TOPIC 1
Introduction to Systems Engineering

Ch. 1

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“The whole is more than the sum of its parts.”
Aristotle, 384 BC – 322 BC
References


Outline

• What is Systems Engineering (SE)?
• Definitions
• Origins of SE
• Examples of systems requiring SE
• SE viewpoint
• SE as a profession
• The power of SE
What is SE?

There many ways to define systems engineering. In this course we will use the following definition:

The function of systems engineering is to (Kossiakoff & Sweet)

Definitions

**Guide:** To lead, manage or direct, usually based on superior experience in pursuing a given course

**Engineering:** The “application of scientific principles to practical ends; as the design, construction and operation of efficient and economical structures, equipment and systems”
The Engineering Design Process

1. Define Problem
2. Analyze the Problem
3. Generate Alternatives
4. Evaluate the Alternatives
5. Select the Preferred Design
6. Implement the Design
OR Approach Fundamental Steps

1. Problem Definition
2. System Identification
3. Model Formulation
4. Solution Procedure
5. Solution Validation
6. Implementation
System:

Complex: Restricts the definition to systems in which the elements are diverse and have intricate relationships with one another
Other Definitions of SE

Sage & Armstrong Jr.

SE is the definition, design, development, production, and maintenance of functional, reliable, and trustworthy systems within cost and time constraints.
Other Definitions of SE

Sage & Armstrong Jr.

Structure: SE is management technology to assist clients thru the formulation, analysis, and interpretation of the impacts of proposed policies, controls, or complete systems upon the need perspectives, institution perspectives, and value perspectives of stakeholders to issue under consideration.

Function: SE is an appropriate combination of the methods and tools of systems engineering, made possible thru use of a suitable methodology and systems management procedures, in a useful process-oriented setting that is appropriate for the resolution of real-world problems, often of large scale and scope.

Purpose: The purpose of SE is info and knowledge organization that will assist clients who desire to define, develop, and deploy total systems to achieve a high standard of overall quality, integrity, and integration as related to performance, trustworthiness, reliability, availability and maintainability of the resulting system.
What is SE?

SE is an interdisciplinary approach and means for enabling the realization and deployment of successful systems. It can be viewed as the application of engineering techniques to the engineering of systems, as well as the application of a systems approach to engineering efforts [Thomé, Bernhard, 1993].

SE integrates other disciplines and specialty groups into a team effort, forming a structured development process that proceeds from concept to production to operation and disposal. SE considers both the business and the technical needs of all customers, with the goal of providing a quality product that meets the user needs [INCOSE].
SE Vs. Traditional Engineering Disciplines

SE differs from mechanical, electrical, aerospace, petroleum, mining and other engineering disciplines in several important ways

SE is focused on the system as a whole – it emphasizes its total operation:

• Looks at the system from the outside as well as the inside
• Interactions with other systems and the environment
• Concerned with not only engineering design but also external factors
SE vs. Traditional Engineering Disciplines …

Even though the primary purpose of SE is to guide, systems engineers play a key role in system design
  • Leading the formative (concept development) stage thru to functional design of the system reflecting the users needs

SE bridges the traditional engineering disciplines
  • Diversity of the elements in a complex system requires different engineering disciplines in their design and development
SE vs. Traditional Engineering Disciplines…

• SE is an inherent part of **project management**
• the part that is concerned with the engineering effort itself, setting its objectives, guiding its execution, evaluating the results, and prescribing necessary corrective actions to keep it on course
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Origins of SE

• **No specific** date can be associated with the origins of SE

• **SE principles have been practiced at some level since building of the pyramids & probably before**

• **Bible records that Noah’s Ark was build to a system specification!**

http://en.arocha.org/images/shared/985l.jpeg

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Origins of SE ...

- Recognition of SE as a distinct discipline is often associated with the effects of WWII
- Especially 1950’s & 1960’s with the publication of textbooks on SE
- In general, SE as a discipline evolved as a result of rapid growth of technology & its application to military & commercial operations during the 2nd half of the 20th century

  - High performance aircraft
  - Military radar
  - Proximity fuse
  - German V1 & V2 missiles
  - Atomic bomb

These were complex systems that revolutionized the application of energy, materials & info; required multiple disciplines; posed developmental challenges; compressed development time schedules due to wartime imperatives let to SE to meet these challenges

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Origins of SE ...

