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INNOVATION IN ENGINEERING DESIGN AND EDUCATION

Abstract

This paper explores innovative approaches to both the engineering design process as well as education regarding engineering design. First, the engineering design process is discussed as a distinct two stage procedure involving (a) architectural design, and (b) subsystem design. The steps in these two stages are articulated and examined. Innovative aspects of the engineering design process are then discussed in terms of some of the ways of "thinking outside the box", as set forth by the author. These ways include (1) broaden and generalize, (2) crossover, (3) question conventional wisdom, (4) back of the envelope, (5) expanding dimensions, (6) removal of constraints, and (7) the systems approach. The final issue involves carrying these notions into education approaches to the engineering design. Examples are provided that demonstrate and explore how these innovative approaches have been used and how they might be expanded.

THE ENGINEERING DESIGN PROCESS

Engineers have been designing systems for a very long time. Accordingly, we have studied the design process itself for many years. A relatively recent way to describe that process is to confirm that it is, or should be, a distinctly two step procedure: architectural design followed by subsystem design. The latter has been more-or-less taken as axiomatic. The former has been somewhat controversial, taking different shapes over the years. For example, Buede[1] has cited the following as the five functions of the engineering design of a system:

1. Definition of the design problem
2. Development of a functional architecture
3. Design of the physical architecture
4. Development of an operational architecture
5. Approval and documentation

This introduces the notion of multiple architectures, i.e., functional, physical and operational. The Institute of Electrical and Electronics Engineers (IEEE), in their treatment of architectures, cites a composite of the functional, physical and foundation architectures[2]. These three architectures are similar to, but not the same as, those suggested by Buede, as noted above.

A key marker for the definition of an architecture is the work of the Department of Defense (DoD) wherein they defined a framework for their approach (DoDAF) in the mid- 1990s[3]. That framework was built upon three views of an architecture, namely, (1) the operational view, (2) the systems view, and (3) the technical view. The specifics of these three views have been defined in quite a lot of detail. The most recent version of DoDAF (version 2.0) continues with this three view notion. Interestingly, the focus of the DoD has been on views of architectures, leaving some ambiguity (to some) with respect to the matter of how to precisely define and develop a system architecture.

Another Approach to Architectural Design

An innovative approach to architectural design is based upon a different perspective. It develops alternative architectures and then seeks the most cost-effective alternative[4]. As such, it more closely follows precepts set forth in the DoD's acquisition guidance[5], especially with respect to (a) the explicit need for an analysis of alternatives (AoA), and (b) the search for a cost effective solution to the user's problem. With this approach to architecting, a set of essential views is suggested that is quite different from the operational, systems and technical views.

In brief terms, this alternative approach has three primary views and corresponding steps: synthesis, analysis and cost-effectiveness. Additional views may be constructed[6] that provide insights into the features of the alternatives under consideration. The DoDAF views can be a subset of these additional views, if desired. A very important aspect of this approach is that each of the three primary views reveals the process by which the view was developed. Thus, the procedure is explicitly supported by the products generated by the process. This is considered to be an especially interesting and useful part of both the process and its outputs.

Synthesis. For this step, a table is constructed whereby:

a. The rows are represented by the system's functions and sub-functions, and
b. The columns show the alternative architectures under consideration. Typically, the procedure recognizes three basic types of alternatives. These are a low cost approach, a high-effectiveness approach, and a best value (or knee-of-the-curve) approach
c. The cell entries show the design choices that are made by the architecting team for each sub-function and each alternative architecture

This table is the short form method of synthesizing three alternative architectures, each of which represents an attempt to find the appropriate cost-effective solution

Analysis. A different table is developed for this step:

a. The rows list the criteria that will be used to evaluate the three alternative architectures
b. The columns, as with the synthesis step, list the three alternative architectures
c. One column is reserved for showing the weights that the architecting team may associate with each of the evaluation criteria
d. The cells contain the evaluation ratings of each alternative against each criterion
e. A score is computed, using the weights and the ratings, for each alternative. This score is a measure of the effectiveness (MoE) of the various alternatives
f. The overall life cycle costs are estimated for each of the alternatives

Cost-Effectiveness. Using the effectiveness measures and the costs for each of the alternative architectures, a graph is constructed showing the costs and effectiveness measures on a numerical grid. This is the primary basis for selecting a preferred system architecture. As a minimum, additional views are developed, as suggested above, that assist in the evaluation and search for a preferred alternative.

