AC 2009-2125: COMPLEX SYSTEMS: WHAT ARE THEY AND WHY SHOULD WE CARE?

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Complex Systems: What Are They and Why Should We Care?

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Abstract

Recently, engineering education research has begun to implicitly employ a discourse of complex systems with terms such as emergence, adaptability and flexibility permeating the discussions. This paper proposes that complex systems offer a unifying perspective for engineering education researchers and will help the discipline move towards a better understanding of the enterprise of engineering education. To explore this issue, the authors will first describe the major characteristics of complex systems and then evaluate whether engineering educators are indeed describing the attributes of engineering education systems as aligning with those of complex systems. Illustrative examples will be provided that show how the framework of complex systems promotes a better understanding of the some of the discrepancies and tensions within the discourse of the engineering education community. This preliminary document analysis research project involves a review of editorials in engineering education journals published in 2008 to determine whether these contributions by the leaders in the engineering education research community are pointing towards a need for a complex systems approach to engineering education practice and research. Specifically, this research explores the validity of the following hypothesis: complex systems provide a needed unifying perspective for engineering education. The preliminary research analysis answers the following research question: To what degree doleaders in engineering education intentionally or implicitly use concepts and language of complex systems when describing current and desired engineering educational systems? While this research is focusing on whether the engineering education is indeed a complex system, future research will be needed that takes a complex systems approach through developing methodologies and models so that researchers can begin to develop a deeper understanding of the nature of the engineering educational system and how to begin to facilitate changes in that complex system in practice.

Context and Background

Since the publication of the Green Report in 1996[1] there has been a strong push within engineering education practice and research to better prepare engineering graduates for the socio-technical world in which engineers are embedded. Surprisingly, this drive to better align engineering education with the socio-technical world began many decades earlier with the Carnegie Foundation's 1918 publication of A Study of Engineering Education[2]. In spite of the effort in recent years to operationalize the student learning of the necessary competencies (e. g. through ABET outcomes[3]) there is a disconnect between what students learn in engineering, what we measure that they learn, and what they ought to be learning. This could be partially due to the shortcomings of the theoretical perspectives that we use to understand the engineering education enterprise.

Many of today's engineering education researchers have emerged from a purely scientific and engineering background and have thus leaned towards a positivistic perspective of understanding and researching the enterprise of engineering education. In recognition of these limitations there has been a push in the discipline of engineering education research to include collaborators from the social sciences and humanities. While this has begun to help by refining our theoretical perspective of engineering educational research studies, there still seems to be a disconnect between research, practice, and management of the enterprise of engineering education, and there is still a tendency to control engineering education from the top-down.

Recently, the Engineering Education Research Colloquies proposed an agenda for engineering education research with one of the suggested research areas being "Engineering Learning Systems[4,5]." Additionally, at the recent Research in Engineering Education Symposium, many leading researchers in the engineering education community expressed a need for a complex systems approach to engineering education research and many used language associated with complex systems in their discussions of engineering education. Although the language of complex systems is entering the discourse of the engineering education research community, there is still little understanding of complex systems and how concepts of complex systems can inform engineering education research.

In this paper, the authors propose that complex systems theory is an alternative, unifying perspective that is potentially useful for advancing the emerging discipline of engineering education research. To determine the degree to which the discourse and concepts of complex systems are already used in engineering education, recent editorials were examined and coded to determine how leaders in the field of engineering education are describing the enterprise of engineering education. This preliminary analysis enables the authors to determine whether complex systems is a useful, unifying perspective for the emerging discipline of engineering education research. The following sections will first provide a needed synthesis of the literature associated with complex systems and will subsequently describe a preliminary, ongoing study designed to determine the extent to which engineering educators are embracing concepts and language inherent in complex systems.

