

2006-2089: COMBINING SYSTEMS ARCHITECTURE AND SYSTEMS ENGINEERING IN AN ENGINEERING MANAGEMENT PROGRAM

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Combining Systems Architecture and Systems Engineering in an Engineering Management Program

Abstract

The discipline of systems engineering is receiving more attention from both the academic and practicing engineering communities. Many high-profile engineering failures (including several recent NASA missions and a variety of product recalls) have all been traced to breakdowns in systems engineering.

However, the architecture of an engineering system has an even greater impact on its performance, robustness, and properties. Outstanding systems engineering and detail design cannot salvage an architecture that is fundamentally flawed. Despite architecture's importance, many organizations do not explicitly explore alternatives and "jump" directly to systems-level design. This prematurely collapses the design space and squanders the opportunity to explore alternatives at the least costly phase in the design process.

Therefore, it is important to educate engineering managers about the key role that both systems architecture and systems engineering play in the success or failure of an engineering system. It is the belief of the authors that this may be accomplished reasonably well in a single course in programs where a more in-depth course sequence is not a realistic option. Although combining these topics restricts the depth at which either may be taught, there are natural synergies that allow this combination.

The goal of this combined course is to familiarize the engineering management students with both systems architecture and systems engineering, to understand the common pitfalls associated with each, and to begin to develop a mindset that continually considers architectural and systems engineering consequences of management decisions. The course focuses more on the "what" and "why" of systems architecture and systems engineering and less on the "how." Detailed discussion of specific tools (such as DOORS) is omitted or significantly abbreviated to allow more time to be spent on fundamentals and case studies.

Background

The authors are associated with the University of Detroit Mercy's Master of Science in Product Development (MPD) program. This program is offered by the College of Engineering and Science and the College of Business. It was developed in collaboration with the Massachusetts Institute of Technology and the Rochester Institute of Technology and six industrial partners: Ford, General Motors, IBM, ITT, Polaroid, and Xerox. The United States Navy and the National Science Foundation also provided input.

The MPD program is cohort-based and operates on a two-year cycle from initiation through thesis completion. Students are immersed in the program through a two-week long "January Experience" that includes coursework and a design challenge (in recent years this has been a radio-controlled robotics competition). The lead author is a recent MPD graduate (working in industry) who has twice been invited to assist with the "January Experience" for subsequent

cohorts; the secondary author teaches five classes in the MPD program and is the Engineering & Science curriculum director for the program.

The University of Detroit Mercy also offers a Master of Engineering Management (MEM) degree; it is a hybrid degree offered by the College of Business Administration and the College of Engineering and Science. The program integrates technical and management studies to produce graduates capable of assuming leadership roles in engineering management.

The primary author was invited to teach and/or develop an elective for the MEM program. Because of his affinity for systems architecture and systems engineering (as well as his passionate belief that these two disciplines are both critical and often neglected), he proposed a blended class that covered both topics in adequate depth for the MEM program. The course was approved and offered in the Fall 2005-2006 semester.

Course Structure

EM 570, Systems Architecture and Systems Engineering, was intended to provide a fundamental understanding of the principles of systems architecture and systems engineering as applied to the development of physical products (not necessarily computer systems). The architecture portion of the course addressed tools and techniques for developing the architecture for a complex system. The systems engineering portion of the course addressed tools and techniques for executing the complete design and validation of a complex system once the architecture has been largely defined.

The course was derived from material taught in the MPD program by the secondary author; he generously granted permission for the reuse and adaptation of his course materials for the MEM class. The primary author chose to split the semester into distinct Systems Architecture (SA) and Systems Engineering (SE) halves.

Maier & Reichtin's *The Art of Systems Architecting* was chosen as the textbook for the SA portion of the class; Kossiakoff & Sweet's *Systems Engineering: Principles and Practice* was used as the SE text. In addition, a variety of freely-available SE handbooks and other references were integrated into the class as extra reading material.

