THE BUSINESS CASE FOR SYSTEMS ENGINEERING

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### Driver | Relationship to Performance (Gamma)
--- | --- | --- | --- | --- |
| 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 |

OUR JOURNEY:

• What are our challenges?
• What is systems engineering?
• Why systems engineering?
• Studies on the value of systems engineering
• ROI for one facet: Requirements Analysis
KICK-OFF EXERCISE:

In groups of 3-4 people, consider the question “what are the greatest challenges that we (you) face in your engineering”? List as many challenges as you can, in the time designated.
WHERE WE HAVE COME FROM
– OOPS GOT THAT WRONG!
TODAY, AND NOT JUST IN KABUL!
THE PROBLEM IN GENERAL:

Standish Group study of 8380 IT-based projects
See also Morris and Hough, “The Anatomy of Major Projects”
For “challenged” and cancelled projects:

Standish Group study of 8380 IT-based projects

Average cost overrun: 89%
THE PROBLEM – SCHEDULE:

For “challenged” and cancelled projects:

Average schedule overrun: 122%

Standish Group study of 8380 IT-based projects
THE PROBLEM – QUALITY:

For “challenged” projects:

Average missing features: 39%

Standish Group study of 8380 IT-based projects
Outward and Upward Looking View
(part of one or more bigger systems)

Object View
(object with required and desired characteristics)

Inward Looking View
(seeing the system destined to become a set of interacting objects, the properties of the whole coming from the objects and their interactions)

System Views

leads to

Requirements + Goals
WHAT IS SYSTEMS ENGINEERING?

A Systems Engineering Process View

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Note 1: The Systems Engineering Process is applied repeatedly to each design object, starting at, for example, the Capability, Mission or Use System, then to, for example, the Prime Mission or Use Product, Maintenance System, Production System, Operational Infrastructure, etc., then to subsystems of these systems.

Note 2: Also, where applicable, validate data products (not shown diagrammatically).

Note 3: The process also performs the integration of the system elements to build the system for the first time (system integration).

Note 4: The process also includes the conduct of verification of the produced system against the requirements for that system, thereby verifying both the system, and the design of the system.

Note 5: The process also includes the conduct of validation of the produced system against the need.
INTEGRATE VERIFICATION & VALIDATION

Verification:
Is the work product correct—meets requirements?

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

Legend:
- A: 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

(e.g., Aircraft, Air Traffic Control System)
(e.g., Propulsion System, Airframe)
(e.g., Engine, Fuel Pump)

PC Portfolio Performance International
www.ppi-int.com
THE ESSENCE OF SE:

- ensure adequate problem definition
- define possible solution alternatives
- qualify solution alternatives for feasibility & effectiveness
- develop qualified alternatives
- use logical design as an aid in developing physical design (model-based design)
- design through levels of abstraction – architecture and detail
- maintain a clear distinction between problem and solution
AND MORE …

• conduct trade-off studies and optimization to maximize overall effectiveness
• 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
• do only work that adds value
• manage the engineering – plan, organize, inspire, assess, control.
WHEN IS SYSTEMS ENGINEERING APPLIED?

• Solution development phase
  • New Systems/Products
  • Families of Products

• Solution build/production phase
  • To correct design deficiencies

• Sustainment/operations and support phase
  • Modifications to track changing need
  • Incremental/competitive improvements for business reasons
  • Response to obsolescence
WHAT IS SYSTEMS ENGINEERING APPLIED TO?

- The enterprise
- Capability/business/enterprise systems
- End-use products
- Production systems
- Maintenance systems
- Training systems
- Project systems
- Engineering systems
- Anything else for which a solution does not already exist, and is sought!
IN WHAT BUSINESS MODELS?

Benefit to Company - e.g. Δ NPV (Net Present Value)

1:1 Customer/Contractor Business Model

Origin on x axis represents a threshold of acceptability.