Theoretical Framework

Engineers are very comfortable working in a world based on the basic philosophy developed by Francis Bacon, Renè Descartes, and Isaac Newton. While a strict adherence to this Newtonian philosophy and the scientific method has served society well in fields of engineering, physics, chemistry, and biology, it has, however, limited application to systems that involve humans, such as educational systems[6]. Traditional engineering disciplines have matured largely due to their success using the scientific method in isolating objects from their environment, learning their behaviors under tightly controlled conditions, and subsequently designing systems of parts that maintain these conditions and provide a function to society that is predictable, controllable, and safe for humans. However, such reductionist approaches to education are severely detrimental if necessary relationships are severed in order to isolate individuals or subject matter. This paper proposes complex systems as an appropriate and needed lens for engineering education research.

While this paper is not suggesting that the rigor of Newtonian thinking be abandoned, it is suggesting that the tendency to apply mechanistic, reductive analysis to complex systems should be addressed. According to Bertalanffy[7], a founder of General Systems Theory, it is necessary to meet the following two conditions in order to effectively apply mechanistic analysis to a system: 1) the interactions between the parts are nonexistent or weak and 2) the relations describing the behavior of a system must be causal (linear, cause and effect). In educational systems, these conditions are rarely, if ever, met; therefore a systems approach to understanding educational systems is going to be proposed in this paper.

On the abstract level of systems theory, a complex system is distinguished from a merely complicated one by a number of characteristics. The core insight that describes complex systems is as old as the works of Aristotle: “The whole [of a complex system] is more than the sum of the parts”[8,9]. This means that a complex system on a global level can have properties which are not “held by any of the components of the system”[10] - these are called emergent properties.

The enterprise of engineering education, as defined here, spans the scales of the classroom, curricula, institution, national education systems, global education market, professional practice, and society. For the purposes of clarity, we will describe specific examples of each of the following characteristics of complex systems. The following section analyzes the general characteristics of complex systems drawn from the existing literature[10,11,12,13] and examines the extent to which they are applicable in the context of engineering education.

1. Large Number of Elements
   One main characteristic associated with a complex system is that it “consists of a large number of elements”11. Looking at engineering education at a typical university, we can certainly identify a large number of agents, or individuals, namely students, teachers, and anyone interacting with those main agents within the framework of the system.
2. Interaction of Elements
   The existence of a large number of elements alone, however, does not distinguish a complex system from one that is merely complicated. A key factor in defining complexity is the interaction of the elements of the system and certain characteristics of this interaction. In the context of engineering education, the fact that individuals interact

is almost a trivial statement since the purpose of education is to impart knowledge through communicating information.

   a) Rich Interaction
      The interaction of elements of a complex system is described as "fairly rich"[11]. This means that "any element of the system influences, and is influenced by, quite a few others"[11]. For engineering programs at a higher education institution, this certainly holds true as teachers interact with students via learning activities such as courses, tutorials, assessment, and other feedback mechanisms. Beyond the teacher/student interaction, students communicate with other students or academic staff on various occasions and in a number of different ways.
   b) Non-Linear Interaction
      The interaction of elements of complex systems is generally non-linear. This means that small influences can have large effects in the system and conversely, that large influences can have small effects. In the educational context, this can be verified for example by looking at the process of formal teaching: Generally the same amount of teaching will not result in the same amount of learning across all students in the class.
   c) Short Range Interaction
      Elements of complex systems typically interact with their immediate neighbors (not necessarily to be understood in a spatial sense). This does not mean that there are no long-range influences on other elements. The trace of the system, however, is usually transmitted over a chain of local elements. In the context of the interaction of individuals in education, the direct transmission of information is evident. In a local sense, it can be direct communication between teacher and students; this can occur in lectures, or in a non-spatial sense, through teacher student interaction via distance learning for example. Also, higher level institutional objectives or regulations are ultimately transmitted and implemented through a chain of interactions between individual teachers, students, and/or staff.

3. History Dependant
   As opposed to deterministic systems which can be comprehensively characterized by their initial conditions, the behavior of complex systems is influenced and determined by its history. With respect to student learning in engineering education, several aspects evidently demonstrate this dependency on the system's history. Institutional tradition is an element of the system's history that explicitly shapes education. On an elementary level, the history of individual agents also enters the system. For example, what is taught today is strongly influenced by what today's teachers were once taught. Similarly, each student brings a history and, thus, certain characteristic into the system.
4. Feedback Loops
   The interaction of elements of complex systems usually contains stimulating or inhibiting feedback loops. This feedback causes the activity of an individual element to reflect back on itself. One aspect of engineering education that illustrates the existence of feedback

loops is the element of formal assessment. A very simplified way to illustrate this is looking at how student learning would ideally lead to good grades (positive feedback) which in turn leads to increased motivation and ultimately more learning.