The above is a brief overview of the suggested architecting method. The full procedure, with examples, is provided in the selected reference[4].

Subsystem Design

The second part of the overall engineering design process is subsystem design. In general, this part is undertaken only after architectural design is completed and approved. Important aspects of this design phase include:

a. Working specifically at the subsystem and lower levels
b. The explicit consideration of alternatives
c. Trade-off studies
d. A cost-effectiveness approach
e. Assurance of interoperability
f. The satisfaction of user requirements
g. Deep subject matter expertise in each subsystem domain

For (a), one is dealing with subsystems like modulators, encryption/decryption devices, multiplexers, antennas, and other similar considerations. The selected architecture is not to be changed through subsystem design or re-design. The only exception is the discovery that the basic architecture will not work.

In the case of (b) above, we continue to define alternatives, even at the subsystem level. These alternatives may be straightforward, but at times they can also be groundbreaking (such as a new chip configuration that achieves higher levels of performance).

One of the ways we attempt to "optimize" the subsystem design is to carry out trade-off studies (item [c] above). This helps in selecting the best alternative from a set of alternatives.

For (d) above, even at the subsystem level, we are seeking a local cost-effective solution. This is generally the approach that guides the subsystem design engineer, except under unusual circumstances (as per a search for a level of performance almost without due regard for cost).

In the case of (e), we must explicitly assure that the selected subsystem designs are interoperable. Typically, this is a task assigned to a systems engineer who has the appropriate background with related subsystems.

For (f), we must keep in mind that all subsystem solutions, in general, must be compatible with the stated user requirements. In a limited number of cases, changes in requirements might be considered for good and sufficient reasons (such as a requirement that drives up cost and/or schedule times to an unacceptable degree).

Finally, appropriate subsystem design requires deep subject matter expertise at the subsystem level, and with respect to each and every one of the implied disciplines. Subsystem design engineers tend to be specialists who have mastered all aspects of the technologies in question.

This second phase (i.e., subsystem design) parallels the architectural design in the consideration of alternatives and the focus on the cost-effectiveness of these alternatives. The architectural phase is considered innovative, especially as it departs from conventional wisdom in this arena. Both the architectural design as well as the detailed design can be enhanced through a deliberate attempt to "think outside the box". Selected aspects of this notion are discussed below.

Thinking Outside the Box

The overall engineering design process of architecting and subsystem design may be improved through a judicious use of "thinking outside the box"[7]. Seven aspects of this type of thinking are explored below with respect to some part of the engineering design process.

Broaden and Generalize. This notion specifically applies to conceiving of the idea of constructing alternative architectures. This broadens our horizons in a quite explicit way. This perspective brings us to possible solutions that might otherwise have been overlooked or simply not considered.

Crossover. This approach involves taking a solution from one domain and applying it in an appropriate manner in another domain. In this way we gain leverage and increased productivity. This may be applied to the design issue, for example, through the application of software reuse. In short, the design alternatives include at least one approach involving large amounts of reuse. If appropriately planned and supported, software reuse suggests the possibility of huge cost and schedule benefits.

Question Conventional Wisdom. The suggested architecting approach clearly questions the conventional wisdom of constructing the operational, systems and technical views as a main focus for the process. There is a way, however, to bring these two notions together, as mentioned earlier with respect to "views".

Back of the Envelope. The key notion here is to try to focus on the essence of a problem, and also try to simplify as much as possible. The boiled-down (simplified) architectural approach leads us to three well-defined steps and their associated views: synthesis, analysis and cost effectiveness.

