16.842 Fundamentals of Systems Engineering

Prof. Olivier de Weck

TA: Maj. Jeremy Agte
16.899 Fundamentals of Systems Engineering
H (permanent number 16.842)
Prereq: Permission of Instructor
Units: 2-0-4
F1-3 in 33-418
Grading A-F

Introduction to the principles and methods of Systems Engineering. Lectures follow the "V"-model of Systems Engineering including needs identification, requirements formulation, concept generation and selection, trade studies, preliminary and detailed design, component and subsystem test and integration as well as functional testing and delivery and operations. ...The class serves as preparation for the systems field exam in the Department of Aeronautics and Astronautics.
O. de Weck and guest lecturers

Students wishing to only participate in the journal club held on F2-3 should register under 16.980 Advanced Special Project for 3 units

Register for 16.980 if taking only the journal club portion, 3-units, attending F2-3, Grading is Pass/Fail
Agenda

• Introductions
  – “How I got hooked on Systems Engineering”
  – Student Introductions

• Syllabus
  – Motivation, Learning Objectives, Format, Grading
  – Schedule
  – Readings (“Journal Club”)

• Systems Engineering Overview
  – Caveats
Personal Intro

• Olivier Ladislas de Weck
  – Dipl. Ing. Industrial Engineering – ETH Zurich 1992
  – 1993-1997 Engineering Program Manager Swiss F/A-18 Project, McDonnell Douglas, St. Louis
  – Associate Professor – dual appointment AA and ESD, Associate Director ESD (since July 2008)
  – Research:
    • Systems Engineering for Changeability and Commonality
      – http://strategic.mit.edu
    • Space Logistics
      – http://spacelogistics.mit.edu
A Transatlantic Journey …

Or .... “How I got hooked on Systems Engineering”
F/A-18 Center Barrel Section
F/A-18 Complex System Change

F/A-18 System Level Drawing

- Fuselage Stiffened
- Original change
- Manufacturing processes changed
- Flight control software changed
- Gross takeoff weight increased
- Center of gravity shifted

Image by MIT OpenCourseWare.
Lessons Learned

• High-Performance Aircraft are very complex internally ... propulsion, avionics, structures ...
• Changing requirements can have ripple effects because everything is tightly coupled
  – The totality of system interactions cannot be fully predicted ahead of time
• The “whole” system is much more than the air vehicle: logistics, training, incl. simulators etc..
• People matter a lot: contracts, culture, incentives ....
Personal Introductions

• Name
• Department Lab/Center Affiliation
• Previous Work or Projects
• Why are you interested in Systems Engineering?
Syllabus

• Motivation
  – Aerospace Systems deliver important functions to society ... air transportation, defense, sensing, exploration ...
  – Complex “machines” with thousands of unique parts and potentially millions of interactions
    • Many aerospace systems require 5-6 levels of decomposition to arrive at indivisible parts that cannot be taken “a-part”
  – Humans play an important role as designers, operators, beneficiaries, maintainers ....
  – Best Practices have emerged since the 1960’s and are continuously evolving ... documented in standards/handbooks
  – Limitations of “traditional” SE
    • System safety ... Columbia and Challenger accidents
    • Designing for lifecycle ... Iridium and Globalstar
    • Co-designing system and supply chain (e.g. Boeing 787 delays ...)
## System Complexity

Assume 7-tree [Miller 1956]

### How many levels in drawing tree?

\[
\text{#levels} = \left\lceil \frac{\log(\text{# parts})}{\log(7)} \right\rceil
\]

<table>
<thead>
<tr>
<th>Item</th>
<th>#parts</th>
<th>#levels</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screwdriver (B&amp;D)</td>
<td>3</td>
<td>1</td>
<td>simple</td>
</tr>
<tr>
<td>Roller Blades (Bauer)</td>
<td>30</td>
<td>2</td>
<td>simple</td>
</tr>
<tr>
<td>Inkjet Printer (HP)</td>
<td>300</td>
<td>3</td>
<td>simple</td>
</tr>
<tr>
<td>Copy Machine (Xerox)</td>
<td>2,000</td>
<td>4</td>
<td>simple</td>
</tr>
<tr>
<td>Automobile (GM)</td>
<td>10,000</td>
<td>5</td>
<td>complex</td>
</tr>
<tr>
<td>Airliner (Boeing)</td>
<td>100,000</td>
<td>6</td>
<td>complex</td>
</tr>
</tbody>
</table>

Learning Objectives

The students in this class will be able to ...

- Enumerate and describe the most important **Systems Engineering standards and best practices**\(^1\)
- Summarize the **key steps in the systems engineering process** starting with stakeholder analysis and ending with transitioning systems to operations
- Appreciate the **important role of humans** as beneficiaries, designers, operators and maintainers of aerospace systems
- Articulate the **limitations of the way that current systems engineering is practiced** in terms of dealing with complexity, lifecycle uncertainty and other factors
- **Apply some of the fundamental methods and tools** of systems engineering to some basic “toy” examples as a stepping stone to more complex and real world projects

\(^1\) Our main “textbook” for the class will be the NASA Systems Engineering Handbook, NASA/TP-2007-6105, Rev 1. All students taking this class will have read the textbook in its entirety by the end of the term.

