Case Studies in Systems Engineering – Central to the Success of Applied Systems Engineering Education Programs

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ABSTRACT

Systems Engineering training must look at systems engineering processes as a multifaceted and multi-disciplined function within and between organizations. Likewise, it must focus on the engineering of systems and the development of a systems engineering mindset through "systems thinking." One key element of this training is the necessity to have applied systems engineering experiences. There are a number of ways to expose students to the applied aspects of systems engineering: exercises, labs, applied homework, mentoring, projects, and the use of case studies. This paper focuses on the development and use of systems engineering case studies in systems engineering education and training programs. Systems engineering case studies are a special category of the engineering cases that are primarily focused on the application of systems engineering methodologies for complex problems. The Air Force Institute of Technology Systems Engineering Case Studies and the Georgia Institute of Technology Berlin Airlift Case Study are showcased.

Keywords: Case Studies, Systems Engineering, Systems Thinking, Complex Systems, Applied Education and Training.

1. INTRODUCTION AND MOTIVATION

The increasing complexity of systems under development have pushed both industry and government organizations to have a growing emphasis on systems engineering. The International Council on Systems Engineering (INCOSE) defines systems engineering as "an interdisciplinary approach and means to enable the realization of successful systems. Systems engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs"[1]. The systems engineer must cope with not only the system complexity but also the organizational complexity behind the product development. These include, but are not limited to, the following:

- multiple, often inversely related requirements,
- ambiguous and competing visions of solutions
- constraints in tension: cost, schedule, performance
- many sources of information, expertise, and innovation
- organizational dissonance among participants and stakeholders
- conflicting goals
- varying levels of commitment and investment
- varying levels of risk tolerance
- missing or inadequate resources

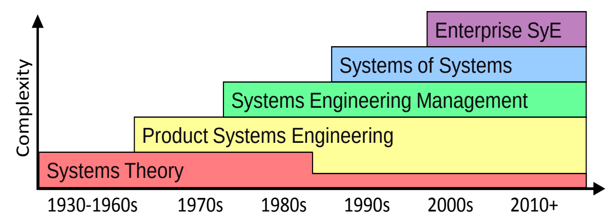

Figure 1: Evolution of System Complexity

Figure 1 illustrates how the increasing complexity of systems has driven development methods from relying strictly on Systems Theory to increasingly more emphasis on Product Systems Engineering and Systems Engineering Management along with Systems of Systems and Enterprise Systems Engineering.

Organizations also recognize that there is a knowledge gap of qualified systems engineers due to retirements followed by inexperienced replacements. All of these issues create a complex environment equally as challenging as the system under development and this complexity in turn, highlights the fact that training is often inadequate for the demands on the system engineer.

The National Defense Industry Association (NDIA) Systems Engineering Division Task Report identified the 2010 top 5 systems engineering issues and one of those included: "The quantity and quality of systems engineering expertise is insufficient to meet the demands of the government and the defense industry" [2].

Systems Engineering training and education programs, therefore, must look at systems engineering process as a multifaceted and multi-disciplined function within and between organizations. Likewise, it must focus on the engineering of systems and the development of a systems engineering mindset through "systems thinking."

2. SYSTEMS ENGINEERING EDUCATION

Just as systems engineering stresses a focus on the lifecycle of a system, education and training programs must also address the entire lifecycle of the systems engineer from early education at the undergraduate level, through retirement in order to foster this 'system thinking'. The core body of knowledge for training relates the underlying principles of the systems engineering process, systems requirements engineering, analysis and design, integration, modeling and simulation, verification and validation, and systems engineering leadership and management. Likewise, systems engineering training and education programs need to help address the increasing and rapidly changing needs of industry and government. One key element of this training is the necessity to have "applied" systems engineering experiences. NDIA goes on to recommend that systems engineering expertise should be developed "through role definition, selection, training, career incentives, and broadening 'systems thinking' into other disciplines"[2].

There are a number of ways to expose students to the applied aspects of systems engineering. These include classroom exercises, labs, applied homework, mentoring, projects, and the use of case studies.

Experiential Learning for Systems Engineers

The use of case studies in systems engineering training stems from their application to the highly effective knowledge transfer achieved through experiential learning. In his book, "Organizational Psychology" and his working papers, David Kolb outlines the experiential learning cycle as shown in Figure 2.