Grading was structured in the following manner:

Class participation	10%
Quizzes	20%
Case Studies	20%
Projects	50%

There was no final examination (the lead author chose instead to use the weekly quizzes to encourage the students to remain up-to-date in their studies). In addition, a premium was given for early completion of work. Three deadlines were assigned for every case study and project: 110%, 105%, and 100%. Each student's assignment score was multiplied by the appropriate value based upon when it was submitted.¹ No group assignments were given.

The University of Detroit Mercy uses BlackBoard web-based instructional software; the MEM students were required to use it for assignment submissions, quizzes (if they were traveling), and on-line discussion board postings. The instructor posted his class notes several days early as a courtesy to a foreign student so that he could make appropriate translations to assist his in-class participation.

Systems Architecture

The lead author adopted the MPD definition of SA that was continually reinforced throughout that program:

Systems Architecting: The mapping of function to form via concept.²

Because of its relative brevity, the students were required to read the entire Maier & Rechtin text. This allowed the instructor to introduce the concept of a system's architecture and explore the topic at an appropriate level for management students. The content was focused on the following areas:

- Maier & Rechtin's Six Pillars of Architecting
- The need for a holistic view of a system
- Architecting across system boundaries
- Functional decompositions
- The importance of solution-neutrality
- Modular & integral architectures
- The use of heuristics

The goal was to provide the students with an appreciation for architectural issues, particularly the need to explicitly address them (rather than implicitly architecting and "jumping" directly to system-level design). The supporting case studies illustrated the inherent weaknesses of products and systems with suboptimal architectures and the superiority of those with robust architectures.

The Defense Systems Engineering Handbook³ was introduced to further class discussion; it includes a section entitled "An Aide Memoire of System Issues" that lists a set of heuristics that can be compared and contrasted with Maier & Rechtin's works.

Feedback from the students was generally positive; none of them had been exposed to SA as a separate discipline and by the end of the first portion of the class they had gained an appreciation for its importance. The general consensus was that none of the SA material was extraordinarily difficult; however, because it is often ignored or given cursory attention organizations routinely blunder.

Systems Engineering

The second half of the course was devoted to systems engineering: robustly executing a given architecture. For the purposes of the class, the definition used in the MPD program was adopted:

Systems Engineering: An interdisciplinary approach and means to enable the realization of successful systems.⁴

The text chosen was Kossiakoff & Sweet's *Systems Engineering: Principles and Practice*; both authors had reviewed a number of available references when it was necessary to select a new book for the MPD SE course and they felt this text interfaced the best with the program's needs.

The lead author reviewed the book and only assigned readings that did not overlap with the Maier & Rechtin text (marking those sections as "optional" in the reading cadence). Students were encouraged but not required to contrast the two texts' approach to architecture.

The SE portion of the course focused on the "what" and "why" of SE and neglected most of the SE tools that would be discussed in a semester-long class. Topics included:

- Relation of SE to SA
- SE's role in the traditional product development processes
- Developing good requirements
- Partitioning & interface management
- Modeling
- Verification and validation

Because many of the cases dwell upon engineering failures that are relatively obvious in hindsight, it was felt that some exposure to the nuts-and-bolts of SE would give the students an appreciation for the difficulties involved in robustly executing the development of a new product. For this reason, the instructor elected to discuss two SE tools in some depth: Quality Function Deployment (QFD) and Design Structure Matrices (DSM). QFD was selected because it helps identify customer wants and needs and assists engineers in translating them into characteristics and specifications. DSM was chosen because it illustrates the relationships and interdependencies between the elements of a system; it can be used for both analysis and management during the execution of a product's development.

To facilitate the exploration of QFD and DSM, the instructor located free software tools that were provided to the students to allow the assignment of brief exploratory exercises. SmartDraw (a freeware drawing tool available at www.smartdraw.com) has a QFD template; MIT's DSM group has made available a set of Excel macros that facilitate the construction and analysis of DSM matrices (available at www.dsmweb.org). The DSM exercise was less successful because the instructor limited the size of the matrix to keep the assignment relatively simple; however, this limited the utility of the tearing and optimization portion of the exercise. In retrospect, a longer-term assignment with a larger, more complex matrix would enhance the students' learning and appreciation for the DSM methodology.

