INCOSE

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Managing Director, Project Performance International

Presentation delivered in Australia, China, Mongolia, Netherlands, Turkey, UK, USA on the Knowledge, Skills and Attitudes Conducive to High Performance Engineering

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A Framework of Knowledge, Skills and Attitudes Conductive to High Performance Engineering

“Systems Engineering is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods"

(International Council on Systems Engineering (INCOSE), 2019)

“Systems Engineering is an interdisciplinary, collaborative approach to the engineering of systems, of all types, that aims to capture stakeholder needs and objectives and to transform these into a description of a holistic, life-cycle-balanced system solution that both satisfies the minimum requirements, and maximizes overall project and system effectiveness according to the values of the stakeholders.”

(Robert Halligan, 2003)

WHAT IS SYSTEMS ENGINEERING?

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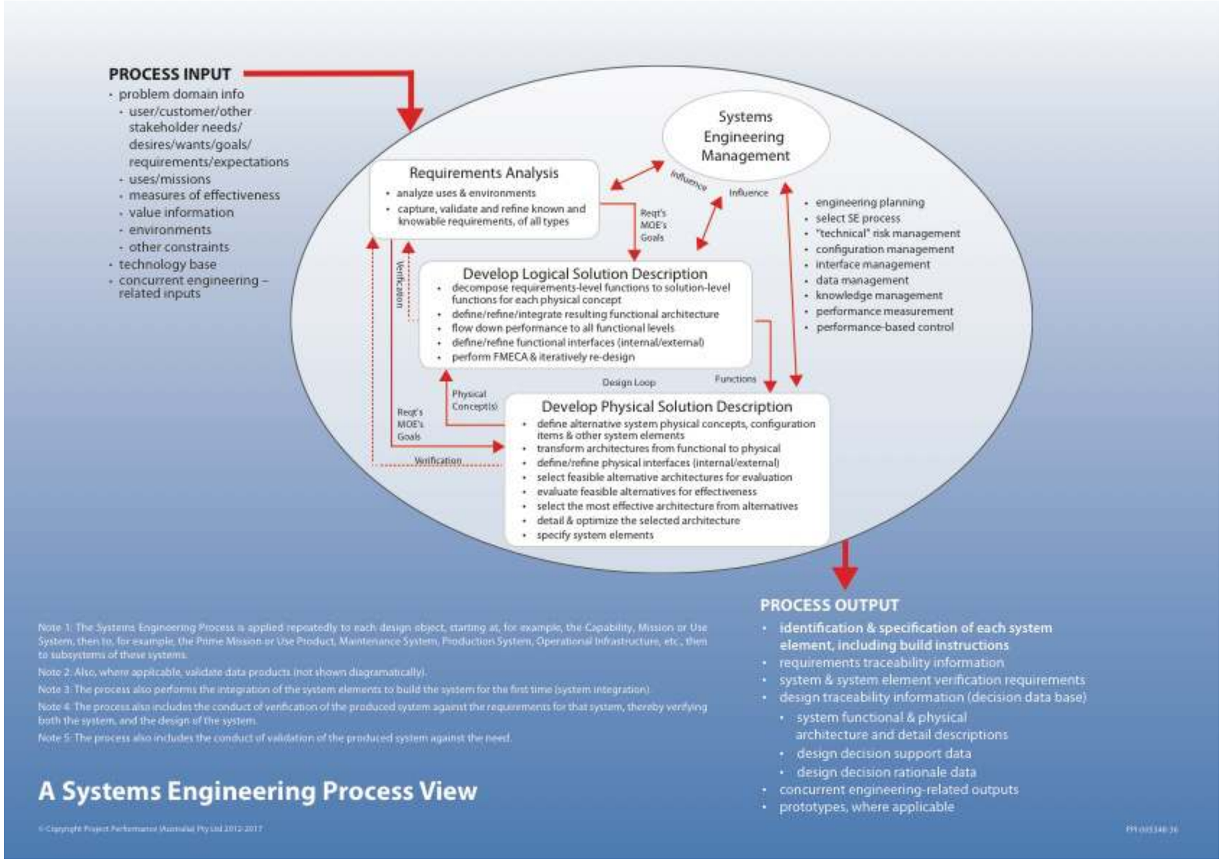


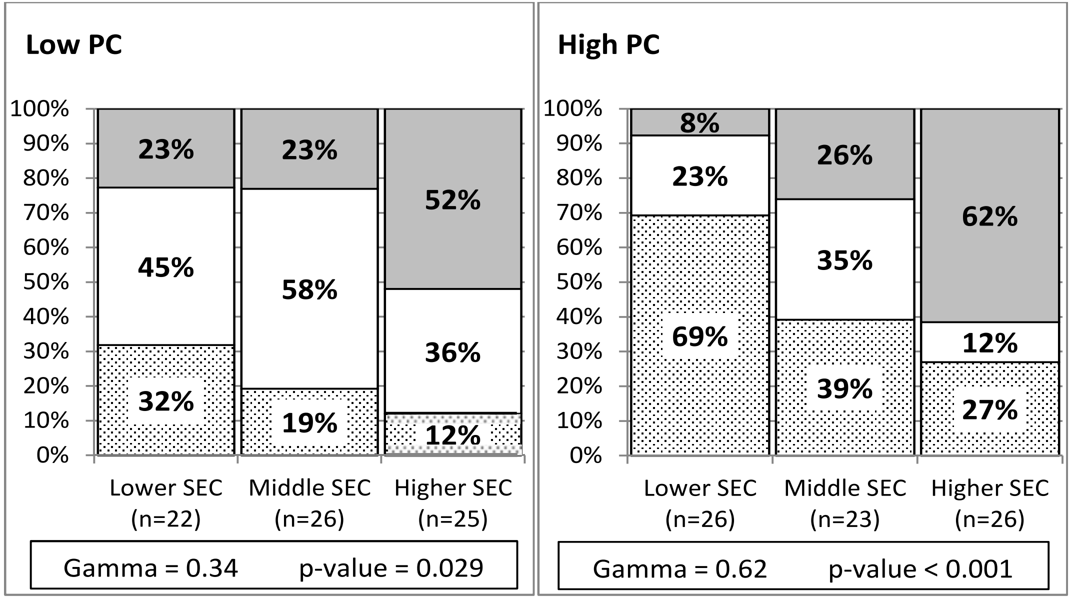
THE ESSENCE OF SE:

- ensure adequate problem definition
- define possible solution alternatives
- qualify solution alternatives for feasibility & effectiveness
- develop qualified alternatives
- where justified by complexity, use logical design as an aid in developing physical design (i.e. model-based design)
- design through levels of abstraction – architecture and detail
- maintain a clear distinction between problem and solution
- design through physical levels – system and subsystems

AND MORE …

- conduct trade-off studies and optimization to maximize overall effectiveness of solution
- specify solution elements to objective adequacy
- integrate engineering specialties with technology expertise
- verify work products (correct – the product right)
- validate work products (needed – the right product)
- employ configuration management
- only do work that adds value
- manage the engineering – plan, organize, inspire, assess, control
- manage risk and opportunity.

