are provided in the specification with additional directions given to the contractor as drawing notes.

Specifications: typically follow the Construction Specifications Institute (CSI) MasterFormat, and are structured into three major parts (CSI 1995): GENERAL, PRODUCTS, and EXECUTION.

The first part usually contains general information, such as the scope of work, quality requirements, references to other specifications, submittal requirements, etc. The second part provides detailed requirements for products to be used, for example concrete, metals, wood, doors, finishes or other products. The third part describes how the products have to be installed and other construction related information.

Estimates: material quantities are taken off plans and specs, combined with labor and construction cost and summarized for the project. Additional factors are incorporated, including but not limited to, overhead and indirect costs, testing & commissioning, contingencies, insurances and escalation costs to determine the final costs.

While the PS&E process describes the deliverables of a civil project, there are a few other characteristics that need to be looked at:

Project Organization: civil projects are usually organized into functional groups or disciplines such as architecture, structures, civil, utilities, real estate, electrical, etc. Typically each group provides their own set of plans and specifications. Integration is ensured by coordinating between these groups. The disciplines all report to the overall project manager.

Integration: the focus is clearly on spatial integration between disciplines or contract packages in larger projects. The responsibility of successful integration is assigned to one of the two interface partners. The integration function serves as an oversight to ensure all interfaces are identified and signed off.

Design-Bid-Build (DBB) Contracts: this approach is the traditional method used to deliver a civil project. There are three main sequential phase: design, bid and construction. In the design phase the bid documents are prepared by a design team. After the contract has been awarded the bid documents are used by the contractor for construction. Typically a general contractor uses several subcontractors to execute the project.

Major Civil Projects: large civil projects are typically subdivided into several subcontracts or contract packages. Matrix organizations are utilized where the disciplines are coordinated by sub-project or contract package managers.

As described above, although Systems Engineering offers many advantages, it still, however, faces a number of challenges when applied in civil projects. The following challenges are described from a Systems Engineering point of view:

Interdisciplinary Approach: Systems Engineering follows a top-down approach, starting with user requirements, followed by systems requirements before high-level and detailed design activities are performed. Business and system analysts are used to determine the operational requirements and derive the system requirements before they are allocated to a high-level system architecture created by system architects. This requires a project organization where the sub-systems (disciplines) report to a technical system integrator type function, and not directly to the project manager. In civil projects however, the disciplines traditionally act as equals and peers. Interdisciplinary coordination relies on the disciplines themselves.

Defining Customer Needs and Required Functionality Early in the Development Cycle: while interaction with the client is typically frequent, the focus of this interaction is often on the selection of certain equipment types, maintenance topics, constructability, and other specific issues, rather than on overall system operation and functionality. Also, stakeholder involvement often occurs individually with specialized groups, such as operations, engineering, maintenance, track, and safety.

Documenting Requirements is often considered to be as simple as updating the plans and creating the bid specification. While design criteria are developed at the beginning of the design, the refinement and clarification of these criteria occurs in numerous meetings, presentations, design and peer reviews and is documented in literally several thousand documents exchanged between the client and project.

There is typically no traceability between the designs and requirements other than relying on the knowledge of the project personnel. Changes to plans and specifications may occur without realizing that these changes were in response to client requests.

This challenge increases when the bid documents are handed over to the contractor. Design knowledge regarding why certain equipment was specified may be lost. Equipment is specified in its entirety without knowing which features are truly necessary to comply with the system-wide user and system requirements.

Proceeding with Design Synthesis and System Validation as described above, design development is often an iterative process where designs are developed and presented for critique as part of design reviews. Designs are refined until they meet the client needs. This frequently leads to scope creep and "gold-plating", as it is not possible to validate the design against an unambiguous set of rules (requirements). Refinements in one design portion may also require changes in another interfacing design element, which often leads to time and cost overruns.

Considering the Complete Problem as described above, civil projects are often subdivided into multiple disciplines; without a system integration function, rather than the project manager, having the authority to direct the separate disciplines.

Each discipline develops their design and coordinates with the other disciplines to ensure integration can be performed successfully. This design approach is described as bottom-up engineering and is in direct contrast the top-down approach employed by Systems Engineering.

Also, since system integration focuses on spatial integration, it is considered successful and complete when design elements fit physically. System design, however, adds a completely new level of complexity, since system elements have to interact with each other exchanging information, and having to provide a system-wide functionality to meet operational needs.