Benefit to Customer (external or internal)

Optimum solution for the company

Internal Project

Optimum solution for the company

Trade Off: Interests of Secondary Stakeholder (Customer) versus Primary Stakeholder (company)
INDICATORS OF EFFECTIVE SE – PRODUCT-ORIENTED ENTERPRISE:

• On, under, or close to development budget
• On, ahead of, or close to development schedule
• High Return on Sales
• Market leadership
• Low warranty costs
• Repeat business is the norm
• High staff satisfaction and retention
INDICATORS OF EFFECTIVE SE – CONTRACT-ORIENTED ENTERPRISE:

• On, under, or close to development budget
• On, ahead of, or close to development schedule
• High contract gross margin
• High customer satisfaction
• Low warranty costs
• Repeat business is the norm
• High staff satisfaction and retention
INDICATORS OF EFFECTIVE SE – INTERNAL PROJECTS:

- On, under, or close to development budget
- On, ahead of, or close to development schedule
- High internal customer satisfaction
- No desire to outsource
- High staff satisfaction and retention
INDICATORS OF EFFECTIVE SYSTEMS ENGINEERING MANAGEMENT:

• Effective systems engineering
• Harnessing of creativity
• A learning environment
• Growing intellectual capital within the enterprise
• High staff satisfaction and retention
• Shared vision of the outcome and a related focus on quality, cost, time
INDICATORS OF NO SE OR INEFFECTIVE SE:

- Milestones missed
- Significant dispute with stakeholders over requirements
- Many problems and delays occurring during system integration
- Significant dispute with customers over testing
- Significant problems occurring in released or fielded systems/products
- Engineering effort tends to be back-end loaded during development
# WHERE DOES THE MONEY GO?

<table>
<thead>
<tr>
<th>Cost component</th>
</tr>
</thead>
<tbody>
<tr>
<td>What proportion of development cost is spent due to genuine system requirements changes?</td>
</tr>
<tr>
<td>What proportion of development cost is spent due to defective system requirements?</td>
</tr>
<tr>
<td>What proportion of development cost is spent due to system design errors undetected in design reviews?</td>
</tr>
<tr>
<td>What proportion of development cost is spent due to system design errors undetected in system testing?</td>
</tr>
<tr>
<td>What proportion of cost in a system integration phase is spent on system integration as opposed to rework?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ideal %</th>
<th>Actual %</th>
</tr>
</thead>
<tbody>
<tr>
<td>There is no ideal.</td>
<td>?</td>
</tr>
<tr>
<td>0%</td>
<td>?</td>
</tr>
<tr>
<td>0%</td>
<td>?</td>
</tr>
<tr>
<td>0%</td>
<td>?</td>
</tr>
<tr>
<td>Close to 100%</td>
<td>?</td>
</tr>
</tbody>
</table>
McKINSEY STUDY (1)

Financial Performance Benefits

Return on Sales p.a., 1987-1991

17 Companies

5 OPTIMISING
4 MEASURED
3 DEFINED
3 DEFINED
2 MANAGED
1 PERFORMED
0 INITIAL

9.30%
6.70%
4.70%
0.50%

Sample Average
4.0%

Sales Growth p.a., 1987-1991

16%
8.10%
7.30%
5.10%

Sample Average
8.0%

### Quality Benefits

<table>
<thead>
<tr>
<th>Equivalent to CMMI Maturity Level</th>
<th>Design Quality</th>
<th>Process Quality</th>
<th>Service Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Market Share %</td>
<td>Scrap%</td>
<td>Rework%</td>
</tr>
<tr>
<td>5 OPTIMISING</td>
<td>&gt;35</td>
<td>&lt;0.8</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>4 MEASURED</td>
<td>&gt;25</td>
<td>&lt;2.0</td>
<td>&lt;2.0</td>
</tr>
<tr>
<td>3 DEFINED</td>
<td>&gt;20</td>
<td>&lt;4.0</td>
<td>&lt;3.0</td>
</tr>
<tr>
<td>2 MANAGED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 PERFORMED</td>
<td>&lt;20</td>
<td>&gt;4.0</td>
<td>&gt;3.0</td>
</tr>
<tr>
<td>0 INITIAL</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