THE VALUE OF SYSTEMS ENGINEERING



Legend: PC Project Challenge
Source: “The Business Case for Systems Engineering Study: Results of the Systems Engineering Effectiveness Survey”, CMU/SEI-2012-SR-009, November 2012

THE VALUE OF SYSTEMS ENGINEERING

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Driver	Relationship to Performance (Gamma)		
	All Projects	Lower challenge	Higher challenge
SEC-Total – total deployed SE	+0.49	+0.34	+0.62
SEC-PP – project planning	+0.46	+0.16	+0.65
SEC-REQ – reqts. developt. & mgmt.	+0.44	+0.36	+0.50
SEC-VER – verification	+0.43	+0.27	+0.60
SEC-ARCH – product architecture	+0.41	+0.31	+0.49
SEC-CM – configuration management	+0.38	+0.22	+0.53
SEC-TRD – trade studies	+0.38	+0.29	+0.43
SEC-PMC – project monitor & control	+0.38	+0.27	+0.53
SEC-VAL – validation	+0.33	+0.23	+0.48
SEC-PI – product integration	+0.33	+0.23	+0.42
SEC-RSKM – risk management	+0.21	+0.18	+0.24
SEC-IPT – integrated product teams	+0.18	-0.12	+0.40

Gamma	Relationship
-0.2 <| *Gamma* | ≤ 0	Weak negative
0 ≤ | *Gamma* | < 0.2	Weak positive
0.2 ≤ | *Gamma* | < 0.3	Moderate
0.3 ≤ | *Gamma* | < 0.4	Strong
0.4 ≤ | *Gamma* |	Very strong

http://resources.sei.cmu.edu/asset_files/specialreport/2012_003_001_34067.pdf

Source: "The Business Case for Systems Engineering Study: Results of the Systems Engineering Effectiveness Survey", CMU/SEI-2012-SR-009, November 2012

INVESTMENT IN PEOPLE

- Ensure a foundation understanding and practice of SE for all engineers
- Ensure that the competencies of each engineer are matched to their role(s)
- Set objective criteria for each necessary competency
- Ensure a deep understanding and practice of SE by engineering leaders
- Ensure a strong commitment to SE by engineering managers
- Ensure an understanding of the business purpose and value of SE by project managers and business leaders
- A way of thinking, a way of life, a way of turning aspirations into reality

THE INCOSE SYSTEMS ENGINEERING COMPETENCY FRAMEWORK

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Systems Engineering Competency Framework

This INCOSE Technical Product was developed and produced in conjunction with the following contributors:

DAU, INCOSE UK, Lockheed Martin, MITRE, NDIA, NPS, Systems Engineering Research Center, WPI

INCOSE Technical Product Reference: INCOSE-TP-2018-002-01.0

THE INCOSE SYSTEMS ENGINEERING COMPETENCY FRAMEWORK – COMPETENCE AREAS

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CORE COMPETENCIES

Core competencies underpin engineering as well as systems engineering.

Systems Thinking	The application of the fundamental concepts of systems thinking to systems engineering;
Lifecycles	Selection of the appropriate lifecycles in the realization of a system;
Capability Engineering	An appreciation of the role the system of interest plays in the system of which it is a part;
General Engineering	Foundational concepts in mathematics, science and engineering and their application;
Critical Thinking	The objective analysis and evaluation of a topic in order to form a judgement;
Systems Modeling and Analysis	Provision of rigorous data and information including the use of modeling to support technical understanding and decision making.

PROFESSIONAL COMPETENCIES

Behavioral competencies well-established within the Human Resources (HR) domain. To facilitate alignment with existing HR frameworks, where practicable, competency definitions have been taken from well-established, internationally-recognized definitions rather than partial or complete re-invention by INCOSE.

Communications	The dynamic process of transmitting or exchanging information;
Ethics and Professionalism	The personal, organizational, and corporate standards of behavior expected of systems engineers;
Technical Leadership	The application of technical knowledge and experience in systems engineering together with appropriate professional competencies;
Negotiation	Dialogue between two or more parties intended to reach a beneficial outcome where difference exist between them;
Team Dynamics	The unconscious, psychological forces that influence the direction of a team's behavior and performance;
Facilitation	The act of helping others to deal with a process, solve a problem, or reach a goal without getting directly getting involved;
Emotional Intelligence	The ability to monitor one's own and others' feelings and use this information to guide thinking and action;
Coaching and Mentoring	Development approaches based on the use of one-to-one conversations to enhance an individual's skills, knowledge or work performance.

MANAGEMENT COMPETENCIES

The ability to perform tasks associated with controlling and managing Systems Engineering activities. This includes tasks associated with the Management Processes identified in the INCOSE SE Handbook.

Planning	Producing, coordinating and maintaining effective and workable plans across multiple disciplines;
Monitoring and Control	Assessment of an ongoing project to see if the current plans are aligned and feasible;
Decision Management	The structured, analytical framework for objectively identifying, characterizing and evaluating a set of alternatives;
Concurrent Engineering	A work methodology based on the parallelization of tasks;
Business and Enterprise Integration	The consideration of needs and requirements of other internal stakeholders as part of the system development;
Acquisition and Supply	Obtaining or providing a product or service in accordance with requirements;
Information Management	Addresses activities associated with all aspects of information, to provide designated stakeholders with appropriate levels of timeliness, accuracy and security;
Configuration management	Ensuring the overall coherence of system functional, performance and physical characteristics throughout its lifecycle;
Risk and Opportunity Management	The identification and reduction in the probability of uncertain events, or maximizing the potential of opportunities provided by them,

TECHNICAL COMPETENCIES

The ability to perform tasks associated primarily with the suite of Technical Processes identified in the INCOSE SE Handbook.

Requirements Definition	To analyze the stakeholder needs and expectations to establish the requirements for a system;
System Architecting	The definition of the system structure, interfaces and associated derived requirements to produce a solution that can be implemented;
Design for…	Ensuring that the requirements of all lifecycle stages are addressed at the correct point in the system design;
Integration	The logical process for assembling a set of system elements and aggregates into the realized system, product or service;
Interfaces	The identification, definition and control of interactions across system or system element boundaries;
Verification	A formal process of obtaining objective evidence that a system fulfils its specified requirements and characteristics;
Validation	A formal process of obtaining objective evidence that the system achieves its intended use in its intended operational environment;
Transition	Integration of a verified system into its operational environment including the wider system of which it forms a part;
Operation and Support	When the system is used to deliver its capabilities, and is sustained over its lifetime.

INTEGRATING COMPETENCIES

This competency group recognizes Systems Engineering as an integrating discipline, joining activities and thinking from specialists in other disciplines to create a coherent whole.

Project Management	Identification, planning and coordinating activities to deliver a satisfactory system, product, service of appropriate quality;
Finance	Estimating and tracking costs associated with the project;
Logistics	The support and sustainment of a product once it is transitioned to the end user;
Quality	Achieving customer satisfaction through the control of key product characteristics.