System integration issues are therefore typically identified very late in the design process, or even during construction, where the cost of correction is several times higher than during early design phases.

SYSTEMS ENGINEERING TAILORING

This section describes how STV introduces Systems Engineering principles and how they are tailored to comply with the plans, specifications and estimates (PS&G) process.

The applied systems engineering approach is based on the VEE model as shown in Figure 1.

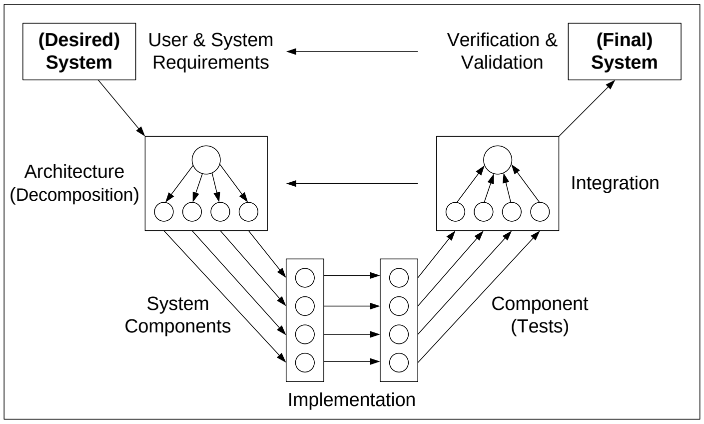

Figure 1: VEE Model

The following text will address system design level as well as civil design level documents that are used to provide a full design that meets both the SE and the PS&E process. For each document, the purpose and relevance to above described processes and challenges are discussed as well as the relationship between the documents, which include, but are not limited too:

System Design Level Documents

- User & Operational Requirements,
- System Control Matrices,
- System Requirements,
- Requirements Traceability Matrix (RTM),
- System Requirements Specification (SyRS),
- System Architecture,
- System to System Interfaces,
- Sequence of Operation,
- Communication Requirements and Interface Details, and
- Schematic System Layouts.

Civil & Contract Integration Documents

- Device Layout Plans,
- Equipment Rack Layout Plans,

- Equipment Room Layout Plans,
- Control Center Layout Plans,
- Cable Plans,
- Conduit Layout Plans,
- Typical Device & Housing Detail,
- Typical Mounting/Installation Detail,
- General Arrangement Drawings,
- System to Civil Interface Plans,
- System to MEP Interface Plans, and
- Construction Interfaces Plans

User & Operational Requirements represent the user requirements in the systems engineering process and are documented in the Concept of Operations (ConOps), describing operational scenarios (Figure 2) from a user & maintainer perspective for the following types of system operation:

- Normal (day to day) operation,
- Emergency operation,
- Maintenance / test operation, and
- Degraded mode / contingency operation.

The scenarios include information such as:

- Actual scenario (why)
- User (who)
- Location (where)
- Timeline (when)
- Roles & responsibilities (what & how)

Identifying the user needs and documenting them is one of the core processes in the Systems Engineering discipline.

The operational scenarios define how the users act in a certain situation and <u>what</u> is expected from the systems to support their activities. For example: the power director uses the Power SCADA system to open traction power circuit breakers, or train dispatcher use the radio system to communicate with train crew in tunnels.

Scenario: ...		
User	Location	Roles & Reponsibility
Timeline: e.g. time of incident		
Train Dispatcher	Control Center	• Action #1 • Action #2 • ...
...	...	...
...	...	...

Figure 2: Operational Scenario Description

The operational requirements are captured in the requirements traceability matrix and traced to both the lower level design as well as to the validation tests. These are performed at the end of the project during start-up and pre-revenue testing to confirm that the right systems were built, meeting the original user needs.

System Control Matrices are a user requirement level document and similar to a responsibility assignment matrix (RAM), linking system components and their functionality at each type of field location to users at central locations.

The system control matrices provide a one page overview drawing for each system validating the user requirements from the ConOps and define high-level functional system requirements for each system.

As part of the user requirements they will be traced to the user acceptance tests and validated as part of pre-revenue testing.

System Requirements represent the technical requirements for a system, typically derived from user requirements. System requirements are typically documented in a system requirements specification (SyRS), as further described below in this paper.

System requirements are differentiated between functional and non-functional requirements. Functional requirements are derived from user requirements starting with an action word. For example:

- <u>Open</u> motor operated switches,
- <u>Disconnect</u> traction power,
- <u>Switch</u> on light,
- <u>Make</u> public address announcement, or
- <u>View</u> CCTV camera.