5. At a local scale, complex systems are in a constant state of flux
   Within complex systems, the local relationships among agents are constantly changing and agents themselves are changing their roles or moving into or out of the system in short periods of time. In other words, there is considerable, varied activity at a local scale. Within engineering education there is much happening at a local scale within a single day or even an hour. There are students in class listening to lectures, working on homework, conducting research on a topic for a project, working in the computer lab, writing papers, relaxing in the student lounge, talking in the hallways, visiting faculty's office hours, talking on the phone to friends and family, working at their part-time or full-time job, and even relaxing at their apartments. There is considerable interaction that occurs at this local scale within a complex system. These interactions occur within and are embedded into curricular, administrative, and professional structures at other levels of the engineering educational enterprise.
6. At a macro scale, complex systems have emergent patterns that evolve slowly over time
   While the relationships among agents at a micro-scale are rapidly changing, the larger, macro-scale properties of the system are stable. This complex system characteristic results in an inherently stable system, i. e. changes can occur within the system without necessarily causing a change to the overall system. These patterns evolve so that they are adaptable to changes beyond the open boundaries of the system. Within engineering education, changes occur at a micro- and agent level often as students enter the program, leave the program, and graduate while faculty and instructors are hired, leave the university, and retire. While these changes are occurring at a micro-scale, the system still retains its overall properties. However, it is important to note that the system constantly evolves and changes over longer time scales[14] as it is an open system that is interconnected within the fabric of socio-technical systems. These changes are temporally much slower than the changes described above on smaller scales.
7. Open Systems
   Complex systems are generally described as open systems which interact with their environment. This entails that for a complex system the definition of the boundaries is not self-evident and this framing strongly depends on viewpoint of the observer. At a local level, the system of interest could be defined as the institution, while in a global education market the interactions and mutual influences of different institutions could be of interest. A detailed analysis of viewing a national education system as the complex system is described in *Two roles for Complex Systems in Education*[15]. Also, universities as a part of larger social systems are certainly open to other aspects of society, such as political or economic systems. This does not only include interaction on the level of the

organization but also the fact that students and teachers are part of those other social systems.

8. Adaptability/ Flexibility

   The local interactions, emergent patterns, and open boundaries that are characteristic to complex systems lead to vital characteristics of complex systems: adaptability and flexibility. Complex systems are flexible so that they can evolve and adapt to changes from within as well as outside its boundaries. This is an important characteristic as it enables the system to evolve in response to changes within the system, e. g. the changes in relationships between agents and their resulting emergence, and to changes beyond the boundaries of the system, e. g. changes to the socio-technical landscape in which the enterprise of engineering education is embedded. Within engineering education, there are inherent links to professional practice and engineering education practice which have evolved in response to these changes. An example of this is apparent in the recent thrusts to include communication in the engineering education curriculum as a result of the inputs from industry and the profession[1]. One would be hard pressed to find an engineering education program that does not include written reports and oral presentations. Currently there is much top-down and external control within engineering education practice, e. g. accreditation requirements and curricular structures, and this control results in structures that do not necessarily embody characteristics of adaptability, flexibility, and emergence.
9. Complexity is Not Embedded in a Single Element

   The complexity of a system emerges from all of the previously described characteristics, i. e. the complexity is not embedded in a single element of the system. More specifically, the structure of the system is embedded within multiple, interconnected levels[16]. Learning experiences are embedded within instructional levels, within administrative levels, and within political levels. In practical terms, this means that a single agent in the system does not “know what [is] happening to the system as a whole. " For example, instructors are not fully aware what information is transmitted in other lectures, how that influences the student learning in their class, and how that learning and teaching aligns with the professional world.
10. Emergence