THE INCOSE SYSTEMS ENGINEERING COMPETENCY FRAMEWORK, EXAMPLE – SYSTEM ARCHITECTURE (1)

COMPETENCY AREA – TECHNICAL: SYSTEM ARCHITECTING
Description: The definition of the system structure, interfaces and associated derived requirements to produce a solution that can be implemented to enable a balanced and optimum result that considers all stakeholder requirements (business, technical….). This includes the early generation of potential system concepts that meet a set of needs and demonstration that one or more credible, feasible options exist.
Why it matters: Effective architectural design enables systems to be partitioned into realizable system elements which can be brought together to meet the requirements. Failure to explore alternative conceptual options as part of architectural analysis may result in a non-optimal system. There may be no viable option (e.g. technology not available).

THE INCOSE SYSTEMS ENGINEERING COMPETENCY FRAMEWORK, EXAMPLE – SYSTEM ARCHITECTURE (2)

EFFECTIVE INDICATORS OF KNOWLEDGE AND EXPERIENCE				
AWARENESS	**SUPERVISED PRACTITIONER**	**PRACTITIONER**	**LEAD PRACTITIONER**	**EXPERT**
Describes the principles of architectural design and its role within the lifecycle. Describes different types of architecture and provides examples. Explains why architectural decisions can constrain and limit future use and evolution and provides examples. Explains why there is a need to explore alternative and innovative ways of satisfying the requirements. Explains why alternative discipline technologies can be used to satisfy the same requirement and provides examples. Describes the process and key artifacts of functional analysis. Explains why there is a need for functional models of the system. Explains how outputs from functional analysis relate to the overall system design and provides examples.	Uses a governing process and appropriate tools to manage and control their own system architectural design activities. Uses analysis techniques to support architectural design process. Assists with the architectural design trade-offs. Contributes to alternative architectural designs that are traceable to the requirements Interprets an architectural design. Contributes candidate concepts (no matter how radical). Assists with the assessment of the feasibility of concepts. Uses appropriate tools and techniques to conduct functional analysis. Contributes to system architectural design activities.	Defines governing systems architecting plans, processes and appropriate tools and uses these to monitor and control system architectural design activities. Generates alternative architectural designs traceable to the requirements. Assesses a range of architectural designs and justifies the selection of the optimum solution. Chooses appropriate analysis and selection techniques Partitions between discipline technologies and works with specialists to derive discipline specific requirements Uses the results of system analysis activities to inform system architectural design. Describes the strengths and weaknesses of relevant technologies in the context of the requirement and provides examples Creates and is open to several possible alternative options and concepts and demonstrates that credible, feasible options exist Tracks key aspects of the evolving design solution and uses this information to adjust architecture, if appropriate. Guides supervised practitioners in system architectural design.	Recognized, within the enterprise, as an authority in system architectural design techniques, contributing to best practice. Defines and documents enterprise-level policies, procedures, guidance and best practice for system architectural design including associated tools. Reviews and judges the tailoring of enterprise-level system architectural design processes to meet the needs of a project. Demonstrates a full understanding of architectural design and functional analysis techniques and their appropriateness, given the levels of complexity of the system of interest. Reviews and judges the suitability of architecture designs and associated analyses. Realizes systems using a model that comprises a complete, coherent, and consistent architectural design. Influences key stakeholders to address enterprise-level system architectural design issues. Coaches new and experienced practitioners in system architecture design.	Recognized, beyond the enterprise boundary, as an authority in system architectural design. Contributes to system architectural design best practice. Influences key stakeholders beyond the enterprise boundary in support of system architectural design. Advises on the suitability of the approach to system architectural design. Advises and arbitrates on complex or sensitive system architecture-related issues. Advises in techniques for concept generation. Champions the introduction of novel techniques and ideas in system architectural design, producing measurable improvements. Coaches lead practitioners in system architectural design.

ANOTHER VIEW - KEY KSA AREAS (KNOWLEDGE-SKILLS-ATTITUDES)

1. Engineering management
2. Requirements Analysis (including MBSE in the problem domain)
3. Physical Design
4. Logical Design (MBSE in the solution domain)
5. Effectiveness Evaluation and Decision – Trade-Off Studies
6. Requirements Specification Writing
7. System Integration
8. Verification
9. Validation

1. ENGINEERING MANAGEMENT

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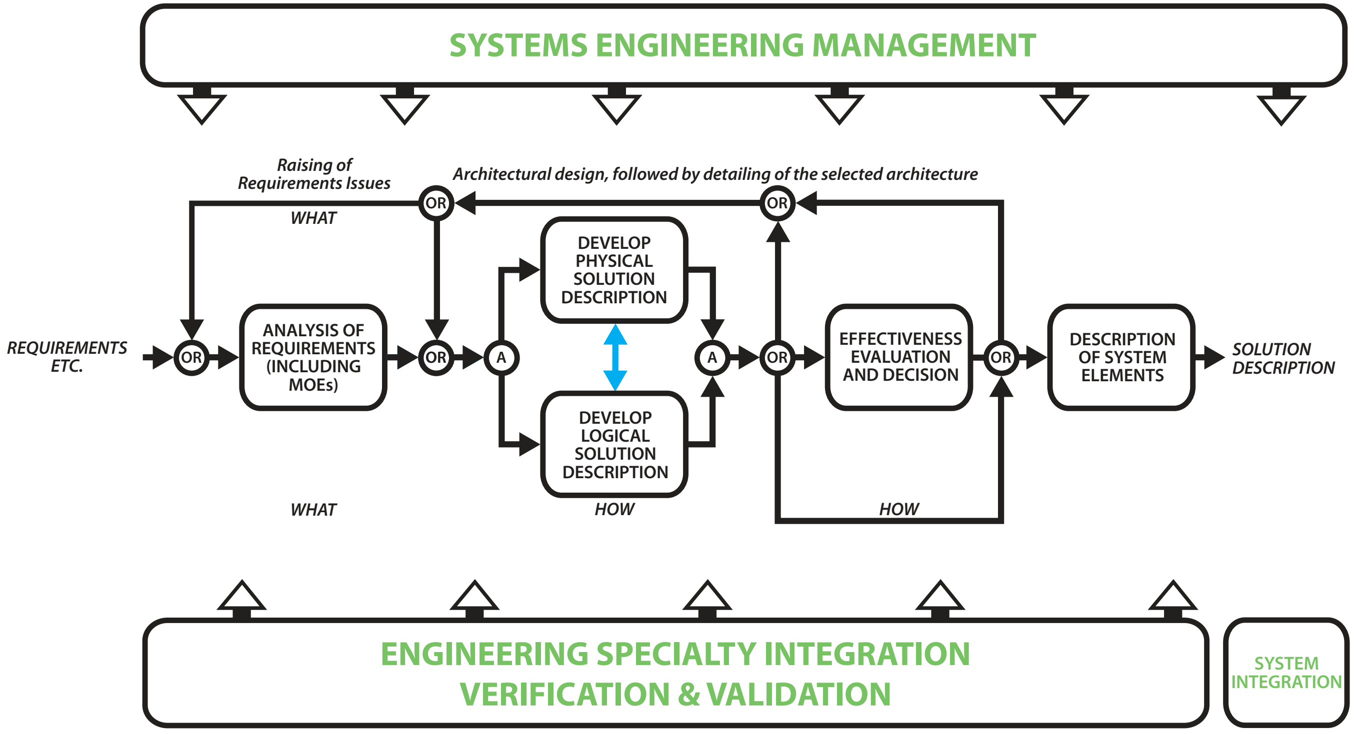
KNOWLEDGE	SKILLS	ATTITUDES
• The technologies involved • The principles and methods of project management • The principles and methods specific to managing engineering • The principles and methods of SE • The foundations of risk and opportunity • Human psychology	• Planning and organising • Measuring and applying corrections • Motivating people • Invoking confidence amongst stakeholders in the engineering work • Applying the principles and methods specific to managing engineering • Risk and opportunity management, including requirements-related risk and the engineering overhead/design complexity tradeoff	• Alignment with the business purpose and context of the engineering • Respect for technical expertise • Results orientation • Willingness to delegate tasks • Focus on issues not personalities • Emotional intelligence • An attitude to risk and opportunity aligned to that of the organization

