Integrating Systems Thinking in Interdisciplinary Education Programs: A Systems Integration Approach

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Abstract

The fast evolution of interdisciplinary programs in educational alliances calls for new approaches in integrating specific learning outcomes across differing education platforms. Where interdisciplinary education programs seem to make sense, sometimes, turn out to be discordant in implementation. The desire to have integrated workforce development for the Air Force makes it imperative to use new approaches for assessing how interdisciplinary programs can fit together, coexist, and be mutually beneficial. In this paper, we present a systems-engineering framework for integrating educational elements from different academic programs to achieve a cohesive interdisciplinary program. This paper presents systems engineering models as a proven methodology to adopt for ensuring the success of interdisciplinary programs through a systems thinking approach. The paper uses the DEJI® systems engineering model to facilitate design, evaluation, justification, and integration of academic program realignment and consolidation in an interdisciplinary collaboration involving the Air Force Institute of Technology (AFIT) and the US Air Force School of Aerospace Medicine (USAFSAM). Such a collaboration ensures that operational policies, practice, education, and training are unified so as to operate in more precise, innovative, collaborative, and systems-based approach.

Introduction

The U.S. Air Force School of Aerospace Medicine (USAFSAM) is an educational center focused on aerospace medical learning, consultation, aerospace medical investigations and aircrew health assessments. The center promotes readiness and protect force and community health by using a range of tools and expertise including environmental and health surveillance, laboratory and risk analysis, process re-engineering, consultation and technological innovation to maximize operational health capabilities and to solve problems through ingenuity and partnerships. The Air Force Institute of Technology (AFIT) is the Air Force graduate school of engineering and management. AFIT is a military organization with an education mission. AFIT provides advanced education to the Air Force and other military and government organizations. The faculty is composed of military and civilian educators. The military faculty rotates on average every three years from their faculty positions into other Air Force assignments. This potentially
disruptive assignment rotation must be managed carefully from a systems perspective, particularly where interdisciplinary alliances are desired. The theme of this paper is to present a systems-engineering model to address this divergent educational setup.

Comprehensive engineering education requires a multi-faceted approach for a sustainable knowledge acquisition and retention. In these days of a multitude of approaches and views, engineering education should not be siloed, as have been in the past. In practice, engineering interfaces with other disciplines to bring about a complete solution to the attendant problems and challenges of the profession. Relevant, responsive, and adaptive curriculum development is the best approach to achieving an integrated delivery of education.

In this paper, we suggest the application of a systems approach to curriculum development, particularly where normally dichotomous disciplines are involved, such as engineering and aerospace medicine. A systems-based view of a robust curriculum permits the inclusion of all (or most) of the facets attendant in each of the collaborating disciplines. Systems thinking is, thus, essential for integrating curriculum elements. Traditionally, a system is defined as the collection of interrelated elements whose collective output (or result) is higher than the sum of the individual elements in the system. In the context of using a systems-engineering model, systems engineering is defined as an interdisciplinary approach facilitating the marriage of technical and managerial efforts required to transform a set of requirements, needs, expectations, and constraints into a sustainable solution for the lifecycle of the product of interest.

**Systems Engineering Models**

Systems Engineering is defined by [5] as “An interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. 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.” The objective of this paper is to adapt this production-centric definition to an integrated curriculum development effort. Some of the models used in systems engineering include:

- The V-Model
- Waterfall Model
- Spiral Model (aka Tornado Model)
- DEJI® model

In this paper, we show an application of the DEJI® model [1] for academic curriculum integration. For context comparison purpose, we also mention the general framework on the V-Model. Readers interested in the range of systems engineering models available in the literature may refer to [2], [4], [6], [7], and [8]. Each systems-engineering model is expected to facilitate the various stages of a systems delivery encompassing the following steps:
• State the problem
• Consider Alternatives
• Develop a Model Represent of the Problem
• Align and Integrate the Proposed Solution with Existing Operating Environment and Prevailing Infrastructure
• Implement the Selected Solution
• Conduct an Assessment of the Performance of the Solution
• Re-evaluate the Solution
• Use Feedback Processes to Modify the Solution, if needed
• Continue to Monitor the Solution for Sustainability

Implementing the above steps for curriculum development requires a disciplined approach. In a production environment, the drive to the organizational “bottom line” may provide an incentive for that disciplined approach. But in a non-product or non-profit environment, it is typical to fall prey to cutting corners and not fully pursue the curriculum integration pathway. We hope the proposed methodology of this paper will encourage curriculum developers to follow the disciplined process of systems engineering.