OTHER OLD CLAIMS

1. Improved Quality of Designs
   • Resulted in reduced Change Orders (> 50%)

2. Product Development Cycle
   • Reduced as much as 40-60% by concurrent rather than sequential design of products and processes

3. Manufacturing Costs
   • Reduced by as much as 30-40% by having integrated product teams integrate product and process designs

4. Scrap & Rework
   • Reduced by as much as 75% through product and process design optimization

Data based on a study of 14 companies that had applied concurrent engineering - Institute for Defense Analysis (IDA), 'The Role of Concurrent Engineering in Weapons System Acquisition', December 1988
NASA AND THE VALUE OF SE

Source: Werner Gruhl
NASA Controller’s Office & Honour 2004

Total Program Overrun
32 NASA Programs

Definition Percent = \[
\frac{\text{Actual + Definition} \$}{\text{Target + Definition} \$}
\]

Program Overrun = \[
\frac{\text{Actual + Definition} \$}{\text{Target + Definition} \$}
\]

\[ R^2 = 0.5206 \]
INCOSE STUDY - COST

SE Effort = SE Quality * (SE Cost/Actual Cost)

90% Assurance (1.6σ)

Average Cost Overrun
SE Effort = SE Quality * (SE Cost/Actual Cost)

90% Assurance (1.6σ)

Average Schedule Overrun
MCPM – MATURITY BY PROJECT CATEGORY MODEL, BRAZIL

Maturity and Success

CMU/NDIA 2007 STUDY RESULTS

Project Performance vs. Systems Engineering Capability

- Projects with Lower SE Capability:
  - Higher Project Performance: 39%
  - Moderate Project Performance: 29%
  - Lower Project Performance: 31%

- Projects with Moderate SE Capability:
  - Higher Project Performance: 59%

- Projects with Higher SE Capability:
  - Higher Project Performance: 56%

## PROJECT ENGINEERING MATURITY MATRIX

<table>
<thead>
<tr>
<th>Maturity Level</th>
<th>Characteristics</th>
<th>Key Process Areas</th>
</tr>
</thead>
</table>
| **5 OPTIMIZING** | Feedback: Process Continuously Improved | System problem prevention  
Technology innovation  
Process management |
| **4 MANAGED** | Quantitative: Process Measured  
Focus on metrics | Process mapping/variation  
Process improvement database  
Quantitative quality plans |
| **3 DEFINED** | Qualitative: Process defined and institutionalized  
Focus on process org. | Enterprise process definition  
Education and training  
Review and testing  
Interdisciplinary teamwork  
Life cycle engineering  
Integrated systems management |
| **2 REPEATABLE** | Intuitive: Process depends on individuals | System requirements mgmt  
Project planning and tracking  
System configuration mgmt  
Quality management  
System risk management |
| 1 | Ad hoc/chaotic: Unpredictable | |

Increased Customer and Producer Satisfaction  
Increased Risk
Executive Summary

The National Defense Industrial Association Systems Engineering Division (NDIA-SED) collaborated with the Institute of Electrical and Electronic Engineers Aerospace and Electronic Systems Society (IEEE-AESS) and the Software Engineering Institute (SEI) of Carnegie Mellon to obtain quantitative evidence of the benefit of systems engineering (SE) best practices on project performance. The team developed and executed this survey of system developers to identify SE best practices used on projects, collect performance data on these projects, and identify relationships between the application of these SE best practices and project performance.

The study found clear and significant relationships between the application of SE best practices to projects and the performance of those projects, as seen in the mosaic chart in Figure 1 and as explained below.