Non-functional requirements specify criteria that describe how well the system functions are to be performed, including but not limited to:

- Performance (e.g. time, load, etc.)
- Reliability, availability, maintainability (RAM)
- Safety, security
- Usability, testability, extendibility, scalability, …

Examples of non-functional are:

- The system shall open the disconnect switches within 5 seconds.
- The system shall be able to handle n CCTV video stream concurrently.
- The system shall provide a system availability of 99.9%.

There are many sources of requirements, including user requirements, design criteria manuals, codes and standards as shown in Figure 3.

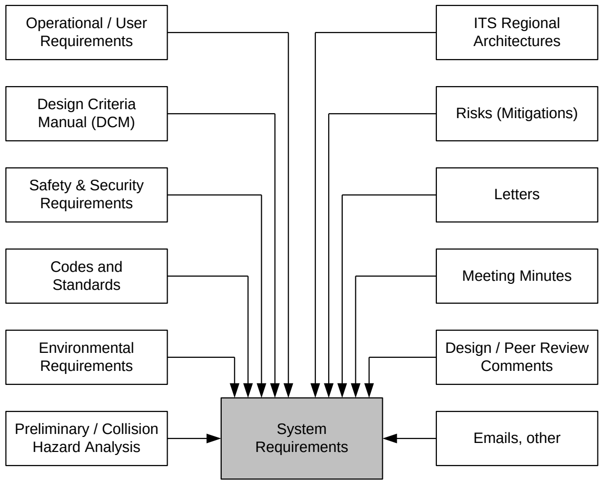

Figure 3. Sources of System Requirements

System requirements are written as verifiable requirements that define what the system will do, but not how the system will do it. System requirements should always be written in an unambiguous way to achieve SMART requirements (Specific, Measurable, Achievable, Realistic, and Timely).

System requirements are captured in the requirements traceability matrix (RTM) and traced to both the lower level design and to the verification tests. These are performed at the end of the project during system start-up testing to confirm that the systems were built right, meeting the system specifications (requirements).

Requirements Traceability Matrix (RTM): provides a methodical way of managing the user and system requirements. Source documents are systematically parsed for requirements which are then traced to the RTM. A reference to the original source location (trace from) is added as shown in Figure 4.

The captured requirements in the source document are identified (highlighted) indicating they have been captured (trace down). Requirements are then further processed, as described in Requirements Management section in this paper.

Source	Ref.	Requirements	Design	Test
ConOps	1.1	The system shall ...	...	...
DCM	2.1	The system shall ...	...	...
...	...	...	...	...

Figure 4. Requirements Traceability Matrix

The requirements traceability matrix is a key document that provides traceability from the requirements to both design and testing. The RTM enables designers to:

- Trace from user and system requirements to the designs enabling effective design reviews,
- Trace from the designs back to the requirements to understand whether and why a design feature is needed,
- Trace from the requirements to the test documentation developing effective test cases proving that the system built is in compliance with the specification (requirements), and
- Trace all relevant safety requirements to the Certifiable Items List (CIL) required for the Safety Certification at the end of the project.

System Requirements Specification (SyRS) typically documents the system requirements as described above. For the duration of the design phase requirements are documented and managed using the RTM. Once the contractor specifications are created, the system requirements are transferred into the Construction Specifications Institute (CSI) specification for each system as shown in Figure 5.

PART 1 – GENERAL

...

GENERAL SYSTEM DESCRIPTION

- System Overview
- Operations and Scenarios
- Subsystems and Interfaces

SYSTEM REQUIREMENTS

- Operational Requirements
- Functional Requirements
- Performance Requirements
- Interface Requirements
- Environmental Requirements
- Reliability, Availability, Maintainability Requirements
- Safety and Security Requirements
- Verification and Validation Requirements
- System Life Cycle Requirements
- Expandability Requirements
- Maintenance/Logistics/Support Requirements

...

PART 2 – PRODUCTS
PART 3 – EXECUTION

Figure 5. System Requirement in CSI Specification

System Architecture represents the high-level design in the systems engineering process and is the first and most important step in designing systems.

Systems are decomposed into subsystems and system components. The breaking points define the interfaces between the components and are documented in the system to system interface drawings (see further below in this document).