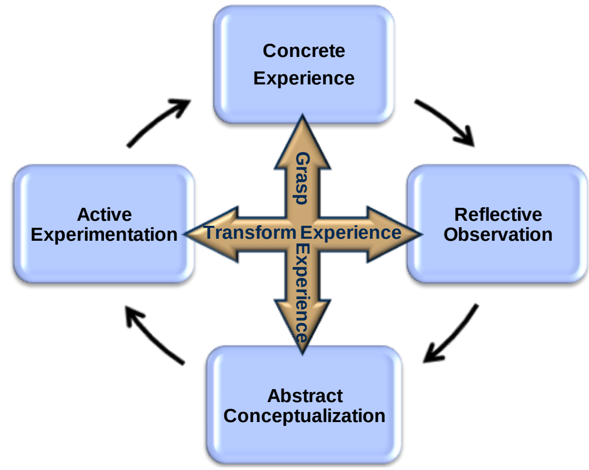

Figure 2: The Experiential Learning Cycle [3,4]

This cycle describes how experiences are transformed into learning. Kolb's experiential learning theory defines learning from experience as the "process of constructing knowledge that involves a creative tension among the four learning modes of concrete experience, abstract conceptualization, reflective observation and active experimentation"[3,4].

Effectively utilizing case studies in systems engineering training enables students to rapidly "experience" systems engineering challenges associated with each case.

Systems Engineering Case Studies

Case studies in engineering have been used for a number of years to introduce students to real programs and the real problems associated with them. Frequently these cases have focused on ethics training for engineers. Many of the cases present open ended problems that the student teams work through and then can compare to actual outcomes. Cases allow instructors to introduce topics that may be difficult to convey through lectures and homework assignments alone.

Systems engineering case studies are a special category of the engineering cases that are primarily focused on the application of systems engineering methodologies to complex problems. The Air Force Institute of Technology (AFIT) has developed and released over a dozen major systems engineering case studies [5]. These cases involve major systems acquisition program such at the Global Positioning Satellite (GPS), A-10 Aircraft, and the Hubble Space Telescope to name a few. Each case presents the system and program development in full detail and is usually 100 + pages in length.

Likewise, the Berlin Airlift Case Study was developed to complement the AFIT cases. This systems of systems challenge, set in the backdrop of the start of the Cold War, involves a number of complex, multidisciplinary domains: Logistics, Maintenance, Airlift Operations, and Airfield Operations, and Leadership.

Learning Principals: The primary learning principals for the application of case studies to systems engineering training include the understanding and development of: Applied Systems Thinking, Organizational Behaviors, Leadership and Decision Making, Requirements and System Architecting, and Project Management for Complex Systems.

The next few sections provide details on the different case studies used in the Georgia Tech systems engineering training and education programs.

3. AFIT SYSTEMS ENGINEERING CASE STUDIES

The AFIT systems engineering case studies are well suited for introducing novice engineers to systems engineering methods, processes and tools as well as challenging experienced engineers with complex systems development issues.

Figure 3: AFIT Case Studies Used at Georgia Tech

The Global Positioning Satellite (GPS), Theater Battle Management Core System (TBMCS), A-10 Aircraft, Global Hawk Unmanned Aero Vehicle, and the Hubble Space Telescope provide a broad range of systems engineering challenges particularly useful for systems engineering knowledge transfer. Each case study provides an overview of systems engineering practices and learning principals conveyed in the case.

The GPS case exemplifies how technology push enabled the fairly rapid development of a game changing technology. The TBMCS case, in contrast, shows how inadequate systems architecture definition lead to major budget and schedule overruns. It goes on to show how corrective systems engineering practices supported the eventual successful completion of the program. The A-10 case demonstrates the impact of political issue with large acquisition programs. Requirements effectively drove design but politics drove the need for additional fly-off demonstrations. And likewise, the Global Hawk case demonstrates how the rapid prototyping phase of the program was a success and why the program stumbled during the transition into the manufacturing and production phases. The Hubble Space Telescope provides a unique look at a space mission designed for on orbit servicing for lifecycle sustainment. These cases provide a rich environment for experiential learning events and major training activities are centered on their use as described in the next section.

Use of AFIT Case Studies at Georgia Tech

Georgia Tech has extended the application of several AFIT case studies to directly target course learning objectives in both the systems engineering continuing education courses and the Professional Masters Degree in Applied Systems Engineering (PMASE) courses.

Fundamentals in Modern Systems Engineering. The TBMCS, GPS, A-10 and Hubble cases are utilized to introduce students to systems engineering in the Fundamentals in Moderns Systems Engineering Continuing Education Course and the PMASE course. Students are divided into team and assigned one of the case study readings. Case study questions, specific to each case, are distributed to each team. These questions guide the case reading assignment and aide in the development of a case study presentation. Each team presents their specific case to the rest of the class. Since these cases are fairly lengthy (100+ pages), team presentations not only provide the students with an opportunity to practice their presentation skills but also enable the class to "experience" a number of cases without having to do the additional reading.