Figure 1: Project Performance vs. Total SE Capability

The left column represents projects deploying lower levels of SE, as measured by assessing the quantity and quality of specific SE work products. Among these projects, only 15% delivered higher levels of project performance, as measured by satisfaction of budget, schedule, and technical requirements. Within this group, 52% delivered lower levels of project performance.

The second column represents those projects deploying moderate levels of SE. Among these projects, 24% delivered higher levels of project performance and 29% delivered lower levels of performance.

Legend: PC  Project Challenge

<table>
<thead>
<tr>
<th>Driver</th>
<th>Relationship to Performance (Gamma)</th>
<th>Gamma</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEC-Total – total deployed SE</td>
<td>+0.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEC-PP – project planning</td>
<td>+0.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEC-REQ – reqts. developt. &amp; mgmt.</td>
<td>+0.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEC-VER – verification</td>
<td>+0.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEC-ARCH – product architecture</td>
<td>+0.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEC-CM – configuration management</td>
<td>+0.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEC-TRD – trade studies</td>
<td>+0.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEC-PMC – project monitor &amp; control</td>
<td>+0.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEC-VAL – validation</td>
<td>+0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEC-PI – product integration</td>
<td>+0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEC-RSKM – risk management</td>
<td>+0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEC-IPT – integrated product teams</td>
<td>+0.18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


http://resources.sei.cmu.edu/asset_files/specialreport/2012_003_001_34067.pdf
Table 9: Summary of Relationships Between SE Deployment and Project Performance

<table>
<thead>
<tr>
<th>Driver</th>
<th>Relationship to Performance</th>
<th>All projects</th>
<th>Lower challenge projects</th>
<th>Higher challenge projects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SEC-Total</strong> – total deployed SE</td>
<td>+0.49 ⇒ Very strong positive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SEC-PP</strong> – project planning</td>
<td>+0.46 ⇒ Very strong positive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SEC-REQ</strong> – requirements development and management</td>
<td>+0.44 ⇒ Very strong positive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SEC-VER</strong> – verification</td>
<td>+0.43 ⇒ Very strong positive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SEC-ARCH</strong> – product architecture</td>
<td>+0.41 ⇒ Very strong positive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SEC-CM</strong> – configuration management</td>
<td>+0.38 ⇒ Strong positive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SEC-TRD</strong> – trade studies</td>
<td>+0.38 ⇒ Strong positive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SEC-PMC</strong> – project monitoring and control</td>
<td>+0.38 ⇒ Strong positive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SEC-VAL</strong> – validation</td>
<td>+0.33 ⇒ Strong positive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SEC-PI</strong> – product integration</td>
<td>+0.33 ⇒ Strong positive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SEC-RSKM</strong> – risk management</td>
<td>+0.21 ⇒ Moderate positive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SEC-IPT</strong> – integrated product team utilization</td>
<td>+0.18 ⇒ Weak positive</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A Look at Return on Investment for One Facet of Systems Engineering: Requirements Analysis
Initial (Originating) Stakeholder Requirements (if any)  
- e.g. user.  
(SyRS, e.g. URS)

Other Info

Analytical work products

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

SyRS-Refined

VRS
OCD
VM

Ref.
Ref.

AND
AND
AND
AND
AND

OR
OR
OR
LP
LP

SyRS-Refined

VRS
OCD
VM

Ref.
Ref.

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.