The following Figure 6 represents a simple Closed Circuit Television (CCTV) system architecture. In large civil projects, typically several control centers, numerous equipment rooms and field component locations exist. The purpose here is to show all types of system elements and their interconnectivity.

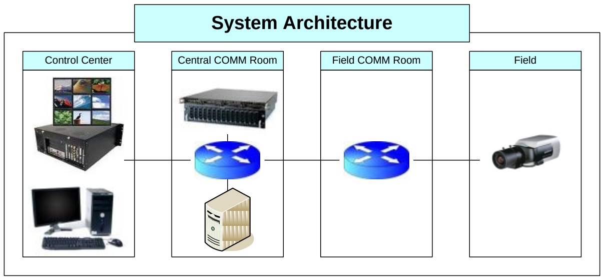

Figure 6. Simple CCTV System Architecture

System requirements are allocated to the subsystems and system components. Sequence of operation diagrams are used to describe in a step-by-step approach how the system functions. Additional communication requirements and interface detail diagrams are used to specify the interface protocols used.

System architectures provide an important input into the failure modes and effects analysis (FMEA) to determine potential failures and their impact on the overall system function as, generally, single point of failures (SPOF) are not accepted.

Since the decomposition identifies all system components, the system architecture also serves as input into the CSI specifications, specifically PART 2 – PRODUCTS and the cost estimates.

Also, system architectures reflect typical designs and will be tailored and detailed for each location in the schematic system layout drawings.

It is of utmost importance to understand that the decomposition process is the exact opposite of the system integration process performed during construction. Successful system integration cannot be performed without defining a project-wide system architecture, which allocates all system requirements and defines all interfaces before the detailed design is performed.

System to System Interfaces: diagrams based on the system architecture provide a graphical overview of all system to system interfaces. A supporting table lists the interface language in more detail with reference to the project-wide integration and interface database. System to system interfaces are tested during system integration testing and are particularly important if they span across contract packages. An example would be the interface between the SCADA system and the ventilation system.

Sequence of Operation defines a system level use-case with input from the user & operational scenarios. Once the user activates a system function, typically several systems have to be coordinated and several steps have to be performed to execute the system function. If available, screen shots can be provided to the contractor to further define the user interface requirements.

Actor	Sequence of Events	User Interface
Operator	• Action #1	Screenshot
System	• System Response	Screenshot
...	...	...

Figure 7. Sequence of Operations

The sequence of operation defines how the systems, subsystems and components work, and define system functions in an unambiguous method. It is crucial to understand what the systems are supposed to do before the detailed design is started.

Sequence of operation diagrams serve as a very important communication tool between the client and the designer and later the contractor. They will also be used to validate the system architectures ensuring that all desired functionality can be supported by the system design.

Sequence of operation diagrams will be used during final system verification testing to ensure that the built systems meet all specified system functions.

Communication Requirements and Interface Detail utilize the system architecture and sequence of operation diagrams to define the interface details following the ISO/OSI model (International Standards Organization / Open Systems Interconnection).

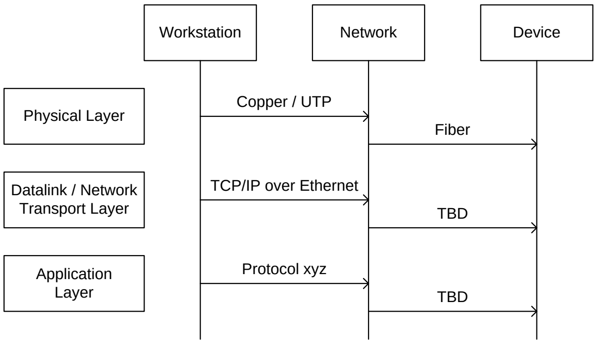

Figure 8. Communication Requirements and Interface Details

Communication requirements and interface detail diagrams include, but are not limited to, network, communication, message and data standards to be utilized between the system components when interacting with each other. Sequence diagrams are used to graphically present the standards used, as presented in Figure 8.

They also reflect the communication, message and data standards defined as part of the architecture flow standards in the ITS (Intelligent Transportation System) regional architecture market packages.

Schematic System Layouts are system one line diagrams. They are key documents defining the interface between system and civil design. The typical designs in the system architectures are laid out spatially and applied per location. The civil design is presented as background in a schematic manner.

These schematic system layouts provide a one page high-level system overview for each location, including all control center, equipment room, and field location equipment, and also all interconnects between them, presented as single lines. It is not important at this stage to define spatial needs or component and interconnect details.