Additionally this class can serve as preparation for the AA Systems Field Exam
Class Format

• Four main elements
  – Lectures (60 min, convey key concepts)
    • Organized roughly along the “V” model of SE
  – Assignments
    • 7 assignments total, based mainly on past qualifying exam questions since 1999, should take ~ 2hrs each
  – Readings
    • Assigned weekly reading of sections from NASA Handbook
    • One or two journal/conference paper per week on advanced material that goes beyond traditional SE
      – Journal Club Format: 20 min prepared summary, followed by 40 min of open discussion
  – Design Competition
    • LEGO Mindstorms (NXT 2.0)
    • Voluntary at the end of semester, paired with social event

• Two quizzes
  – Mid-term (October 16, 2009)
  – End-of-term (December 4, 2009)
  – Quizzes will be administered online (surveymonkey.com) and are open book
V-Chart

16.842 Fundamentals of Systems Engineering

Fall 2009

Stakeholder Analysis

Requirements Definition

System Architecture

Concept Generation

Tradespace Exploration

Concept Selection

Design Definition

Multidisciplinary Optimization

Cost and Schedule Management

System Integration

Interface Management

Verification and Validation

Commissioning Operations

Lifecycle Management

Human Factors

System Safety

16.842
Grading

For those enrolled in the 6-unit course (registered under 16.899) the grading will occur on the letter scale A-F following standard MIT grading policy. The grade will be composed as follows:

Assignments (total of 7 assignments[1]) 60%
Mid-Term and End-of-Term Quizzes 30%
Active Class Participation 10%
Total 100%

Students registering only for the 16.980 Advanced Individual Study (journal club) will be graded strictly on pass/fail. To obtain a passing grade students must present one paper and participate in at least 70% of the discussion sessions

[1] We will use the best six grades from the assignments, thus one assignment can be missed and students may still achieve a grade of A if they miss one assignment.
Schedule

• F1-3
• 33-418
• 12 Sessions
  – First today Sept 11, 2009
  – Last official session Dec 4, 2009
• Bakeoff session December 11, 2009
• See syllabus for details
References ("Journal Club")

• Systems Engineering Standards

• Selected Conference and Journal Articles
  – Topically synchronized with lectures
  – Explore beyond traditional SE
  – MIT Centric

These are suggestions based on my best knowledge/experience. Feel free to make additional suggestions
Systems Engineering Overview
de Weck’s framework for Systems Engineering Part (1)
Conception, Design, Implementation

The Environment: technological, economic, political, social, nature
de Weck’s framework for Systems Engineering Part (2)
Operate, Upgrade, Liquidate

The Environment: technological, economic, political, social, nature

The System
- System ID
- behavior prediction

The Enterprise
- Architect
- Designer
- System Engineer

Operate
- test
- validation
- verification
- deploy
- accept
- real
- control
- usage

Upgrade
- monitor
- virtual
- monitor
- control
- usage
- degrade

Liquidate
- EOL

End of Lifecycle

Customer
- Stakeholder
- User
NASA Version of SE

Requirements

NASA Policy Directives (NPD)
NASA Procedural Requirements (NPR)
- NPD 7120.4 Program/Project Management
- NPR 7120.5D Program/Project Management
- NPR 7150.2 Software Eng. Req.
- NPR 8000.4 Risk Management
- NPR 7123.1A Systems Engineering
- Mandatory Standards
- etc.

Agency

Guidance

NASA Handbooks
- etc.

Center

Center Handbooks

Center Policy Directives
Center Procedural Requirements
Center Work Instruction
Purpose of the NPR 7123.1A

• To clearly articulate and establish the requirements on the implementing organization for performing, supporting and evaluating systems engineering.
  
  – Systems engineering is a logical systems approach performed by multidisciplinary teams to engineer and integrate NASA’s systems to ensure NASA products meet customer’s needs.
  
  – This systems approach is applied to all elements of a system and all hierarchical levels of a system over the complete project life-cycle.
NASA/SP-2007-6105 Rev 1

- Makes The Bridge From “Typical” Guidance Back To NASA Systems Engineering Process (NPR 7123.1)
  - Guidance From Practitioners
    - Written by practitioners for practitioners
  - “How” Vs “What”
  - Fills Gaps

- Updates The Guidance from SP-6105 (basic)
  - Updates The Practice/Methodology from 1995

- Provides Top-level Guidance for Systems Engineering Best Practices; It Is Not Intended In Any Way To Be A Directive

- Adds Additional Special Topics
  - Tools
  - NEPA
  - Human Factors
Common Technical Processes

“SE Engine”

Requirements Flow Down from Level above

System Design Processes

Requirements Definition Processes
1. Stakeholder Expectations Definition
2. Technical Requirements Definition

Technical Solution Definition Processes
3. Logical Decomposition
4. Design Solution Definition

Technical Management Processes

Technical Planning Process
10. Technical Planning

Technical Control Processes
11. Requirements Management
12. Interface Management
13. Technical Risk Management
14. Configuration Management
15. Technical Data Management