The GPS and A-10 cases are also extended to lab exercises in the PMASE course. The GPS case is the basis for the Requirements Analysis Lab where the students analyze a new "user segment" utilizing GPS. Example systems include Life Logging and Smart Roads. The students then go on to develop the functional architecture for this system in their System Architecture Lab.

The A-10 is also extended to an Analysis of Alternatives AOA) Lab. Here the students use the extensive data presented in the case study to build an AOA tool set that enables them to determine the "best" aircraft based on the original selection criteria. They then analyze their results and compare them to the actual case study results to determine additional factors associated with the system selection.

Leading Systems Engineering Teams. Similarly, the Global Hawk Case Study is extended to a systems engineering leadership and organizational workshop for the Leading Systems Engineering Teams PMASE course. Students are again divided into teams to further analyze the case in terms of organization factors associated with the systems engineering of the Global Hawk. Students continue with their analysis on how the organization also impacted the systems lifecycle phases of product development. Each team provides an out brief of their findings but they also extend these findings to their own course projects based on rapid product development similar to the prototype phase of the Global Hawk. The contrast between the initial rapid development in a small organization and the full deployment in a large defense contractor provides great insight into organizational and programmatic decisions.

The end result is additional insight into the cases as well as developing skills targeted for each course.

4. BERLIN AIRLIFT CASE STUDY

The Berlin Airlift may appear at first to be an unlikely case to develop for systems engineering training. But due to the nature of the operation, which includes complex relationships between logistics, cargo, airlift, flight operations, personnel, and maintenance, it presents an ideal vehicle for training systems engineering leadership and management as well as systems thinking. The Berlin Airlift case study is particularly valuable in providing experiential learning opportunities as well as an opportunity to immerse the students in a complex system of systems engineering challenge.

Case Study Development

Following the lead from the AFIT systems engineering case studies, the Georgia Institute of Technology has developed a detailed account of the Berlin Airlift to provide another opportunity for experiential treatment of systems engineering concepts. The case promotes innovative, interdisciplinary systems engineering education, melds theory and experience, and advances systems thinking and practice further into technological future.

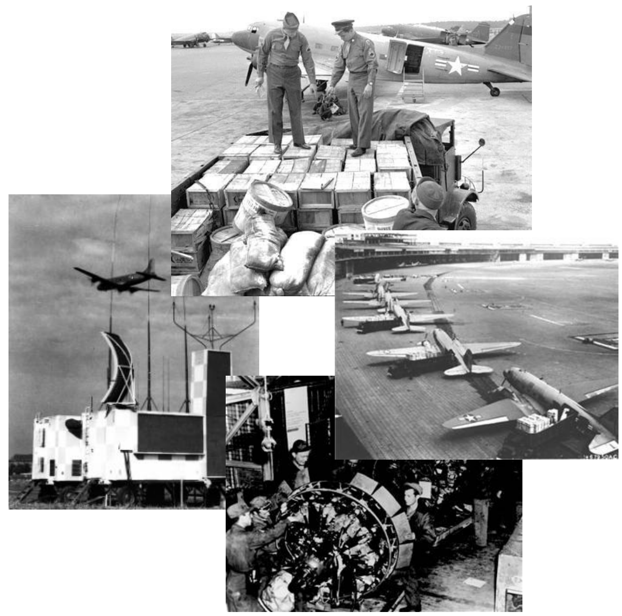

Figure 4: The Berlin Airlift – A Complex System of Systems

One of the key concepts practiced in the Berlin Airlift case study is that of applied systems thinking. INCOSE defines systems thinking as "a unique perspective on reality; a perspective that sharpens our awareness of wholes and how the parts with those wholes interrelate" [1]. The Berlin Aircraft Case Study emphasizes leadership and broad thinking by placing the students in various organizational structures with different leadership roles, and by providing them with organizationally disperse set of data to encourage communication and broad thinking. Figure 5, from the course, provides a model for the learning outcomes by placing the students into an iterative discovery process where they must listen to others in the simulation, look broadly across the mission and data sets, provide leadership to the others in their team, and repeatedly iterate their understanding of the problem set to arrive at a plan for mission accomplishment. Note that the applied systems thinking model complements and resembles the experiential learning cycle described previously and shown in Figure 2.