The failure modes and effects analysis (FMEA) is performed a second time ensuring that the system layout is not negatively affecting the system requirements (e.g. redundant network cables using path diversity do not share the same physical space).

The schematic system layout drawings provide input into a number of layout plans on civil backgrounds. Field components will be placed on device layout plans, control center equipment will be shown on control center layout plans, and central system components will be shown on equipment rack layout plans which will finally be placed on equipment room layout plans.

The single lines representing the connectivity are used to determine cabling needs, which then can be used to calculate conduit sizes, using fill factors and other considerations.

Since all equipment is laid out at this stage, the drawings can also be used to determine all quantities for each type of equipment for the cost estimates. Central equipment can be sized properly, based on the amount of field equipment connected.

Schematic system layout drawings also provide the advantage of being independent of the civil plans, which often change frequently at this stage of the design phase.

Device Layout Plan is to show field equipment such as signals, catenary poles, public address speakers, etc. at the place of their installation on civil background drawings. Additional notes are given to the contractor to direct him in the installation. This type of drawing generally focuses on construction and the appropriate installation guidelines.

Device layout plans receive their input from the schematic system layout diagram and refer to typical detail defined for system components, housing, wiring, and installation.

Integration of system components with the civil design is shown on general arrangement drawings and summarized on civil interface plans, providing an overview of all system to civil interfaces within a certain location or contract package. Device layout plans also serve as input into the site installation test plans, verifying that all installations have been performed as required.

Equipment Rack Layouts depict central system components installed within an equipment rack. Often one rack is used for one system only. The type of equipment is determined in the system architecture while the amount of equipment is determined from schematic system diagrams, which identify the amount of field devices that are served from a specific rack in specific equipment room. Racks are then placed on equipment room layout plans to determine the size of equipment rooms.

Equipment Room Layout Plans are similar to device layout plans, only that the devices in this case are typically equipment racks and local user workstations presented on a room plan showing the dimensions and all equipment placed in this room. Examples of room layout plans are signal central instrument houses, elevator machine rooms, and communications equipment rooms. Equipment room plans serve an important role in space-proofing efforts, ensuring that the civil design provides sufficient room for all systems equipment.

Control Center Layout Plans are similar to equipment room layout plans only that in this case user desks, workstations, video walls and other office equipment is spatially arranged on a room plan. Examples of control centers are rail control centers, station operation centers, fire command posts, and yard towers.

Control center layouts are also verified against system control matrices to ensure that all user positions and functions have been considered for each control center location.

Control center plans play also an important role in space-proofing efforts, ensuring that the civil design provides sufficient room for all systems equipment and the operator needs.

Cable and Conduit Layout Plans depict cables and conduits between system components installed at control centers, equipment rooms and field locations. An important input into the cable and conduit layout plans are the schematic system layout diagrams identifying all interconnections between the system components.

Integration of conduits within the civil design is also typically shown on general arrangement drawings ensuring that sufficient space is provided for system conduits. The general arrangement drawings are also used as construction interface drawings since often conduits are installed as part of the civil design but used by the systems contractor when dealing with more than one contract.

General Arrangement Drawings are important drawings to show how systems elements are integrated with civil design (system to civil interfaces) at specific location. Input for the general arrangement drawings is received from device layout plans, equipment room layouts, control center layouts and conduit layout plans, providing usually a typical detail design.

System to Civil Interface Plans provide a one page overview of all system to civil interfaces within a certain location or contract package. Additional interface details are provided in tabular format with reference the plans which provide the detail information. A supporting table lists the interface language in more detail with reference to the project-wide integration and interface database.

System to MEP Interface Plans provide a one page overview of all system to mechanical, electrical and plumbing (MEP) interfaces within a certain location or contract package. Typically MEP systems are designed by a different discipline other than railroad systems. Reference is made to other plans such as rack layout plans Equipment room layout plans also provide the electrical load calculations needed to define the power requirements that the MEP systems must supply to adequately support the railroad systems. A supporting table lists the interface language in more detail with reference to the project-wide integration and interface database.

Construction Interface Plans utilize general arrangement drawings to highlight responsibilities of the contractor. If two different contractors have to perform work in the same area, the same general arrangement drawings is used with different highlights. For example, if conduits are to be installed by contractor A for contract B, the first set of plans would used to give installation instructions for contractor A indicating that these conduits are reserved for contract B. Contractor B's responsibility would be to inspect the conduits at the start of that contract and utilize them as indicated on the contract drawings.