Technical Assessment Process
16. Technical Assessment

Technical Decision Analysis Process
17. Decision Analysis

Product Realization Processes

Product Transition Process
9. Product Transition

Evaluation Processes
7. Product Verification
8. Product Validation

Design Realization Processes
5. Product Implementation
6. Product Integration

Requirements Flow Down to Level below

System Design Processes applied to each WBS Model down and across system structure

Realized Products to Level above

Realized Products from Level below

Product Realization Processes applied to each product up and across system structure
Top-Down Bottom-Up Approach

Top Down System Design
Bottom Up Product Realization
## Program & Project Life Cycles

<table>
<thead>
<tr>
<th>NASA Life Cycle Phases</th>
<th>FORMULATION</th>
<th>Approval for Implementation</th>
<th>IMPLEMENTATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Life Cycle Phases</td>
<td>Pre-Phase A: Concept Studies</td>
<td>Phase A: Concept &amp; Technology Development</td>
<td>Phase C: Final Design &amp; Fabrication</td>
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<tr>
<td></td>
<td>KDP A</td>
<td>Preliminary Project Plan</td>
<td>KDP C</td>
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<tr>
<td></td>
<td>FAD Draft Project Requirements</td>
<td>Baseline Project Plan</td>
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<tr>
<td>Project Life Cycle Gates &amp; Major Events</td>
<td>Phase B: Preliminary Design &amp; Technology Completion</td>
<td>Phase E: Operations &amp; Sustainment</td>
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<tr>
<td></td>
<td>KDP B</td>
<td>Launch</td>
<td>KDP E</td>
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<td>Agency Reviews</td>
<td>ASP</td>
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<td>KDP F</td>
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<tr>
<td>Human Space Flight Project Reviews</td>
<td></td>
<td></td>
<td>Final Archival of Data</td>
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<tr>
<td></td>
<td>CDR / PRR^2</td>
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<td>Peer Reviews, Subsystem PDRs, Subsystem CDRs, and System Reviews</td>
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<tr>
<td>Re-flights</td>
<td>ORR</td>
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<td>Robotic Mission Project Reviews</td>
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<td>Launch Readiness Reviews</td>
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<tr>
<td>Supporting Reviews</td>
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### Footnotes

1. Flexibility is allowed in the timing, number, and content of reviews as long as the equivalent information is provided at each KDP and the approach is fully documented in the Project Plan. These reviews are conducted by the project for the independent SRB. See Section 2.5 and Table 2-6.
2. PRR needed for multiple (≥4) system copies. Timing is notional.
3. CERRs are established at the discretion of Program Offices.
4. For robotic missions, the SRR and the MDR may be combined.
5. The ASP and ASM are Agency reviews, not life-cycle reviews.
6. Includes recertification, as required.
7. Project Plans are baselined at KDP C and are reviewed and updated as required, to ensure project content, cost, and budget remain consistent.

### Acronyms

- ASP—Acquisition Strategy Planning Meeting
- ASM—Acquisition Strategy Meeting
- CDR—Critical Design Review
- CERR—Critical Events Readiness Review
- DR—Decommissioning Review
- FAD—Formulation Authorization Document
- FRR—Flight Readiness Review
- KDP—Key Decision Point
- LRR—Launch Readiness Review
- MCR—Mission Concept Review
- MDR—Mission Definition Review
- NAR—Non-Advocate Review
- ORR—Operational Readiness Review
- PDR—Preliminary Design Review
- PFAR—Post-Flight Assessment Review
- PLAR—Post-Launch Assessment Review
- PNR—Preliminary Non-Advocate Review
- PRR—Production Readiness Review
- SDR—System Definition Review
- SAR—System Acceptance Review
- SIR—System Integration Review
- SMSR—Safety and Mission Success Review
- SRR—System Requirements Review
Gentry Lee’s Critical Behaviors of Systems Engineering*

Behavioral Characteristics of a Good Systems Engineer

- Intellectual Curiosity – ability and desire to learn new things
- Ability to make system-wide connections
- Comfortable with uncertainty and unknowns
- Proper Paranoia – expect the best, but plan for the worst
- Strong team member and leader
- Self Confidence and Decisiveness – short of arrogance
- Exceptional Two-way Communicator
- Diverse Technical Skills – ability to apply sound technical judgment
- Appreciation for Process – rigor and knowing when to stop
- Comfortable with change
- Ability to See the Big Picture – yet get into the details
Caveats

• NASA Systems Engineering processes are very helpful and valuable, but ...
  – Assume mostly “clean sheet” design, but many real projects are modifications of previous systems
    • How do “redesign”, use legacy components etc...?
  – Assume that system/mission requirements and stakeholder needs are known and stable over time, but in reality they change with new administrations
    • Impact of externalities (e.g. policy) is underrepresented
  – Effect of design iterations and rework on budgets and project outcomes is more important than the linear “waterfall” process suggests
  – Etc...etc..
  – We will explore some of the responses to the caveats in the journal club section of the class.
Questions?