SYSTEMS ENGINEERING – BASIC PROCESS ELEMENTS



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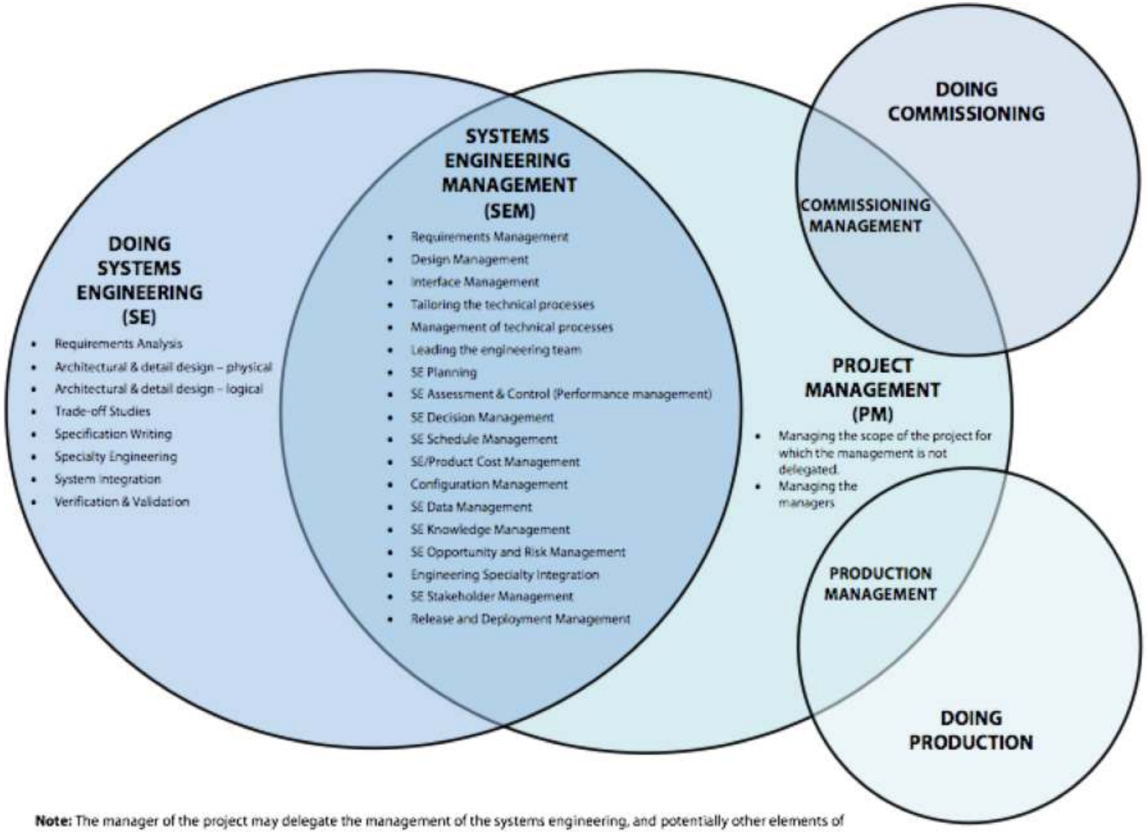
SE-ENGINEERING MANAGEMENT-PM RELATIONSHIP



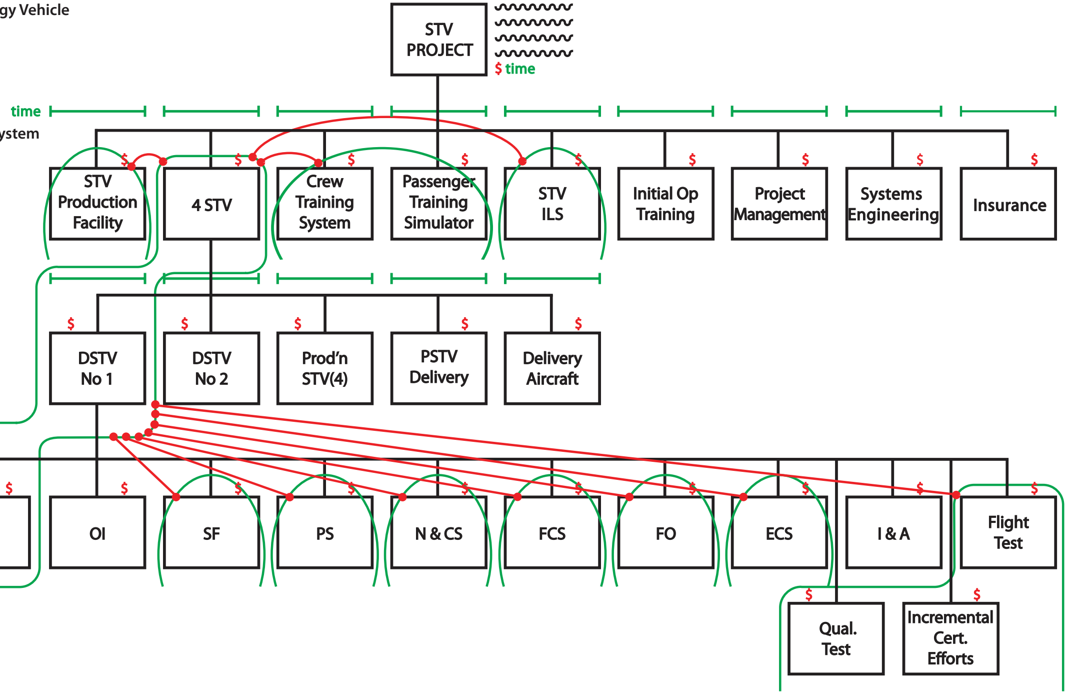
Note: The manager of the project may delegate the management of the systems engineering, and potentially other elements of project scope, e.g., production, commissioning, contract.