---

**FUNCTIONAL ANALYSIS**

**PARSING ANALYSIS**

**ERA ANALYSIS**

**OTHER CONSTRAINTS SEARCH**

**OUT-OF-RANGE ANALYSIS**

**REST OF SCENARIO ANALYSIS**

**CONTEXT ANALYSIS**

**STATES & MODES ANALYSIS**

**PLAN THE SRA**

**READ & ASSESS INPUTS**

**IDENTIFY STAKEHOLDERS**

**MEASURE REQUIREMENTS QUALITY**

**DESIGN REQUIREMENTS ANALYSIS**

**S/H VALUE ANALYSIS**

**VERIFICATION REQUIREMENTS DEV.**

**OCD DEVELOPMENT**

**CLEAN-UP**
REQUIREMENTS QUALITY AND REQUIREMENTS ANALYSIS EFFORT

\[ \text{WORK} = f(0.85 - 0.98 \times \text{Need}) \]

Risk L
Have 0.5

Risk M

Risk H

Need 0.9

WORK!
(SRA)

WORK = f(Have Need Number of Requirements Skills Tech-Environment Access & Cooperation)
### IMPACT OF REQUIREMENTS DEFECTS

<table>
<thead>
<tr>
<th>Organization/Project</th>
<th>Overruns Attributed to Requirements Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA over two decades (Werner Gruhl)</td>
<td>70% of overruns</td>
</tr>
<tr>
<td>U.S. Census Bureau project 2009</td>
<td>80% cost overrun locked in solely due to poor requirements</td>
</tr>
<tr>
<td>Marine One Helicopter Program</td>
<td>83% cost overrun attributed by Lockheed to requirements problems</td>
</tr>
<tr>
<td>Schwaber, 2006; Weinberg, 1997; Nelson et al, 1999</td>
<td>“Requirements errors are the single greatest source of defects and quality problems”</td>
</tr>
<tr>
<td>Hofmann and Lehner, 2001</td>
<td>“Deficient requirements are the single biggest cause of software project failure”</td>
</tr>
<tr>
<td>Standish Group, The Chaos Report on 8300 IT projects</td>
<td>60.9% of an average 89% cost overrun</td>
</tr>
</tbody>
</table>
## REQUIREMENTS ANALYSIS ROI TO CUSTOMER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contract value</td>
<td>$4B</td>
</tr>
<tr>
<td>Requirements on the Ship</td>
<td>27,000, only fair in quality</td>
</tr>
<tr>
<td>Consequence if uncorrected</td>
<td>At least 20% loss of capability, costing at least $800M; or</td>
</tr>
<tr>
<td></td>
<td>Rework costs exceeding 20%</td>
</tr>
<tr>
<td>Cost of fixing the requirements</td>
<td>$8M (0.2% of contract value)</td>
</tr>
<tr>
<td>Return on Investment</td>
<td>Approximately 100:1</td>
</tr>
</tbody>
</table>
## REQUIREMENTS ANALYSIS ROI FOR A CONTRACTOR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Sales spent on marketing</td>
<td>12.5%</td>
</tr>
<tr>
<td>% Sales spent on bidding</td>
<td>9-10%</td>
</tr>
<tr>
<td>Win ratio for the more successful companies</td>
<td>1 in 2 to 1 in 4</td>
</tr>
<tr>
<td>Typical cost/bid, % Total Contract Value</td>
<td>2-3% TCV</td>
</tr>
<tr>
<td>Cost of winning business from a new customer vis-à-vis a satisfied existing customer</td>
<td>5:1</td>
</tr>
<tr>
<td>Cost of preserving customer satisfaction through requirements analysis</td>
<td>0.2% TCV</td>
</tr>
</tbody>
</table>

TCV: Total Contract Value
CONCLUSIONS:

1. **The practice of engineering can be immature**
   - Sometimes ad hoc and chaotic – that is destructive to success via satisfaction of users and other stakeholders.

2. **The evidence is now compelling that the practice of systems engineering contributes to enterprise success in terms of:**
   - reduced costs
   - shorter timeframes
   - increased value achieved in using the system.
We will review the list of challenges from earlier, and the contributions made by "a systems approach to the engineering of systems".
THE QUESTION IS NO LONGER, “SHOULD WE BE PRACTICING SYSTEMS ENGINEERING?”
"YES" IS BEYOND DOUBT.

TODAY'S QUESTION IS, “HOW BEST DO WE DO IT?”

Robert J. Halligan
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