General Framework of the V-Model

The V-Model of Systems Engineering, first introduced in the 1980s, is emerging as the de facto standard for model-based systems engineering approaches. The V-Model is presented in Figure 1, in the context of developing an integrated academic curriculum. The elements in the V-Model relate to a specific problem orientation. The central core of the winged “V” model shows the problem definition, implementation, and verification processes. The right “wing” shows the operations and maintenance, changes and upgrades, and, ultimately, the retirement of the system. The wings are a key structure of the model because it is important to consider the entire lifecycle of the project. Due to space limitation, we will not enunciate all the elements shown in Figure 1. A description of the “Concept of Operations” as the starting point will suffice to get the point across for the other elements. The concept of operations is a foundation document that frames the overall problem and sets the technical, administrative, and managerial paths for the overall project. Its purpose is to clearly convey a high-level view of the problem in terms that stakeholders can understand and relate to. For a curriculum development effort, the inputs and requirements of students (the customers) should be considered, although a weighted level of criticality may be associated with each source of input. We should not compromise the integrity of the curriculum process and characteristics by over-weighing the inputs of stakeholders who may not fully appreciate the overall academic process and program-delivery constraints. The Concept of Operations should clearly state the following from the perspective of the different stakeholders:

• Who
• What
• Where
• When
• Why
• How
Typical questions may include Who are the stakeholders? What are the elements and the high-level capabilities of the proposed system? Where is the implementation supposed to take place geographically or physically? When will the sequence activities involved take place? Why is the proposed integrated curriculum needed? How will the system be operated and sustained?

**Figure 1. V-Model of Systems Engineering for Integrated Curriculum**

**Case Example of V-Model Implementation**

The US Air Force School of Aerospace Medicine (USAFSAM), located at Wright-Patterson Air Force Base, Ohio, is the hub of technical education and training for the full spectrum of aerospace medicine in the US Air Force. These disciplines include flight medicine as the home for the Residency in Aerospace Medicine program. Also included are the initial and advanced training courses as well as consultation and research services for Occupational and Environmental Health and Public Health. Having these functions co-located facilitates integration of operational and research developments into the classroom. A Concept of Operations for USAFSAM education and training courses begins with various stakeholders periodically meeting for a Utilization and Training Workshop (U&TW). In addition to USAFSAM representatives, stakeholders include senior and junior leaders from different elements of the operational Air Force community for the specific career field. During this meeting, the participants discuss and agree to a given course’s purpose and objectives followed by additional details on course delivery modalities (e.g., required classroom and laboratory elements). Even more detailed design includes the specific knowledge outcomes and pre-requisites. In short, the Concept of Operations answers who, what, where, when, why, and how of the course for each stakeholder.
USAFSAM instructors then implement the U&TW’s plan by developing specific lectures and other course material in accordance with current science, policy and practice. By design, USAFSAM’s mission also provides consultative and research services to the operational Air Force. In many cases, the educational and consultative missions work closely together under the same leadership and regularly interact to achieve common goals. Having this expertise co-located enables leveraging of resources for the classroom rarely enjoyed by other educational institutions. Consultants share the latest in policy and practice with USAFSAM’s instructors to ensure curriculum is constantly current. Researchers similarly share their discoveries and innovations with fellow consultants and instructors to ensure operational practice and classroom instruction remains relevant with the latest developments in their fields. One example of this special relationship is the recent development of policy on how to measure and evaluate impact noise such as from gun fire on shooting ranges. Occupational health researchers and consultants realized past policy had not caught up with the state of the science. Collaborations with each other and among leading world-class researchers led to executable policy that afforded the best hearing protection while ensuring operational mission success. This development in policy was immediately translated into relevant classroom instruction.