- During the cold war of the 1950’s – 70’s military requirements continued to drive the growth of technology
  - Jet propulsion
  - Control systems
  - Materials
  - Solid-state electronics
    - Still evolving ‘information age’
    - Power of computing & communication
  - Digital computer & associated software
  - Replacement of human control to automation
  - Computer control increasing complexity of systems
The relation of modern SE to its origins can be understood in terms of three basic factors:

1. **Advancing technology**: provides opportunities for increasing system capabilities, but introduces development risks that require SE
   - Risks
   - Growth of automation

2. **Competition**: require seeking superior & more advanced system solutions thru the use of systems-level
   - Trade-offs

3. **Specialization**: requires partitioning of the system into building blocks that can be designed and built by specialists, and strict management of their interfaces and interactions
   - Interfaces, interactions
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Examples of “Non-Complex” Systems

The generic definition of a system, “a set of interrelated components working together as an integrated whole to achieve some common objective” fits most familiar appliances.

- Washing machine
- Refrigerator
- Microwave oven
- Dishwasher
- Vacuum cleaner
- Radio
- Television

However, these appliances involve only 1 or 2 disciplines, & the design is based on well-established technology.

Thus they fail the criterion of being complex.
“Complex” Systems

Since the development of modern systems is strongly driven by technology, we shall add one more characteristic to a system requiring SE, i.e. some of its key elements use advanced technology.

The characteristics of a system whose key development, test, and application require the practice of SE are that the system:

- Is an engineered product and hence satisfies a specified need
- Consists of diverse components that have intricate relationships with one another and hence is multi-disciplinary and relatively complex
- Uses advanced technology in ways that are central to the performance of its primary functions and hence involves development risk and often relatively high cost
# Examples of Systems Requiring SE

## Table 1-1

<table>
<thead>
<tr>
<th>System</th>
<th>Inputs</th>
<th>Process</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather satellite</td>
<td>Images</td>
<td>Data storage, Transmission</td>
<td>Encoded images</td>
</tr>
<tr>
<td>Terminal air traffic control system</td>
<td>Aircraft beacon responses</td>
<td>Identification, Tracking</td>
<td>Identity, Air tracks, Communication</td>
</tr>
<tr>
<td>Truck location system</td>
<td>Cargo routing requests</td>
<td>Map tracing, Communication</td>
<td>Routing info, Delivered cargo</td>
</tr>
<tr>
<td>Airline reservation system</td>
<td>Travel requests</td>
<td>Data management</td>
<td>Reservations, Tickets</td>
</tr>
<tr>
<td>Clinical information system</td>
<td>Patient ID, Test records, Diagnoses</td>
<td>Information management</td>
<td>Patient status, History, Treatment</td>
</tr>
<tr>
<td>Fire spread prediction system</td>
<td>Forest Weather data</td>
<td>Fire spread</td>
<td>Fire growth</td>
</tr>
</tbody>
</table>
# Examples of Engineered Complex Systems

## Table 1-2

<table>
<thead>
<tr>
<th>System</th>
<th>Inputs</th>
<th>Process</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger aircraft</td>
<td>Passengers, Fuel</td>
<td>Combustion, Thrust, Lift</td>
<td>Transported passengers</td>
</tr>
<tr>
<td>Modern harvester combine</td>
<td>Grain field, Fuel</td>
<td>Cutting, Threshing</td>
<td>Harvested grain</td>
</tr>
<tr>
<td>Oil refinery</td>
<td>Crude oil, Catalysts, Energy</td>
<td>Cracking, Separation, Blending</td>
<td>Gasoline, Oil products, Chemicals</td>
</tr>
<tr>
<td>Auto assembly plant</td>
<td>Auto parts, Energy</td>
<td>Manipulation, Joining, Finishing</td>
<td>Assembled auto</td>
</tr>
<tr>
<td>Electric power plant</td>
<td>Fuel, Air</td>
<td>Power generation, regulation</td>
<td>Electric AC power</td>
</tr>
<tr>
<td>Open-pit mine, Oil platform</td>
<td>Ore/oil field, Energy</td>
<td>Excavation, extraction, refinery</td>
<td>Metal, Coal, crude oil</td>
</tr>
</tbody>
</table>
Examples of Engineered Complex Systems...
Other Examples of Engineered Complex Systems

• Modern automobile, space vehicle, ISS, …
In-Class Exercise:

Students should break into teams of 4-5

Q. List at least five examples of new engineered complex systems developed in the last 10 years.

The oldest person in the group will do the typing and email me the write-up!