Expanding Dimensions. The architecting dimensions are clearly expanded when we look at low cost, high performance and best-value notions. In the final selection, however, we may wind up narrowing back to, for example, several alternatives within the "best-value" domain.

Removal of Constraints. Considering the history and force behind the DoDAF approach to architecting, one might tend to accept this approach as a constraint. If we "remove" that constraint, other notions may be acceptable and possibly found to be even more desirable. In addition to the synthesis, analysis and cost-effectiveness method of architecting, it might well turn out that for some, the MoDAF (Ministry of Defence Architectural Framework) is even more applicable[4]. Perhaps the same is true in terms of adopting an enterprise architecture approach in a particular environment or situation[4].

The Systems Approach. Although there are many aspects to what can be defined as the Systems Approach, two stand out in this connection[4]: (1) a full consideration of alternatives, and (2) a cost-effective solution to the problem, as posed by the customer. These are two of the most important features of the innovative architecting procedure.

Impact in the Classroom

The two-step engineering design process discussed here has had a definitive impact in the classroom. Of special note is its integral part of the Systems Engineering courses and program at the graduate level, leading to a Master's degree. All such students must take Systems Engineering as a core course, and therefore all of the students are directly impacted.

Even after earning a Bachelor's degree in one or another field of engineering, a significant number of students have not had sufficient grounding in the "design" process. Emphasis for them has been placed upon "analysis", and they come to our Systems Engineering courses lacking in understanding as to how to truly design a system. We accept it as a responsibility that this is a core notion and skill, and that no student shall graduate at the Master's level without an appropriate level of mastery in this arena. Further, the two-step process of architecting followed by detailed subsystem design is often not well understood, even after an undergraduate course or two that emphasizes design, including a design "laboratory". For those that have the appropriate background, an attempt is made to enhance the design process through a formal use of ways of "thinking outside the box".

AN INNOVATIVE EDUCATION APPROACH

A more-or-less conventional approach to engineering education involves the following simplified steps, within any of the engineering disciplines: (1) select the most important concepts that need to be part of the core and elective curricula, (2) structure the above into a series of tracks, and courses for each track, (3) make these results available to attract prospective students and respond to their perceived needs, (4) present the courses to whichever students are admitted and register for their selected curricula, and (5) maintain quality control over the above, including re-engineering the steps when the faculty believes it is necessary to do so. This "open enrollment" model appears to be the rule, rather than the exception, with respect to engineering education. Further, it has been largely successful, over the years. Even with the advent of the Internet, and its facilitation of the course delivery process, there has been little change in the conventional approach, as defined and outlined above.

This author has been part of an innovative approach that significantly changes important aspects of the above-cited steps. This approach, rather than being open to all admitted students (the open enrollment model), has been a closed enrollment, cohort-based model. This latter approach has been applied successfully by entering into agreements with industrial as well as government entities. These agreements specify the overall focus of study, and lead to Master's degrees for those students that successfully complete the set of individual courses. The course standards are identically the same as with the open enrollment model. Some of the important differences are outlined in the Table following:

OPEN ENROLLMENT MODEL	COHORT-BASED MODEL
Students select focus of studies, and sign up individually for courses of interest to them	Institution selects focus of studies, and agrees to support one or more cohorts
Students pay for courses, and may or may not be reimbursed by a sponsor	Institution pays for courses at an agreed-upon rate
Individual students follow their own paths and paces, taking one or more courses/semester	Institution decides who will be admitted to each cohort; all students in lock-step schedule
Students take courses at facility designated by University	Courses typically given at Institution's specified facility; close to where students are located
Courses are modified from time to time, based largely upon faculty perceptions and individual student feedback over time	Courses are modified from time to time, based largely upon faculty, student, and Institution feedback