Case Studies

Each class period began with one or more lead-in case studies that served to illustrate key concepts from that day's lecture. The secondary author has used these with success in the MPD program and the primary author has assisted with the identification of topics, research, and the collection of supporting resource material. The cases from the MPD program chosen for inclusion were:

- Theodoric's tomb
- The Pantheon
- HMS *Dreadnought*
- Boeing 787/Airbus 380
- Goddard's Rockets/Project Orion
- Hubble Space Telescope
- Mars Pathfinder
- Cassini/Huygens
- Therac-25

In addition, three new cases were developed for the course:

- NASA's Great Observatories (considered as a system: Hubble Space Telescope, Compton Gamma Ray Observatory, Chandra X-Ray Observatory, Spitzer Space Telescope, James Webb Space Telescope)
- The Curta mechanical calculator
- The pipe organ

The organ case study was the most involved; in addition to historical material obtained from James Heustis Cook of Birmingham-Southern College, two videos were presented to the class. The first showcased a virtuoso playing a recently restored pipe organ;⁵ the second⁶ showed the manufacture, testing, and installation of a pipe organ in addition to "behind the scenes" clips showing the mechanisms of a large organ.

The organ case was well-received by the students; not only was it a topic with which all of them were very familiar (although they did not realize that the organ's architecture is over 2 millennia old) but it also illustrated a variety of SA/SE concepts. The students engaged in one of the most lively class discussions after the conclusion of this presentation; in addition to the strengths of the material, it was delivered sufficiently late in the term that the class had developed the appropriate vocabulary to discuss the topics.

As the final assignment, students were asked to develop their own case study presentations...drawing from topics that interested them and illustrating their mastery of the course material. They were directed to choose either an outstanding success or a dismal failure...and to integrate course topics as appropriate (but to avoid "stretching" to include every concept). The most important directive was to "tell a good story," since without some interesting aspect to engage students any case study loses effectiveness.

The students selected a variety of topics for their cases, including the Panama Canal, the Abioco artificial heart, and Taipei 101 (a skyscraper).

Field Trip

One of the major projects in the class was structured around a field trip to the Henry Ford Museum in Dearborn, Michigan. The instructor regularly visits the museum with his family and was struck by its potential as a showcase for alternate architectures. There are hundreds of items on display, many of which are grouped into exhibits that can be readily used for SA/SE discussions (for example, six locomotives from various time periods). He felt that bringing students into that environment and having live discussions about design tradeoffs, technological innovations, and other SA/SE topic would be a valuable supplement to the curriculum.

The students were given the following assignment:

“The class will visit the Henry Ford Museum on October 13th. As part of that field trip, we will discuss a variety of complex engineering systems. Take notes about architectural features of interest (and images as appropriate) to support the following:

Select one class of complex engineered product (for example, locomotives, automobiles, vacuum cleaners, etc.) with at least five examples on display at the Museum.

Your paper should contain the following sections:

General Background (1 page)

Discuss the general class of items (when was it introduced, key features, intended customer, is it still in use, etc.). You should also develop and include a timeline of the individual examples to help place each in the proper context in the next section.

History of the Individual Examples (1 page of text each)

Provide a brief history of each example and discuss its architecture. Discuss supporting infrastructure/systems (i.e. energy sources). Compare and contrast its architecture with those of its peer group, highlighting key differences. Draw conclusions about the architecting process used, characterize the architecture as integral vs. modular, and discuss applicable architectural pillars (not all may apply). Insert images or sketches as appropriate to illustrate key features.

Functional Decomposition (1 page)

Construct a generic, graphical functional decomposition (use Visio, MS Word Org Chart, etc.) for an item in this class.