THE PROJECT BREAKDOWN STRUCTURE (PBS/WBS)

Legend:

- Boundary of scope of an Integrated Product Team
- Cross-team membership
- Schedule: start and finish

DSTV -	Developmental Space Technology Vehicle
ECS -	Environmental Control System
FCS -	Flight Control System
FO -	Fitout
I & A -	Integration & Assembly
ILS -	Integrated Logistics Support
N & CS -	Navigation & Communication System
OI -	Operating Instructions
PS -	Propulsion System
PSTV -	Production STV
SD -	System Design
SF -	Spaceframe
SRA -	System Requirements Analysis
STV -	Space Technology Vehicle (STV)



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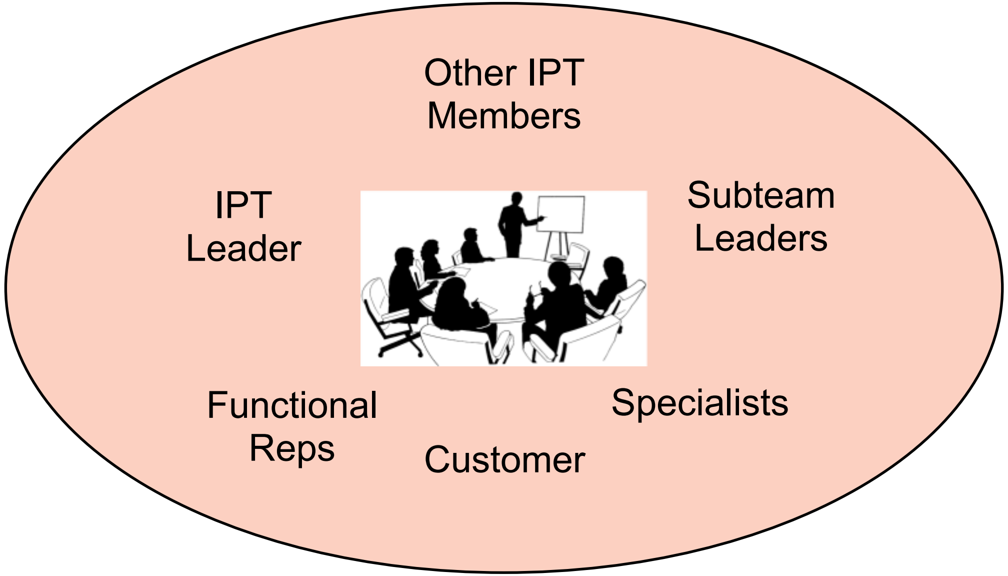
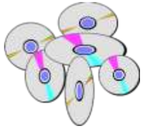
INSIDE AN INTEGRATED PRODUCT TEAM

Stake-holder needs



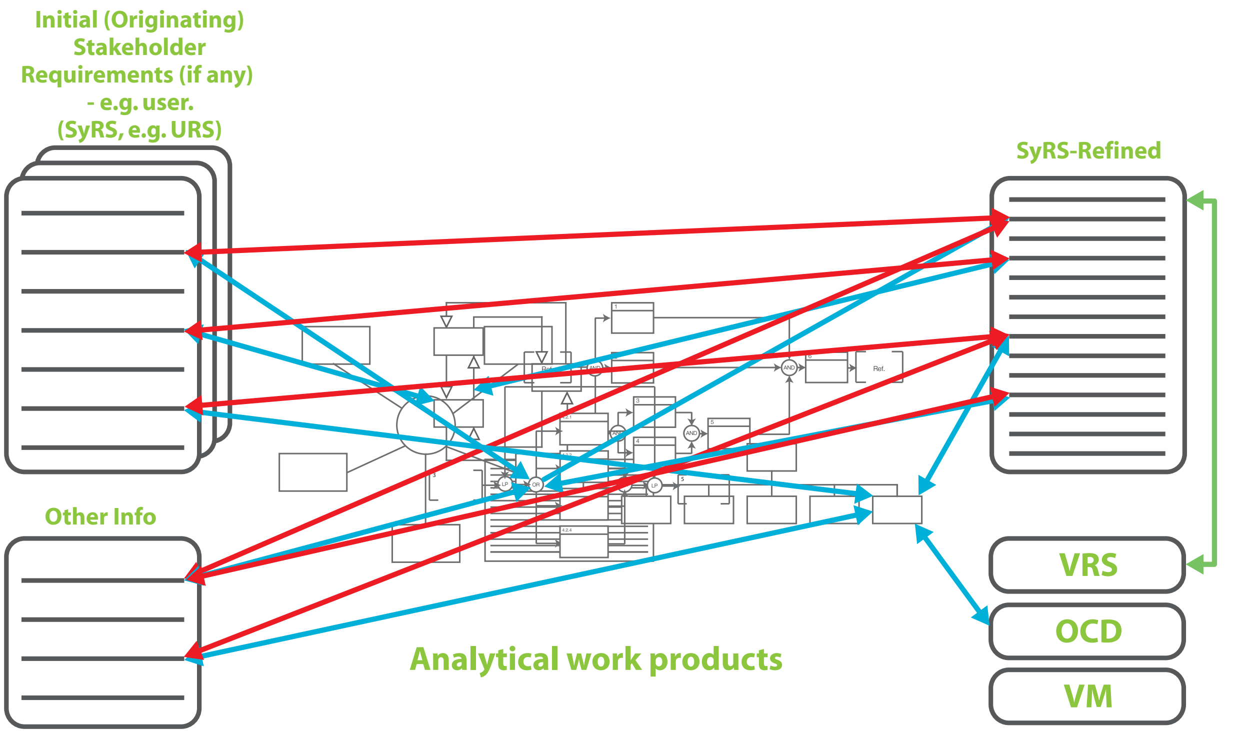


Product to customer / higher level team

- A *multi-disciplinary*, *cross-functional*, *stake holder-focussed* team solely responsible for taking a product from need to delivery
- Knowledge, skills and attitudes of the team members are complementary

2. REQUIREMENTS ANALYSIS

KNOWLEDGE	SKILLS	ATTITUDES
• History and role of RA in project outcomes • Parameters that define "the problem" • Fundamentals of risk and its management • Principles and methods of RA • The application domain(s) for the item subject to RA	• Applying the principles and methods of RA • Identifying defects in requirements • Distinguishing and switching thinking between problem and solution domains • Measuring requirements quality • Human verbal communication • Writing individual requirements • Development of verification requirements	• Respect for the owners of requirements • Acceptance of approximation and incompleteness of requirements for ‘adequacy’ over ‘perfection’ • Attention to detail, subject to adequacy • Motivation to ensure that the thing that needed is the thing that is developed



OCD:	operational concept description (CONUSE)
URS:	SyRS of user requirements
SyRS:	system requirements specification
VM:	value (or system/software effectiveness) model
VRS:	verification requirements specification