Other Drawings and Plans major civil projects prepare many other types of drawings and plans including, but not limited to, typical device & housing detail, typical component detail, typical mounting and installation detail. However, the most important systems engineering documents and their integration with the traditional plans, specifications and estimates approach have been addressed.

REQUIREMENTS MANAGEMENT

Proper requirements management is one of the most important topics in systems engineering. Missing user input (operational requirements) and incomplete or changing system requirements are the leading reasons projects run late, exceed budget or get cancelled. Requirements drive the project scope, directly feeding the system design and subsequent project schedule and cost. Any addition or change to requirements has an immediate impact on these parameters.

To improve a project's chances of success, requirements should be documented and baselined before design work starts. These are the main objectives in requirements management:

- Capture 100% of client-provided requirements,
- Organize, analyze, and flow-down captured requirements to each system,
- Employ either simple EXCEL spreadsheets or requirements management tools such as RequisitePro to maintain a Requirements Traceability Matrix (RTM),
- Support the design engineers in their efforts to derive SMART requirements from captured client requirements, and
- Support the design engineers in the preparation of specifications for each system.

The following steps are performed to create and manage requirements in the RTM as shown in Figure 9.

Parse: source documents as shown in Figure 3 are methodically searched for user and system requirements.

Capture: identified requirement is placed into RTM with originating language as shown in Figure 9 in the "Requirements" column. The captured requirement in the source document is identified (highlighted) indicating that it has been captured (traced down).

Trace: an accurate trace is assign for each captured requirement referring to the original source location, including document title, revision, section number, page number and location within page.

Analyze: determines the type for each requirement as discussed in the System Requirements Specification (SyRS) section above in this paper; for example whether the requirement can be classified as operational, functional, performance, interface requirement, etc., as shown in the "Classification" column of Figure 9.

Testing requirements are also determined, based on the source and type of requirements and documented in the "Testing" column:

Flow-down: requirements are assigned to systems/subsystems as shown in the "Allocation" column. The actual allocation may be more detailed, as shown in Figure 9. For example, communication systems can be further decomposed into network, public address, CCTV, radio, SCADA, and other systems depending on the complexity of the project.

Derive: source requirements are interpreted and/or rewritten as unambiguous SMART requirements in a design. Multiple sub-requirements are likely to emerge, specifically if a system-wide function requires several subsystems to interact. In this case the “Allocation” column is checked for more than one system and requires specific interface requirements to be developed.

Specify: the requirements specifications are written in “shall” terms, here the contractor specifications are documented as described above in the System Requirements Specification (SyRS) section.

Verify: each requirement will be verified both in design and testing. Before the actual design starts, target documents (“Design” column) are identified for each requirement, for example a functional system requirement should be described in a sequence of operations diagram, etc. Once the design has completed traces (“Trace” column) to the design drawings and specification sections are provided by the designer and verified during the quality assurance/control (QA/QC) process.

Req #	Source	Ref.	Requirements	Classification				Alloation				Design				Trace	Testing				
				OPS	FUN	PER	...	ET	STC	COM	...	USR	SYS	ARC	...	Doc Ref.	...	SIT	VER	VAL	SAF
1	ConOps	1.1	Operational Req. #1	X				X				X				Drwg. No.				X	
2	ConOps	1.2	Operational Req. #1	X					X			X				Spec. Section				X	
...	...	...	...				...				...	X			...	...	...				
...	DCM	2.1	System Req. #1		X					X			X		...	...	...		X		
...	...	...	...				...				...				...	...	...				
...	CHA/PHA	1.1	Safety Req. #1			X	...		X		...				...	...	...		X		X
...	...	...	...				...				...				...	...	...				

CLASSIFICATION	
OPS	Operational Requirement
FUN	Functional Requirement
PER	Performance Requirement

ALLOCATION	
ET	Electric Traction System
STC	Signals & Train Control System
COM	Communication System

DESIGN	
USR	User Requirement (e.g. ConOps, System Control Matrix)
SYS	System Requirement (e.g. SyRS, Sequence of Operation)
ARC	System Architecture (e.g. Communication Detail and ...

TESTING	
SIT	System Integration Test
VER	System Verification Test
VAL	System Validation Test
SAF	Safety Certification

Figure 9. Requirements Traceability Matrix (RTM)

SYSTEM TESTING

Systems are tested against requirements following the VEE model (as shown in Figure 1) and using the RTM. Requirements can be filtered by system, type of requirements, or type of tests to selected specific requirements that need to be tested.