    Arguably the most important characteristic of a complex system is the emergence of patterns and properties. This emergence occurs not as a result of one agent within the system but as a higher order phenomenon that occurs as agents and scales interact with one another[17]. Such higher level phenomena "emerge as a result of nothing more than the interaction between the various elements of the system,"[11] which can in turn be stimulated by the outside influences. This strongly suggests that engineering education does exhibit complex behaviors – in particular, the emergence of global properties - as do other complex systems such as neural networks[12] or national economies[14]. A focus on the objects alone (breaking down a system to its parts) within complex systems provides a

> very limited view of the system and will result in little understanding of the potentials of the system, that result from the rich connections and diversity of agents, as well as the open boundaries of the system. The interaction between agents and levels within a system results in emergent system attributes that are not caused by any single agent or an imposing structure. This emergence transcends the summed attributes of all agents within the system; i. e. the whole is greater than the sum of the parts.

While this outline of complexity in relation to engineering education is necessarily brief and somewhat simplified, it nevertheless establishes the key elements and how they interact. Other phenomena such as student's competence formation, student retention, and the like can be explained from the characteristics of the system as described by these ten points.

Research Methodology

The previous sections presented the hypothesis that complex systems concepts provide a framework to shed light on current issues within the enterprise of engineering education. More specifically, this paper contends that engineering educators are implicitly using complex systems notions to discuss developments in the field or to frame research endeavors, and the discourse of complex systems will help advance these discussions and research endeavors. To provide the theoretical basis for the exploration of this hypothesis, the framework of complex systems and their characteristics were presented.

To test this hypothesis and demonstrate the usefulness of the proposed framework, this ongoing study examined editorials from leading journals in the area of engineering education research. The specific focus of the qualitative analysis was on the ways in which engineering educators describe or discuss the enterprise of engineering education. The enterprise of engineering education was defined in the most general sense to include, for example, the following two dimensions: the first ranges from discussions of classroom developments to considerations of national or global education markets and the second dimension ranges from deliberations of the achievement of learning outcomes to contributions concerning the role of engineering within society. Using this broad definition, the research was able to capture the widest possible range of contributions that implicitly use complex systems concepts in the sense of an exploratory study. The selection of editorials from leading journals in the area of engineering education (Journal of Engineering Education and International Journal of Engineering Education) reflects thinking at the leading edge of the field and is thus likely to be an indication as to whether complex systems thinking is entering the discourse of the research community. The initial list of journals included all of the engineering education journals on the American Society for Engineering Education website. Many journals were not included because they did not meet the following criteria: 1) inclusion of editorials, 2) published in 2008, and 3) the scope and mission include the enterprise of engineering education. In the pilot study presented here, we focused on editorials from 2008 editions of the respective journals. In addition to being a pragmatic choice, this also takes into account the accelerating development in the field[5].

The analysis was based on an interpretive analysis procedure using the qualitative research software NVivo 7. Through constant comparison and iterative re-reading of the editorials, a number of categories of ways in which the authors describe the enterprise of engineering education emerged. Examples for the categories that emerged during this first stage of the project are:

- How students develop into engineers
- How engineering universities are situated in society
- Engineering education research is / needs to be interdisciplinary

Results

Once the categories of descriptions were established and proved stable in their application to further sources, the next step of the research explored the relationship of the categories to the characteristics of complex systems presented earlier. This exploration took the form of a mapping between the coding categories and the characteristics of complex systems. It was, however, not expected nor desired that this establishes congruence between the two. Rather, this process served to explore similarities as well as tensions between a systems understanding and the concepts used in the current debate of engineering education.

In this early stage of the research and for the purpose of this paper, the aim of this exploration was to demonstrate the usefulness of framing engineering education from a complex system perspective. More specifically, this means to identify where engineering educators are implicitly employing these notions in very diverse areas of engineering education. In this context, complex systems thinking can thus provide a unifying framework for these diverse and seemingly disparate research endeavors. Additionally, exploring instances where more traditional views of engineering education conflicted with a complex systems perspective could lead to insight into a number of educational phenomena or conundrums that could not be previously resolved.