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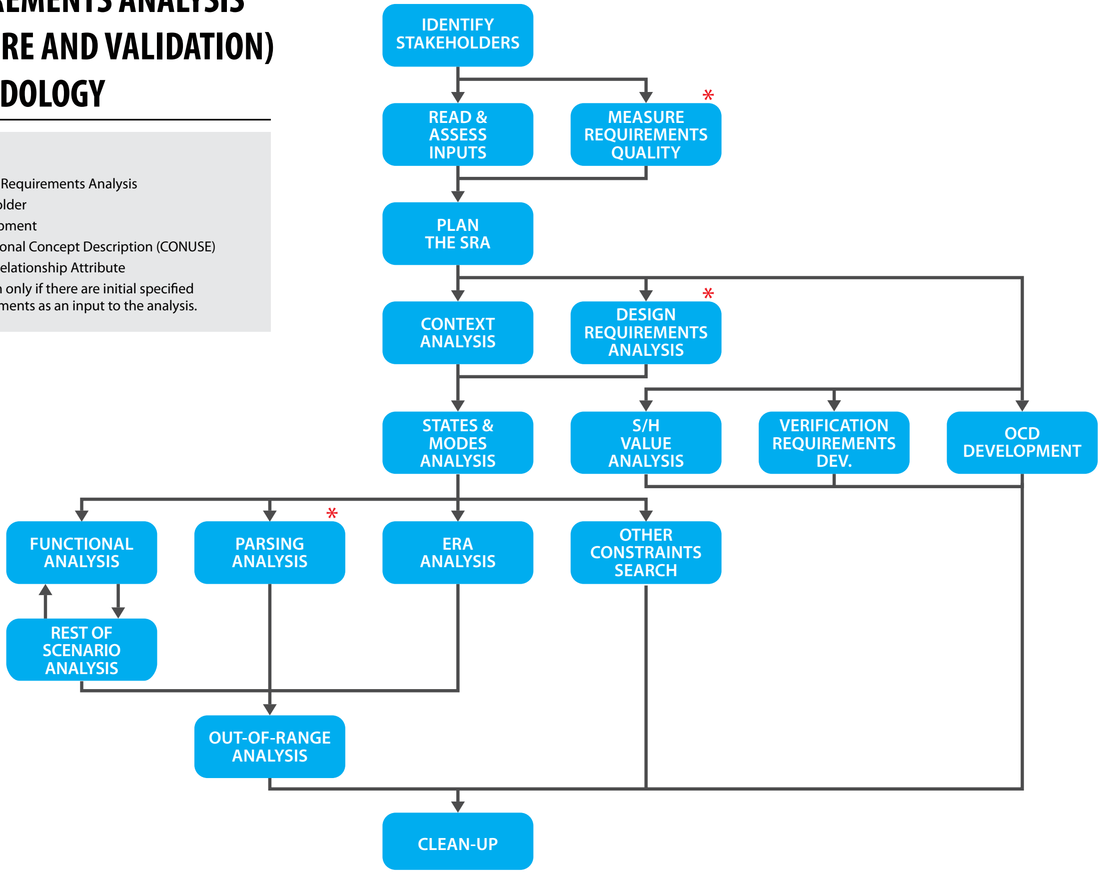
is a restatement of

traces to/from

REQUIREMENTS ANALYSIS (CAPTURE AND VALIDATION) METHODOLOGY

Legend:

SRA System Requirements Analysis
S/H Stakeholder
DEV Development
OCD Operational Concept Description (CONUSE)
ERA Entity Relationship Attribute
* Perform only if there are initial specified requirements as an input to the analysis.



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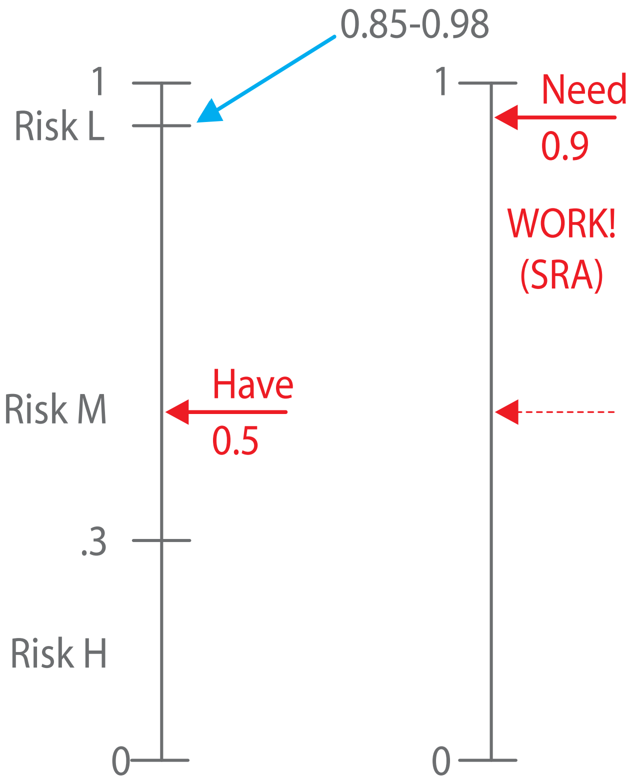
REQUIREMENTS QUALITY AND REQUIREMENTS ANALYSIS EFFORT



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WORK = f(

Have

Need

Number of Requirements

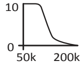
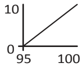
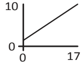
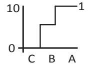
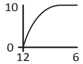
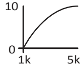
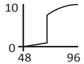
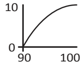
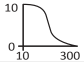
Skills

Tech-Environment

Access & Cooperation)

CONSIDER MOEs & GOALS, NOT ONLY REQUIREMENTS

VALUE (SYSTEM EFFECTIVENESS) MODEL

MOEs	Worst	Best	Pri	Pts	Weight %	UF
Cost, $ks per unit	200	50	1	100	25	
Reliability, %	95	100	1	100	25	
Interoperability	0	17	7	14	4	
Size(A/B/C)	C	A	8	3	1	
Schedule (Months)	12	6	3	40	10	
Visible Optical Range	1000	5000	5	30	7	
Duration of Transmission, hr	48	96	6	27	6	
Readiness, %	90	100	4	39	10	
OS & D Cost, $k pu/10 years	300	10	2	50	12	
				403	100	