Testing and validation is an important part of USAFSAM’s educational mission. Instructors design exams to assess student understanding based on previously determined knowledge objectives. However, consultants and researchers are invited to review and critique exams before being administered to students to help ensure they meet the desired objectives. Student performance on the exams and other performance-based measures also serve as continual feedback to the instructors as an indication of successful course administration. True course success, however, lies beyond the walls of the classroom. After students graduate from a USAFSAM course and puts instruction into practice in the field, instructors routinely solicit feedback from both students and supervisors to gauge course efficacy. These stakeholders are asked primarily through formal surveys if graduates have the necessarily understanding and skills to do their jobs adequately. Similarly, instructors seek feedback on how to improve all facets of the course, from the lecture material to laboratory and field exercises. Periodically, typically every two to three years, stakeholders meet again to hold another U&TW for the course. Here the cycle starts again in order to continuously improve the course and ensure USAFSAM meets the ever-changing needs of the operational Air Force community.

AFIT Application of the DEJI Model

The focus of this paper is to show an AFIT application of the DEJI® model, which structurally guides users through the stages of Design, Evaluation, Justification, and Integration. The application illustrated here is for a program realignment and consolidation (PRAC) to accommodate responding to a new interdisciplinary need in USAFSAM and the 711th Human Performance Wing of the US Air Force. The efficacy of the model centers on the fact that it explicitly calls out “Integration” as a cornerstone of a sustainable implementation of a new system. This is essential for curriculum development purposes, which is often subject to “shelf-it-and-forget-it” tendencies once the curriculum is implemented. Figure 2 shows the basic graphical representation of the DEJI model.
The DEJI (Design, Evaluation, Justification, and Integration) model encourages the practice of building relevance into a product right from the beginning so that the integration stage can be more successful. Figure 3 illustrates a specific application of the four-legged DEJI model to an integrated curriculum development effort.

The Design Framework of the DEJI Model

The design of a curriculum for integration should be structured to follow point-to-point transformations. A good technique to accomplish this is the use of state-space transformation, with which we can track the evolution of a curriculum from the concept stage to a final output stage. For the purpose of design, an understanding of the product “state” and product “state space” is essential. A state is a set of conditions that describe the product at a specified point in
time. The state of a product refers to a performance characteristic of the product which relates input to output such that a knowledge of the input function over time and the state of the product at time \( t = t_0 \) determines the expected output for \( t \geq t_0 \). This is particularly important for assessing where the product stands in the context of new technological developments and the prevailing operating environment. A product state-space is the set of all possible states of the product lifecycle. State-space representation can solve product design problems by moving from an initial state to another state, and eventually to the desired end-goal state. The movement from state to state is achieved by means of actions. A goal is a description of an intended state that has not yet been achieved. The process of solving a product problem involves finding a sequence of actions that represents a solution path from the initial state to the goal state. A state-space model consists of state variables that describe the prevailing condition of the product. The state variables are related to inputs by mathematical relationships. Examples of potential product state variables include course enrollment, schedule, output quality, cost, due date, resource, resource utilization, operational efficiency, course throughput, and instructional technology alignment.

For a product described by a system of components, the state-space representation could follow the framework below:

\[
Z = f(z, x); \quad Y = g(z, x),
\]

where \( f \) and \( g \) are vector-valued functions. The variable \( Y \) is the output vector while the variable \( x \) denotes the inputs. The state vector \( Z \) is an intermediate vector relating \( x \) to \( y \). In generic terms, a product is transformed from one state to another by a driving function that produces a transitional relationship given by:

\[
S_s = f(x | S_p) + e,
\]

where \( S_s \) = subsequent state; \( x \) = state variable; \( S_p \) = the preceding state; \( e \) = error component.