The sections below demonstrate the explanatory power of the complex systems framework on the basis of three illustrative examples and the mapping of their preliminary coding categories to the elements of complex systems thinking.

I. How students develop into engineers.

This coding category provides an example of tensions or “fault lines” in the current discourse within the engineering education community that can be better understood from a complex systems perspective. To illustrate the contrasting views of how students develop into professional engineers, the following two illustrative examples from the data are considered.

Rogers[18] describes

> *"the importance of developing efficient processes through understanding how the curriculum is mapped to the outcomes and making a purposeful decision about where the assessment data should be collected. "*

In contrast, Vest[19] states that

> *"although we cannot know exactly what they should be taught, we can focus on the environment in which they learn and the forces, ideas, inspirations, and empowering situations to which they are exposed. "*

The first quote speaks of the desire and need to structure students' education in meaningful ways. The focus is on implementing a curriculum that achieves the desired learning outcomes in a controlled and measurable way. This helps align engineering education with the requirements of current and future practice in the spirit of the visionary re-definition of the goals of engineering education that was outlined in the Program Outcomes[3]. The second quote, in contrast, discusses the development of students into engineers with a focus on the students' educational experience rather than on the teachers' intent and the structures implemented. This acknowledges the influence of the environment in shaping engineering students' professional way of being – processes that cannot be structured or implemented in a controlled fashion[20].

From a complex systems perspective, these seemingly conflicting perspectives on student learning point to questions of the different scales of interaction within a complex system (see points 3 & 4). The discussion of the mapping of learning activities to outcomes in the first quote refers to large scale structures on a macro level of the educational system such as the curriculum in an institutional or national sense. The contemplation of the influence of the educational environment on students emphasizes the learning that emerges from small scale local interactions within the system.

The complex systems perspective outlined above suggests that the views presented in the two quotes are not necessarily contradictory but rather focus on different scales or aspects of the same system – namely large scale structures and small scale interactions. This unifying perspective also sheds light on ways in which the focus on students' experiences and a view to a purposeful structure of the education system can be combined. The systems perspective implies that no rigid control of student learning is possible or desirable; this does not, however, suggest that engineering educators do not have any structuring influence on student learning. Put differently, structure and educational intent are necessary but they should allow for flexibility and growth to emerge from the complexity of the system. In the area of complexity thinking authors[21] speak of the need to "nudge" the system into the desired direction rather than trying to force it into a rigid process. Examples of such flexible educational settings that are currently implemented are programs for creating situated learning experiences[22] or using problem-based learning approaches[23,24,25].

II. How engineering education is situated in the larger societal context

The contributions in this category discuss the response of engineering education to the rapid societal, technological and economic changes of the past decade. This reflects the national and global reform efforts that were initiated by, for example, the ASEE report[3] "Engineering education for a changing world. " The complex systems view presented here can provide a useful lens to understanding the magnitude and the particular characteristics of this challenge.

Sheppard *et al.*[26] explain

> *"As a consequence, what engineers do is increasingly and intimately involved in creating and shaping this multi-faceted and highly-integrated world."*

The fact that this discussion was still very prevalent in the 2008 data set is an indication that those issues are still, or even ever more, pressing today. The data coded for this category represents the dilemma of engineering education that results from the need to prepare engineering students for a changing and uncertain professional world with essentially unknown characteristics and requirements.

From a complex systems perspective, the open nature of systems provides a way of understanding this dilemma. Engineering education is open to a number of other systems that are in themselves complex. An example is the constant 'flow' of students through the system. New agents come into the system with diverse backgrounds and preconceptions and thus change the fabric of the system. As an example we might consider the debate around the challenges of educating students of today's generation. Graduates leave the system with an assumed uniform set of competencies but are diverse in their personal and professional qualities. These graduates enter a professional world that is slightly different from what their peers experienced only a few years earlier and is radically different from the professional environment their instructors might have experienced[27].

To address the openness of the system suggests implementing flexible and emergent learning opportunities. These ideally help students integrate the rigid elements of learning content that are necessary into a fluent whole that can adapt to the changing needs of professional practice[28]. In concrete terms this could mean to foster the openness on an agent level of the system. This can take the form of facilitating students' work or interaction with the wider community. Existing examples of such efforts are service learning programs that successfully help students contextualize their learning in a social setting.