Legend:
Pri: Priority
Pts: Points
UF: Utility Function

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3. PHYSICAL DESIGN

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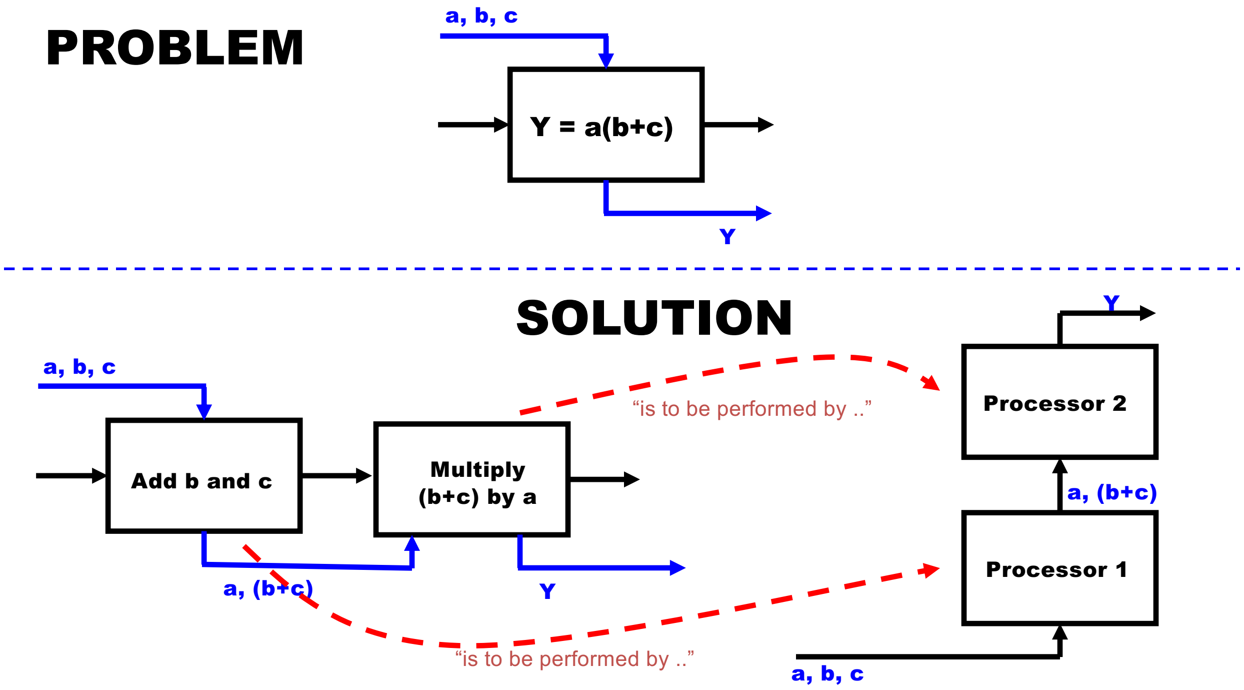
KNOWLEDGE	SKILLS	ATTITUDES
• The problem domain • Relevant solution technologies • Problem-solving principles and techniques • Understanding of risk and the influence of risk in design • Understanding that design creates requirements on solution elements • The design overhead / complexity trade-off	• Distinguishing and switching thinking between problem and solution domains • Creating and innovating to develop candidate solutions • Strong mathematical skills • Explaining designs verbally and in writing • Creating sound requirements on solution elements integral to sound design	• Respect for owners of requirements • Focus on designing to meet requirements • Focus on maximizing value to stakeholders • Attention to detail • Constructive response to questions/criticism • Willingness to raise requirements issues with stakeholders • Seeing design as a "team sport"

4. LOGICAL DESIGN

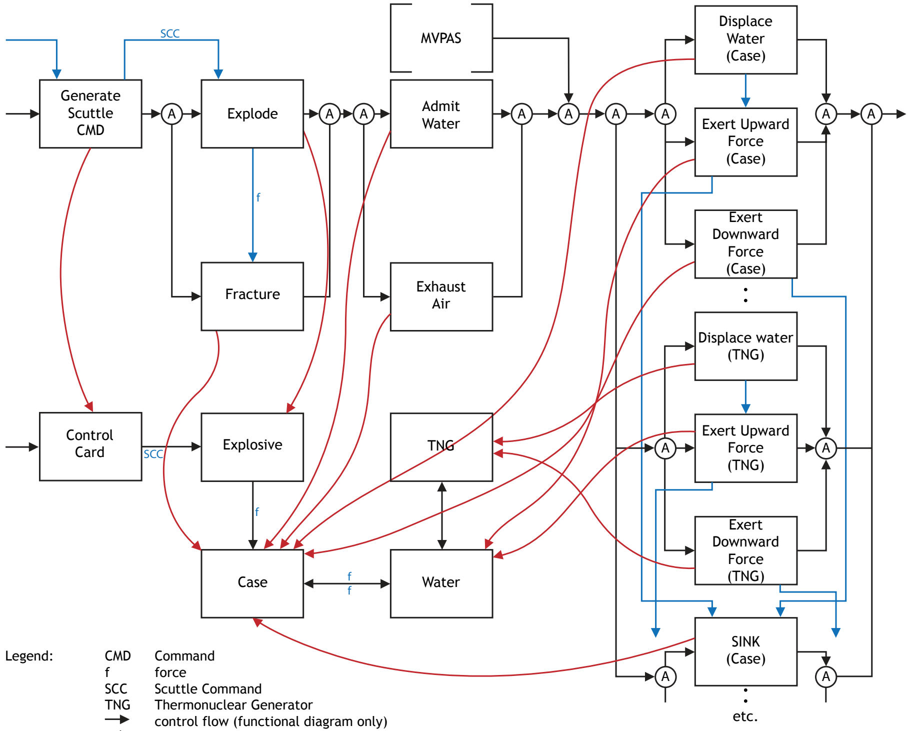
KNOWLEDGE	SKILLS	ATTITUDES
• All the knowledge required for physical design • Types of logic, especially functional and state • Principles and methods of logical design • Relevant modeling languages and relevant software tools • Understanding that logical design enables correct and effective physical design	• All the skills required for physical design • Applying principles and methods of logical design • Using relevant software tools • Judging or estimating the cost-benefit of logical design – the engineering overhead/design complexity trade-off	• All the attitudes required for physical design • Seeing MBSE as a means to an end, not an end in itself • A willingness to accept approximation and incompleteness in logical design

MBSE: Model-Based Systems Engineering

PHYSICAL AND LOGICAL DESIGN - EXAMPLE



PHYSICAL AND LOGICAL DESIGN - EXAMPLE



Legend:

CMD	Command
f	force
SCC	Scuttle Command
TNG	Thermonuclear Generator
→	control flow (functional diagram only)
→	interface (schematic diagram only)
→	item flow
→	“is to be performed by”

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5. EFFECTIVENESS EVALUATION AND DECISION

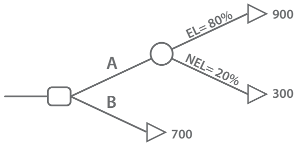
KNOWLEDGE	SKILLS IN	ATTITUDES
• The role of effectiveness evaluation of design, and of design decision-making, within SE • The methods of characterization of design alternatives w.r.t. MOEs • Understanding of the concept of "expected value" • Principles and methods of effectiveness evaluation and design decision making • Understanding of risk and opportunity	• Applying the principles and methods of effectiveness evaluation of design, and design decision-making • Risk analysis • Combining risk and opportunity • Methods of characterizing design alternatives w.r.t. MOEs • Analysis of effectiveness data to identify options for design improvement	• Focus on maximizing the expected value to stakeholders • Respect for the right of owners of the problem to define their values • Comfort with the concept that a good decision can lead to bad results • Patience in explaining rationales for decisions made