<table>
<thead>
<tr>
<th>System Name</th>
<th>Advanced Technology Used</th>
<th>Societal need</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Predecessor “Complex” Systems

Skylab: 1973 - 1979

Concorde: 1969 - 2003

MIR Space Station: 1986 - 2001
# 2008 Student’s Examples of Recent “Complex” Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Technology</th>
<th>Societal Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid Vehicle</td>
<td>Motor/IC Engine/Battery</td>
<td>Clean environment, save fuel/money</td>
</tr>
<tr>
<td>Cell Phones</td>
<td>Wi-Fi/Mobile technology</td>
<td>Wireless Communication</td>
</tr>
<tr>
<td>USB Storage</td>
<td>Solid state drives</td>
<td>Easy/large storage, access</td>
</tr>
<tr>
<td>Blue-Ray Disc</td>
<td>Lightly compressed data</td>
<td>Large storage, up to 25GB</td>
</tr>
<tr>
<td>SAP R/3</td>
<td>Software architecture</td>
<td>Better database management</td>
</tr>
<tr>
<td>Microsoft Surface Computer</td>
<td>Wireless/multitouch screen</td>
<td>Speed &amp; flexibility</td>
</tr>
<tr>
<td>MAC AIR</td>
<td>Materials/wireless compute processor</td>
<td>Flexibility</td>
</tr>
<tr>
<td>Commercial GPS</td>
<td>Digital/satellite tracking</td>
<td>Convenience</td>
</tr>
<tr>
<td>Flatscreen HD TV</td>
<td>Digital/composite materials</td>
<td>Convenience, govt regulation</td>
</tr>
<tr>
<td>Digital Media Players</td>
<td>Digital medium/materials/processors</td>
<td>Convenience</td>
</tr>
<tr>
<td>Ipods</td>
<td>Radio, microprocessors</td>
<td>Data storage, music on the move</td>
</tr>
<tr>
<td>Drill Ships</td>
<td>GPS</td>
<td>Extracting oil economically</td>
</tr>
<tr>
<td>Clones (animal, human, …?)</td>
<td>Adv. In genetics &amp; biomedical sciences</td>
<td>Scarcity &amp; limited supply of resources (organs)</td>
</tr>
<tr>
<td>SCADA: Supervisory Control &amp; Data Acquisition</td>
<td>PLC's, human interface, E.g. RTV's</td>
<td>Real time control, less labor</td>
</tr>
<tr>
<td>RFID?</td>
<td>Sensors</td>
<td>automated inventory control</td>
</tr>
<tr>
<td>Bluetooth?</td>
<td>Short range radio frequency</td>
<td>Transmit &amp; receive data</td>
</tr>
<tr>
<td>Bionic Body Parts</td>
<td>Micro-electric systems</td>
<td>Improve quality of life, reduce disability</td>
</tr>
<tr>
<td>Wireless Internet</td>
<td>Radio frequency for data transmission</td>
<td>Mobile internet connection</td>
</tr>
<tr>
<td>Digital Camera</td>
<td>CMOS technology</td>
<td>Electronic storage &amp; ease use of images</td>
</tr>
<tr>
<td>UAV</td>
<td>Software for guidance &amp; navigation</td>
<td>Pilot safety</td>
</tr>
<tr>
<td>AGV</td>
<td>GPS, ?</td>
<td>Unmanned transport</td>
</tr>
<tr>
<td>Airbus A-380</td>
<td>?</td>
<td>Jumbo jet, saves fuel, economical</td>
</tr>
<tr>
<td>ASIMO Robot</td>
<td>?</td>
<td>Helping the disabled/needy</td>
</tr>
<tr>
<td>?</td>
<td>Nanofibres</td>
<td>Communication, current generation</td>
</tr>
<tr>
<td>?</td>
<td>Duo Core</td>
<td>Faster computing</td>
</tr>
</tbody>
</table>
Outline

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System Engineering Point of View

- Makes the central objective the *system as a whole* and the *success* of its mission

- Takes a “*big picture*” or *holistic*, or *gestalt*, view of large-scale problems and their proposed technological solutions
SE Point of View

• A balanced system

Fig. 1-2  The ideal missile design from the viewpoint of various specialists.
SE Point of View: The “Best” System

- “The best is the name of the good”
- “SE is the art of the good enough”
  - SE seeks the “best” possible system, which often is not the one that provides the best performance
  - SE views performance as only one of several critical attributes: affordability, timely availability to the user, ease of maintenance, adherence to an agreed-upon development schedule, …

- The Systems Engineer seeks the “best balance” of the critical attributes
SE Point of View

- The law of diminishing returns

Fig. 1-1a  Performance vs. cost.
SE Point of View

- Establishing a “balance”

Fig. 1-1b Performance/Cost vs. cost.
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• **SE as a profession has not been widely recognized despite:**
  - Increasing prevalence of *complex systems*
  - Essential role of SE in the *development of systems*

• **SE primary recognition has come in companies specializing in the development of large systems**
  - Military
  - DoD Contractors
  - NASA
  - Boeing – (Show PTQ video)
  - Etc
Perhaps the main reason for the slowness in recognition of SE as a career is the fact that it does not correspond to the traditional academic engineering disciplines.