A second conclusion to draw from the recognition of the open nature of the education system is that outside influences are simply inevitable. The students bring different backgrounds or preconceptions to the educational process while the university simultaneously is influenced by various social and political processes. The complex systems perspective suggests embracing and creatively utilizing this diversity rather than treating it as a perturbation to a rigid process. In the current education system some diversity programs, such as Women in Engineering and Minority Engineering Programs, are examples of utilizing the diversity of students to benefit the overall educational process[29].

III. Engineering education research is / needs to be interdisciplinary.

This category provides an example of tensions in the current discourse within the engineering education research community regarding research methods, e. g. the need for interdisciplinary research methods and the tension between qualitative and quantitative research methods. By considering the relationships between agents and scales, these tensions can be better understood and unified from a complex systems perspective. To illustrate the tensions that have developed within this debate concerning research methods, the following illustrative examples from the data are considered.

Wald[30] describes the following

> *"The creation of engineering education departments, and the increased emphasis on interdisciplinary connections, studies and globalization of dissemination and cooperation activities is a sign that something is brewing in the direction of a community of engineering education which tries to find its feet."*

Michel[31] explains that

> *"the concept [sustainability] only gradually gained acceptance: its rather qualitative nature [of methods] did not make it very appealing for the quantitative mindset of natural scientists and engineers"*

These quotes describe the current tension in the engineering education research community to find the most appropriate research methods. The first quote by Wald describes the engineering education research community as trying to "find its feet," which suggests that the community is looking beyond its disciplinary boundaries for a theoretical perspective. Borrego and others have discussed this sense of uncertainty in describing the emerging discipline of engineering education[32,33]. Moreover, Michel's quote describes the tension between quantitative and qualitative research methods, especially in a field dominated by a quantitative mindset. Engineers' historical quantitative mindset has likely helped push engineering educational researchers outside of the traditional disciplinary boundaries. The research paradigm is currently being negotiated and discussed within this community which has led to much debate over rigorous research and research methods within engineering education.

This category relates to complex systems as described by the interactions characteristic above (see point 2). When describing a complex system one could take an average view of the system with quantitative research methods or one could look closer at the rich interactions in detail with qualitative research methods. While these research methods have different aims and purposes, they are both helpful in understanding the behavior of the one complex system. For example, a swarm of bees could be considered as a complex system. The quantitative researcher would average the movement of the bees to determine where the swarm of bees travels while a qualitative researcher may look at the movement and relationships between a small number of bees to better understand their behavior at a more detailed scale which would lead to a richer description of the bees movement.

In the context of engineering education research, the complex systems perspective suggests that the apparent dichotomy between research methods could be resolved into a coherent research paradigm. This perspective could help unify these seemingly disparate ways of doing research and demonstrate that these research methods are not separate and in tension but part of a continuum. This is in line with the feedback from participants in the Rigorous Research in Engineering Education workshops, as they preferred a continuum over a dichotomy of research methods[33]. These are different ways of looking at a system and consequentially examine the interactions (see point 3) each with a different intent and purpose. This is a step towards negotiating this tension in the engineering education and education community.

Conclusion

This paper contends that complex systems thinking provides a useful framework for the advancement of engineering education practice and research. In fact, the data collected from editorials of engineering education journals indicated that engineering educators are already implicitly using complex systems concepts in discussing current issues in the field and in framing research projects. To explore this hypothesis, the paper first provided an overview of the characteristics of complex systems, and secondly it presented preliminary results from the qualitative analysis that categorized the ways in which leaders in the field describe or discuss the enterprise of engineering education.

To demonstrate the usefulness and explanatory power of the complex systems framework, the paper presented three coding categories (Students development into professional engineers, engineering education in the societal context, and interdisciplinarity of engineering education research) with illustrative examples from the data. The exploration of the similarities and tensions between these categories of description and the complex systems characteristics demonstrated that the complexity framework provides deeper insight and a unifying perspective for a variety of current issues in engineering education and engineering education research.

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