MOE: Measure of Effectiveness

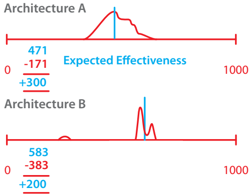
Value (System Effectiveness) Model

Architecture A Evaluation

MOEs	Worst	Best	Pri	Pts	Weight %	UF	Value of MOE	RVC	AVC (RVC x wt)	
Cost, $k's per unit	200	50	1	100	25		~~55k~~ 57	10	250	
Reliability, %	95	100	1	100	25		~~95.5%~~ 97	~~100~~ 5	~~25~~ 125	+100
Interoperability	0	17	7	14	4		0	0	0	0
Size(A/B/C)	C	A	8	3	1		~~C~~ B	~~0~~ 5	~~0~~ 5	+5
Schedule (MonthS)	12	6	3	40	10		~~7~~ 8	~~10~~ 9	~~100~~ 90	-10
Visible Optical Range	1000	5000	5	30	7		~~1200~~ 2500	~~2~~ 5	~~14~~ 35	+21
Duration of Transmission, hr	48	96	6	27	6		50	0.5	3	
Readiness, %	90	100	4	39	10		~~91~~ 95	~~1~~ 5	~~10~~ 50	+40
OS & D Cost, $k pu/10 years	300	10	2	50	12		~~200k~~ 106	~~1.5~~ 8	~~18~~ 96	+74
				403	100				Σ 560	



80% x 900 = 720
20% x 300 = 60
TOTAL 780



Document Number: P006-003868-1

6. REQUIREMENTS SPECIFICATION WRITING

KNOWLEDGE	SKILLS	ATTITUDES
• The types of requirements/goals • The principles of writing individual requirements • The principles of requirements specification structure for each type of requirements subject • The subject matter of the requirements/goals • Alternative means of expressing requirements and their application	• Applying the principles and methods of requirements writing to individual requirements • Identifying and relating types of requirements to placement in a requirements specification • General natural language skills • Skills in expressing requirements in alternatives to natural language.	• Attention to detail • Willingness to raise issues when defects in requirements are discovered • Willingness to accept and respond to constructive criticism of specified requirements and of the requirements specification • User-focus in selecting the means of requirements expression

7. SYSTEM INTEGRATION

KNOWLEDGE	SKILLS	ATTITUDES
• The principles and methods of system integration • The different integration strategies and their application • The technologies that are subject to the integration • Tools and test equipment to be used in the integration	• Reading, understanding and acting upon an integration plan • Diagnosing unwanted behaviours in various aggregates created in system integration • Clearly and meticulously recording actions taken and effects observed	• Desire to discover and take action on problems encountered • Attention to detail, including the keeping of SI records meticulously up-to-date • Willingness to raise issues

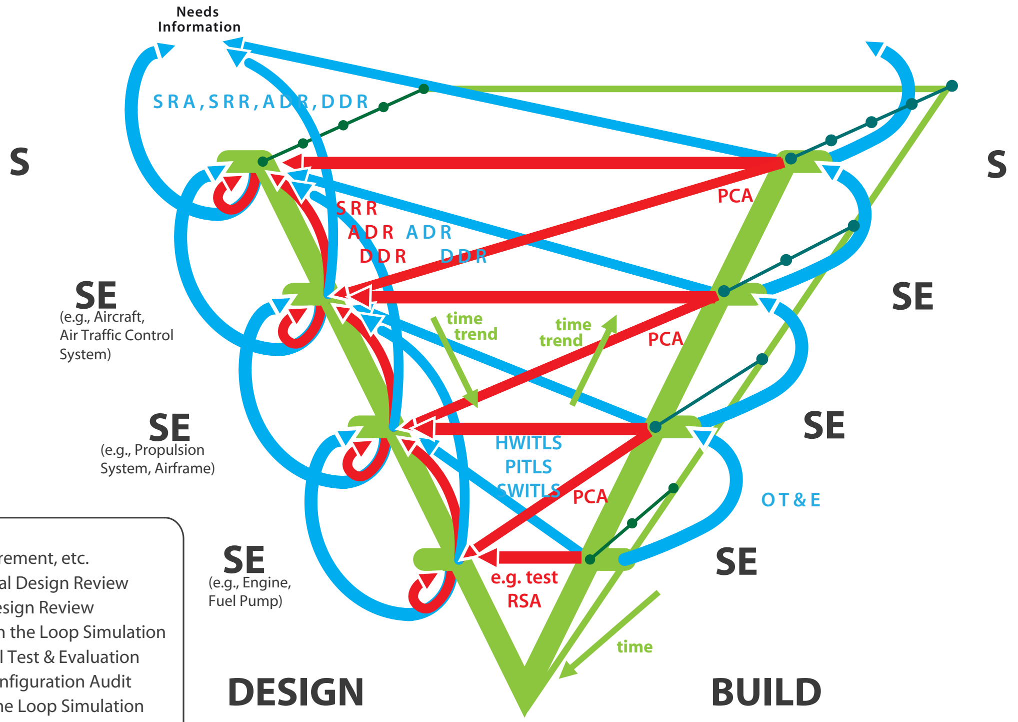
8. VERIFICATION

KNOWLEDGE	SKILLS	ATTITUDES
• The principles and methods of verification of requirements, design, subsystems, system and other work products • Tools, test equipment and software that can be used in verification • Technologies related to the item being verified • Understanding of the cost/risk reduction trade-off in performing verification	• Reading, understanding and acting on verification procedures • Communicating constructively with the person whose work product is to be verified • Clearly and accurately recording verification results • Tact	• Desire to find and communicate defects discovered in verification • Objectivity • Attention to detail • Willingness to record and discuss any concerns of the stakeholders • Focus on issues, not competencies or motives • Concern with defect discovery and reporting, not defect correction

9. VALIDATION

KNOWLEDGE	SKILLS	ATTITUDES
• The principles and methods of validation of requirements, design, subsystems, system and other work products • The artifacts that can be used in validation • The application of the item being validated • An understanding of the cost/risk reduction trade-off in performing validation	• Reading, understanding and acting on validation procedures • Communicating constructively with product developers and other stakeholders • Clearly and accurately recording validation results • Tact	• Desire to find and act upon problems within the scope of the validation • Objectivity • Attention to detail • Willingness to record and discuss any concerns of the stakeholders • Focus on issues, not competencies or motives • Concern with defect discovery and reporting, not correction

VERIFICATION AND VALIDATION



Legend :

●	A Build, increment, etc.
ADR	Architectural Design Review
DDR	Detailed Design Review
HWITLS	Hardware in the Loop Simulation
OT&E	Operational Test & Evaluation
PCA	Physical Configuration Audit
PITLS	People in the Loop Simulation
RSA (FCA)	Requirements Satisfaction Audit
S	Top-Level System
SE	System Element
SRA	System Requirements Analysis
SRR	System Requirements Review
SWITLS	Software in the Loop Simulation

PPI-006003-10

Verification:
Is the work product correct-meets requirements?

Validation:
Does the work product satisfy the need for the work product?

WEDGE MODEL™

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