Additional installation tests are performed as described below. Depending on the size, type of systems and complexity of the project, test requirements are typically required as Part 3 EXECUTION of the CSI specification or as independent specification focusing only on testing with various levels of details.

Component Tests are tests of single system components conducted to ensure they are functional before used in more complex subsystem and system tests. They are often performed by the manufacturer who provides test certifications. System components are tested against tge component requirements specified in Part 2 PRODUCTS of the CSI specification.

Subsystem and Factory Acceptance Testing (FAT) is the testing of subsystems are often provided by one supplier or subcontractor. The subsystems are typically tested at the factory where errors can be found more easily and corrected before the subsystems get installed and integrated with other subsystems. Tests are written and performed against subsystem and interface requirements specified in Part 1 GENERAL of the CSI specification

Site Installation Testing (SIT) is testing that all equipment, cables, conduits, etc. have been installed correctly as specified on device layout, rack layout, equipment room layout and control center layout plans as well as cable and conduit layout plans, and follows typical installation detail drawings and other installation guidelines.

Site Performance/Acceptance Testing (SPT/SAT) is performed to test the function of the system at the installation site once the equipment has been installed and tested as part of the SITs. Schematic system layouts as described above are most useful as input for these tests. Typically local control equipment is provided, such as local control panels (LCP) in a signal house, a fan control room, or a traction power substation.

System Integration Testing is performed at different levels whenever system components are integrated. This tests the interfaces between components, subsystems and systems at and between various sites.

System interfaces are documented on the system architectures, system to system interface plans, communication requirements, interface detail diagrams and in Part 1 GENERAL - interface requirements of the CSI specifications.

System Verification Testing (Start-Up Testing): once single interfaces between systems have been tested, complete systems are tested end to end from control centers down to field equipment, including all interim system components, networks, SCADA systems, etc. against the system requirements that were documented on the sequence of operation plans, and in Part 1 GENERAL - system requirements of the CSI specifications.

The main purpose is testing whether the systems were built right (verification), as opposed to testing whether the right systems were built (validation).

System Validation Testing (Pre-Revenue Testing): the purpose of these tests is to ensure that the right systems have been built, and that they meet the user and operational needs as defined in the concept of operations, system control matrix and operational requirements as defined in Part 1 GENERAL of the CSI specifications. Typically, unstructured testing that identifies uncovered system issues is also involved.

SAFETY CERTIFICATION

Safety certifications are performed at the end of the testing phase verifying that all safety relevant requirements have been met. The requirements traceability matrix conveniently allows the filtering of all safety requirements, their sources as well as all design and test traces, and provides a certifiable items list (CIL) template pre-filled with relevant CIL information as shown in Figure 10. All safety tests were performed during overall system testing as described in the previous section of this paper. The CIL is basically a subset of the RTM filtered for safety requirements.

Certifiable Element: **Revision:**			**Project XZY** **Specification Conformance and Operational Readiness Checklist**		**Date:** **Prepared By:** **Approved By:** **Verification Approval:**					
Req #	**Requirement Reference Description**	**Design**			**Construction / Install. / Testing**			**Final Verification**		
		Requirement Refererence	**Design Refererence**	**Verified by & Date**	**...**	**...**	**...**	**...**	**...**	**...**
001	The system shall ...	Doc. Ch. X Sec. Y ...	Spec. Ch. X Sec. Y ...	Initial / Date	...	...	...	...	...	...
001	The system shall ...	Doc. Ch. X Sec. Y ...	Drwg. # XZY	Initial / Date	...	...	...	...	...	...
003	The system shall ...	...	...	...	...	...	...	...	...	...
n	The system shall ...	...	...	...	...	...	...	...	...	...

Figure 10. Certifiable Items List (CIL)

SUMMARY

STV applies the Systems Engineering principles to reduce the risk of schedule and cost overruns and provide high quality projects to clients.

The paper described how STV scales and tailors the Systems Engineering process to address the specific needs of major capital projects.

The paper also described how operational and system requirements are identified, captured and managed using the requirements management process.

It addressed system integration, verification, validation and other tests to prepare for successful system startup and pre-revenue testing.

Finally the paper described how the systems engineering and requirements management process is used to provide for the final safety certification.

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