Table 1 – Some differences between open enrollment and cohort-based models

Perceived Advantages and Disadvantages

The cohort-based model is perceived to have several advantages that are separately noteworthy. The first is the fact that the courses are presented in locations that are convenient to the students. Typically, these locations are in the same buildings in which the students are located. This "student-convenience" approach appears to be appreciated as one of the most important factors. A second advantage is that the students do not have to put forth significant amounts of money in order to participate. This is not a surprise since cash flow is widely understood, especially by students. Another advantage is that the people in a cohort often feel special in that they have been accepted into a program that is not open to everyone. Indeed, in some cases, special rewards are part of the consideration in terms of ultimate successful completion of the program. In effect, the institution is saying "we are willing to make a special investment in you and your future with us". Another advantage is that the University is often challenged to do better by facilitating inputs from the participants in relation to topics of special relevance and interest. This can only make the overall program improve over time. Yet another advantage is that the University is able to make the programs available at a lower cost, largely due to the fact that it is delivered "off campus". In that context, the cost of facilities can be lower, especially when it is on the institution's premises. It has also been clear that the costs of marketing cohort programs have been less than the open enrollment programs. The reason: once a program is accepted by an institution, it tends to continue and does not have to be "re-sold" year after year. Finally, the institution is able to track progress and get more involved in a cohort program by its very nature. Since all students are from the same institution, its needs can be more accurately reflected in the choice of courses, and they can be assured that all students have experienced the same subject matter delivery.

There are perceived disadvantages that have been raised by some, from time to time. One has to do with cost and price, and some have argued that all courses, whether provided on campus or off campus, should have the same exact per credit hour price. In the same vein, they would generally not support differential pricing, and the possible consequences that might ensue. Some have also questioned whether or not the institutional partner might have some undue influence on the nature of the courses in the program. Yet another perceived disadvantage has to do with the stress placed upon the Department and faculty as they respond to the program's often extremely challenging needs. Delivering cohort-based courses is indeed a challenging activity for all concerned parties, especially when the University is based on the East coast and is delivering courses, week-by-week, on the West coast. Finally, some have voiced the view that the cohort-based programs have not contributed in an appropriate way to the research agenda of the University.

The above perceptions will give the reader some idea as to the diversity of opinion regarding the cohort-based vs. the open enrollment model. The fact that the cohort-based model has grown substantially over the years indicates that the latter has been successful by at least the standards applied by the University's partners. Over this ten year time period, the University has in fact supported the program, for what appear to be good and sufficient reasons. Thus the program has been both innovative and successful over a decade of time. Whether or not it becomes a preferred approach vis-à-vis the more conventional approach (i.e., the open enrollment model) remains to be seen.

Program Measures

For a variety of reasons, considerable data has been kept relative to both the cohort and the open enrollment models in terms of overall Master's degree programs. These data tend to record such variables as:

a. numbers of students
b. backgrounds of these students
c. grades achieved by the students
d. names and backgrounds of instructors
e. locations of courses
f. instances of course modifications
g. instances of program modifications
h. costs and pricing, by year, by location
i. levels of expressed satisfaction and dissatisfaction.

The latter item is recorded as a matter of policy in terms of all courses, in what is called a set of student evaluations. These evaluations have 15 questions ranked from (A) through (E), and a 16th that calls for other comments in a text format. Numerical values for the above measures have not been approved for release at this time.

SUMMARY

This paper has explored two innovative approaches. One is in the important domain of system architecting, itself a key aspect of engineering design. In distinction to some current practices, this approach is based upon the steps and views associated with (1) synthesis, (2) analysis, and (3) cost-effectiveness. The second approach has to do with engineering education. It uses a cohort-based model rather than an open enrollment model. Both innovative approaches have been utilized in the real world for more than ten years, and have thereby established their value.

In addition, the suggested architectural approach has been examined in the light of ways to systematically "think outside the box".

There is also room for future expansion of both innovative approaches. In the case of architecting, expansions may be expected in matters involving interoperability, complexity, requirements, decomposition, and systems integration. For the approach to engineering education, new ideas may be expected with respect to integrating the Internet, greater use of video and storage technologies, ways to better respond to student and institution needs and creating even greater efficiencies while at the same enhancing the areas of focus, courseware and educational experience. Finding new ways and means of expanding these notions can be supported by using some of the recommended "out of the box" thinking.

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