Alternate Architecture (2 pages)

Develop an alternate architecture that draws upon the best features/lessons learned from the items discussed above; you may also include modern

technology as appropriate. Provide a sketch of this architecture and a written description of how it meets the functional requirements from the decomposition. Describe any assumptions/constraints, what features are borrowed & why, what features are new and why, how integral vs. modular is it and why.

Chunking (1 page)

Arrange the elements of your architecture and “chunk” them. Explain why you chose to associate elements. Discuss any advantages/disadvantages to this arrangement and how it would impact coordination of system suppliers (if appropriate). Comment on the interfaces between chunks and how they would be managed.

Management & Models (1 page)

Describe what models would be appropriate for managing the implementation of your architecture (as an architect). What disciplines would require the most depth?

Heuristics

Generate at least three new heuristics (these may be reused in the final project) based upon the lessons learned from this exercise. Give a brief explanation of each.”

The field trip began with a visit to a display of stoves; one student was somewhat skeptical about the field trip concept but was won over once the class spent forty-five minutes simply discussing the stoves on display. The diversity of the class played a role in this discussion; one student, an immigrant from Nigeria, explained the finer points of one stove type still in widespread use there.

The class also visited and discussed:

- Cameras
- Farming implements (tractors, combines, etc.)
- Firearms
- Automobiles
- Locomotives
- Presidential Limousines
- Furniture
- The Dymaxion House⁷

Each of these categories of items were examined at some length; the instructor would steer the discussion with inquires about how/why certain features were present, questions about historical context (both social and technical), and specific statements about topics covered in class. Once the class tour was complete, the students were released to take further notes and take photographs to support their papers.

Topics chosen for the projects included the farm tractors (including locomotive-sized tractors with less than 50 effective horsepower), automobiles, and Presidential limousines (from Theodore Roosevelt's brougham to Ronald Reagan's limousine).

Student feedback about the field trip was positive; the ability to see multiple examples of the same general architecture greatly facilitated the group's discussions. Although the Henry Ford Museum is unique in the size and scope of its collection, other museums' exhibits could provide suitable field trip opportunities.

Conclusion

The fusion of two semester-length MPD courses into a single MEM elective was successful. The engineering management students were given an appreciation of the importance and complexities associated with the robust execution of SA and SE disciplines. The use of lead-in cases enabled students to associate presented topics with examples drawn from both history and current headlines. Finally, the field trip and final case study enabled the students to explore the topics themselves and relate them to real-world examples. The authors feel such a course is essential to develop engineering managers capable of effectively leading teams developing complex engineered systems.

Bibliographic References

- [1] The lead author adopted this system from Carroll E. Mobley, Ph.D., an instructor he had as an undergraduate. Professor Mobley believed that it was better to have most of the answer to an engineering problem quickly (so it could be tested and refined) rather than an exhaustively researched solution "three days after your company went out of business." It is the author's experience that delays tend to accumulate but early completions rarely, if ever, do...this grading system was meant to encourage the students to adopt a more nimble mindset that will hopefully carry over into their management style.
- [2] Edward Crawley, Ph.D.'s definition of Systems Architecture, presented during curriculum development meetings between the University of Detroit Mercy, Massachusetts Institute of Technology, and Rochester Institute of Technology, 1999.
- [3] The Defence Engineering Group Department of Mechanical Engineering, University College London, *The Defence Systems Engineering Handbook*: available at www.deg.meng.ucl.ac.uk/DSE_GUIDE_EDITION_1A.PDF, 2002.
- [4] SE Handbook Working Group, *Systems Engineering Handbook*: International Council on Systems Engineering, 1999.
- [5] Hans-André Stamm, *Bach: Greatest Organ Works*: Geneon Entertainment, 2001.
- [6] *Pulling Out All the Stops: The Pipe Organ in America*: Independent Communications Associates, Inc., 1996.
- [7] The only surviving example of a housing concept designed by Buckminster Fuller. Although it was ineligible for use on the assignment, Fuller's vision illustrated key

SA/SE principles (it was a novel architecture for a prefabricated aluminum house intended for fabrication by an aircraft company).