The function \( f \) is composed of a given action (or a set of actions) applied to the product. Each intermediate state may represent a significant milestone in the project. Thus, a descriptive state-space model facilitates an analysis of what actions to apply in order to achieve the next desired product state. A graphics representation at this stage may involve the transformation of the curriculum from one state to another through the application of human decisions and actions. This simple representation can be expanded to cover several components within the curriculum framework. Hierarchical linking of elements provides an expanded transformation structure. The product state can be expanded in accordance with implicit requirements. These requirements might include grouping of curriculum elements, linking precedence requirements (both technical and procedural), adapting to new instructional technology developments, following required communication links, and accomplishing reporting requirements. The actions to be taken at each state depend on the prevailing curriculum scenario. The nature of the subsequent alternate states depends on what actions are implemented. Sometimes there are multiple paths that can lead to the same desired end result. At other times, there exists only one unique path to the desired objective. In conventional practice, the characteristics of the future states can only be recognized after the fact, thus, making it impossible to develop adaptive plans. In the implementation of the DEJI model, adaptive plans can be achieved because the events occurring within and outside the product state boundaries can be taken into account.

If we describe a product by \( P \) state variables, \( s_i \), then the composite state of the output at any given time can be represented by a vector \( S \) containing \( P \) elements. That is,
The components of the state vector could represent either quantitative or qualitative variables (e.g., cost, enrollment, instructor availability, and course schedule). We can visualize every state vector as a point in the state space of the product. The representation is unique since every state vector corresponds to one and only one point in the state-space. Suppose we have a set of actions (transformation agents) that we can apply to the product information so as to change it from one state to another within the project state-space. The transformation will change a state vector into another state vector. A transformation may be a change in course prerequisite or a change in the course delivery mode. The number of transformations available for a product characteristic may be finite or infinite. We can construct trajectories that describe the potential states of a product evolution as we apply successive transformations with respect to curriculum values. Each transformation may be repeated as many times as needed. Given an initial state $S_0$, the sequence of state vectors is represented by the following:

$$S_n = T_n(S_{n-1}).$$

The state-by-state transformations are then represented as $S_1 = T_1(S_0); S_2 = T_2(S_1); S_3 = T_3(S_2); \ldots; S_n = T_n(S_{n-1})$. The final State, $S_n$, depends on the initial state $S$ and the effects of the actions applied. Of course, in a curriculum development environment, the work is done mostly on qualitative basis rather than the technical pathway described above. This aspect of the DEJI model is that it keeps curriculum developers cognizant of the elements that should be considered in the process.

**DEJI’s Evaluation Stage of an Integrated Curriculum**

Assessment is the key requirement in an integrated curriculum. Instructors, particularly at the graduate level, often resist the imposition of assessment requirements in their courses. But the point of using a systems model is to impress upon instructors the importance and value of conducting course assessments. The evaluation of the assessment results will guide the instructors in the proper directions for course improvement efforts. A curriculum can be evaluated on the basis of delivery cost, instructional quality, course delivery cycle, and relevance for program outcome requirements. There are many quantitative metrics that can be used in evaluating a product at this stage. Learning curve analysis is one relevant technique that can be used because it offers an evaluation basis of a curriculum with respect to instructional proficiency over time, as more and more deliveries of the course are implemented. Learning curves are particularly useful for designing curriculum whose lifecycles stretch into the future and more subject to changes in instructional modes and job market needs.