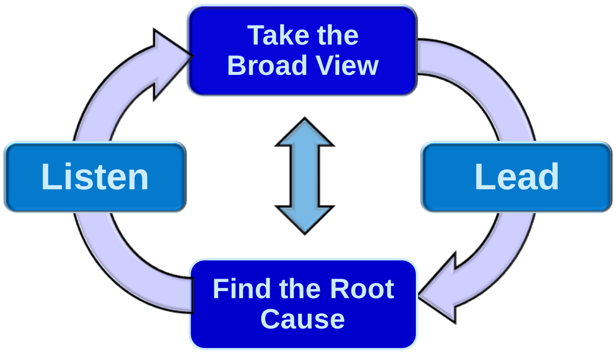

Figure 5: Systems Thinking in Practice

Case Study Delivery

The Berlin Airlift case study is conducted as a role playing exercise where the students are immersed in the execution of the mission. The objective of the case study exercise is to prepare a concept briefing for the commanding General for the rapid execution (and eventual sustainment) of the Berlin Airlift. Through the development of this briefing, students employ a number of systems engineering methods, processes and tools and are exposed to the complex systems of systems nature of the Berlin Airlift mission. Similarly, the students develop an organizational structure whereby they execute their systems engineering efforts.

Integrated Product Teams (IPT). The class is divided into 5 person IPTs and each team member selects a role to play during the exercise: Team Lead or one of four subject matter experts (SME). The Team Leaders orchestrate the activities of their experts in Logistics and Cargo, Airfield Operations, Airlift, and Maintenance and Servicing. The team members become SMEs by reviewing detailed fact sheets for the role they selected. The teams prepare products that support the concept briefing that include a SWOT analysis (**S**trengths, **W**eakness, **O**pportunities, **T**hreats), Stakeholder Identification and Lifecycle Selection, all of which help to define the personnel, plans, and risks for the mission. The team also documents the mission vision and purpose along with goals and values. These are used to encourage leadership aspects of the exercise to be focused on broad goals and objectives instead of "the answer." Additionally, the team develops critical success factors and measures of success. Next, using the wealth of information from the fact sheets, the SMEs develop use cases and a concept of operations for the mission. These are then used to identify driving requirements that lead to the development of the mission architectural view. Using the SWOT analysis, the team identifies risks and develops the plans to mitigate these risks. Finally the team brings together all of this data and prepares the mission deployment plan and briefing for the commanding General.

Mission and Organizational Change. This case also provides an opportunity to expose the IPTs to changes in the mission profile and their organization. This is accomplished by interrupting the exercise and announcing a mission change, extending the Berlin Airlift operation to a long term, sustainment mission. The teams are also reorganized at this break into centralized, functional units. This means the IPTs are broken up and each of the separate SME form a functional unit. Then the Team Leads become the briefing team and they then must coordinate the Airfield Operations, Logistics and Cargo, Airlift, Maintenance and Servicing, and Logistics functional units just created.

The mid-course restructuring of the case study exercise highlights the importance of organizational structure, leadership, communications, and collaboration between teams, the precise learning principals targeted for this case study.

During the out briefs the leadership team and SME's are evaluated as a group by their "command." This evaluation discusses their presentation skills, integration of SME's into the presentation, appropriate presentation of the data (particularly risks), and appropriate estimation of their resources and capabilities to conduct the mission. At completion, the instructors' feedback relates the outcome of their exercise back to the core set of systems engineering disciplines via a discussion of their outcomes and their experience.

Our experience with the Berlin Aircraft Case Study to date indicates that the individual performance of the briefing teams can vary widely but the learning tends to be very consistent with each class based on the discussion material at the end of the exercise. The case study has been designed and formatted to allow a great deal of flexibility in its "delivery," which we can tailor based on class size and relative background experience of the teams. Student feedback on the exercise and the course content has been consistently high, generally in the 90-95% positive range.

5. CONCLUSIONS

The demands on systems engineers to cope with the ever increasing complexity of systems development challenges require training programs that can provide rapid knowledge transfer from the systems engineering domain. The solution to this knowledge transfer is to expose students to applied systems engineering experiences. One key element to this experiential approach is the use of systems engineering case studies in training and education programs. These cases are extensions of traditional engineering case studies that expose students to open ended problems, focused on the application of systems engineering methodologies to complex problems and foster systems thinking.

The Air Force Institute of Technology case studies provide a wealth of resources that readily enhance any systems engineering training program. The applied aspects of the cases can be further improved by extending the cases into other exercises and systems engineering labs.

The Berlin Airlift, a complex system of systems case study, provides students with an opportunity to experience learning by doing. It exercises team building, engineering leadership and systems thinking skills as well as system architecting which are all essential to any system development challenge.

The future of systems engineering case studies is full of opportunities to develop and utilize cases in training and education programs. There are ample partners in industry and the government who could support the development of other case studies as well as implement them in their training programs. Case studies are critical to the success of applied systems engineering training programs.

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