Engineering disciplines are built on
- Quantitative relationships
- Obeying established physical laws
- Measured properties of physical material, energy, or information

SE, on the other hand deals mainly with problems for which there is
- Incomplete information
- Whose variables do not obey known equations
- Where balance must be made among conflicting objectives involving incommensurate attributes
SE as a Profession…

- The establishment of SE as a unique discipline has been inhibited by the
  - Absence of a quantitative knowledge base

- Despite those obstacles, the recognized need for SE in industry and government has spurred the establishment of a number of academic programs offering master’s degrees in SE
  - Mainly as components of part-time continuing education
  - A few universities are offering undergraduate degrees in SE as well

- There has also been a relatively recent recognition of SE as a profession in the formation of a professional society
  - International Council on SE (INCOSE)
  - One of whose primary objectives is the promotion of SE education, and the recognition of SE as a professional career.

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Orientation of Technical Professionals

Scientist:

Typically dedicated to understanding the nature and behavior of the physical world. Asks the questions “Why?” and “How?”

Mathematician:

Primarily concerned with deriving the logical consequences of a set of assumptions, which may be quite unrelated to the physical world. Develops the propositions “If A, then B.”

Engineer:

Usually concerned with creating a useful product. The engineer exclaims “Voila!”
Orientation of Technical Professionals ...

Technical Orientation Phase Diagram

Fig. 1-4a  Technical orientation phase diagram.
Orientation of Technical Professionals ...

Technical Orientation Population Density Distribution

Fig. 1-4b  Technical orientation population density distribution.
The Challenge of SE

- SE represents a deviation from a chosen established discipline to a more diverse, complicated and uncertain professional practice
  - Requires investment of time and effort to an extensive broadening of the engineering base
  - Learning communication and management skills
  - A much different orientation from the individual’s original professional choice

- One may conclude that a career in SE is a difficult road, not obviously rewarding, and altogether not very attractive.

- “For a SE, success is measured by the apparent absence of program difficulties rather than by spectacular successes.”
The Challenge of SE …

- Why do very good people devote their lives to SE?
  - The answer may lie in the challenges of SE rather than its direct rewards
  - Systems engineers deal with the most important issues in the system development process
  - They do not design the components, but do design the overall system architecture and the technical approach
  - They prioritize the system requirements in conjunction with the customer, to ensure that the different system attributes are appropriately weighted when balancing the various technical efforts
  - They decide which risks are worth undertaking and which are not, and how the former should be hedged to ensure program success.
The Challenge of SE …

• It is the systems engineers who map out the course of the development program that prescribes the type and timing of tests and simulations to be performed along the way.

• They are the ultimate authorities on how the system performance and the system affordability goals may be achieved at the same time.

• When unanticipated problems arise in the development program, it is the system engineers who decide how they may be solved.
The Challenge of SE …

• Systems engineers derive their ability to guide the system development not from their position in the organization, but from their superior knowledge of

  • the system as a whole
  • its operational objectives
  • how all its parts work together
  • all the technical factors that go into its development
  • proven experience in steering complex programs thru a maze of difficulties to a successful conclusion
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The Power of Systems Engineering

• SE has a **great influence** over the design of the system
  • **Major characteristics**
  • **Success or failure of the system development process**

• The influence comes from SE knowledge, skills, and attitude
  • **Multidisciplinary knowledge**
  • **Approximate calculation**
  • **Skeptical positive thinking**
Multidisciplinary Knowledge

• A successful system requires
  • Specialists in different disciplines
  • Each specialist has its own
    • Language foreign to non-specialists
    • Knowledge base

• Systems engineers provide the linkages that enable these disparate groups to function as a team
Approximate Calculation

- SE requires the ability to make “approximate calculations” to ensure that a critical omission or error has not been committed
  - Based on past experience
  - Use first principles
  - Apply basic relationships
  - Examine basic assumptions and conditions
Skeptical positive thinking

- **Skepticism** is important to temper the traditional optimism of the design specialist
  - Probability of success of a chosen design
  - Insistence of validation of the approach selected at the earliest possible opportunity

- **Positive thinking**
  - Necessary in reacting to failure/apparent failure of a selected technique or design approach
  - Many design specialist who encounter failure are plunged into despair
  - The systems engineer cannot afford to be in despair
    - Need to find ways to circumvent the cause of failure
Show PTQ video – Boeing 777

~ 5 minutes