**Justification Stage for an Integrated Curriculum**

We need to justify a curriculum on the basis of quantitative value assessment. The Systems Value Model (SVM) is a good quantitative technique that can be used for justifying decisions and actions in an integrated curriculum on the basis of value-adding needs. The SVM model provides a heuristic decision aid for comparing alternatives. For example, course substitutions in an integrated curriculum need to be justified on the basis of the value-added or value-diminished impact of the substitution. Value is represented as a deterministic vector function that indicates the value of tangible and intangible attributes that characterize the integrated curriculum. It is
represented as \( V = f(A_1, A_2, \ldots, A_p) \), where \( V \) is the assessed value and the \( A \) values are quantitative measures or attributes. Examples of curriculum attributes are instructional quality, course throughput, compatibility with instructional infrastructure, instructor proficiency, course modularity, course delivery cost. Attributes are considered to be a combined function of factors. Examples of curriculum factors are enrollment demand, scheduling flexibility, student acceptance, student satisfaction, and classroom environment. Factors are themselves considered to be composed of indicators. Examples of indicators are student course loads, frequency of course offering, instructor responsiveness, back-up instructors, and graduation requirements. By combining the above definitions, a composite measure of the operational value of an integrated curriculum can be quantitatively and/or qualitatively assessed. In addition to the quantifiable factors, attributes, and indicators that impinge upon overall curriculum value, the human-based subtle factors should also be included in assessing overall curriculum value.

**Case Application of the DEJI Model**

The systems-based approach to curriculum development was successfully used for curriculum integration in the Department of Systems Engineering & Management at the Air Force Institute of Technology in 2011. Figure 4 illustrates how the elements of the integrated curriculum are factored into an enhanced curriculum that caters to the various student stakeholders of the department and mitigates the previously siloed delivery of options in the department. The nomenclature in the figure are:

- ENV (Department Code)
- GES (Graduate Environmental & Science Engineering program)
- GEM (Graduate Engineering Management program)
- GSE (Graduate Systems Engineering program)
- CE GEM (Civil Engineer GEM program)
- GRD (Graduate Research & Development program)
- GIR/ESI (Graduate Information Resources program with Enterprise Integration Track)
- GCA (Graduate Cost Analysis program)
- GSE DL (Distance Learning delivery of GSE program)
- OpTech (Certificate program for Operational Technology)
- HSI (Human Systems Integration) Track for 711th Human Performance Wing (Specialized Track for US Air Force)

The HSI track is a special-delivery program that caters to the specific workforce development requirements for an external customer by leveraging an integrated coalescing of program elements that exist in the department. In the process of doing a systems-based remodeling of the programs, it was found necessary to integrate, eliminate, or redesign some of the legacy programs. Without an over-arching systems approach, this accomplishment would not have been possible. Key to this process was an in-depth analysis of the value of each program to the overall department mission. With a clear delineation of the values (or lack thereof) of some programs, it was possible to justify changing previously-sacred programs as well as realize synergistic relationships among the various programs and tracks.
Assessment of the Application of the DEJI Model

As illustrated in Figure 4, a collaborative effort of program realignment and consolidation was achieved through a process of bringing everyone on board by using structured stages of communication, cooperation, and coordination via a systems-thinking approach. Without the systems model, the mutual accomplishment of the effort would not have been possible or would have taken an inordinately long time to get faculty agreement. Through the DEJI model, a win-win end result was presented to everyone. This simplified the cooperation process. With cooperation assured, the team was able to coordinate and integrate efforts in the final stage of the DEJI model. The human-systems-integration curriculum that emanated from the interdisciplinary effort is still going strong and meeting the needs of the US Air Force.

Conclusion

The proposed approach of the DEJI model will facilitate a better alignment of curriculum design with future academic needs. The stages of the model require research for each new curricular element with respect to DEJI. Existing analytical tools and techniques can be used at each stage of the model. Presented below are guidelines and important questions relevant for curriculum integration.

• What are the unique characteristics of each component in the integrated curriculum?
• How do the characteristics complement one another?
• What physical interfaces exist among the components?
• What data and information interfaces exist among the components?
• What ideological differences exist among the components?
• What are the data flow requirements for the components?
• What internal and external factors are expected to influence the integrated curriculum?
• What are the relative priorities assigned to each component of the integrated curriculum?
• What are the strengths and weaknesses of the integrated curriculum?
• What resources are needed to keep the integrated curriculum operating satisfactorily?
• Which organizational unit has primary responsibility for the integrated curriculum?

References


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