Teaching and Assessing Engineering Design Thinking with Virtual Internships and Epistemic Network Analysis

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Abstract

One of the goals of engineering education is providing students with authentic and meaningful design experiences, as well as assessing the development of design thinking. In this paper, we review virtual internships, online simulations of 21st century engineering design practice, as one method for providing students with authentic experiences. To assess the development of design thinking in virtual internships, we used epistemic network analysis (ENA), a tool for measuring complex thinking as it develops over time. We provide an example of how ENA can be used to quantitatively measure student teams' qualitative discourse in a virtual internship program in order to assess performance in engineering. The combination of virtual internships and ENA provides opportunities for students to engage in authentic engineering design, receive concurrent feedback on their design thinking, and develop the identity, values, and ways of thinking of 21st century professional engineers.

I. Introduction

The pool of engineers in the United States is neither large enough nor diverse enough to meet the needs of a growing high-tech economy, and student interest in pursuing engineering degrees is declining [1, 2]. In addition to improved recruitment, better retention of students who express interest in engineering can address this national need. The largest decrease in enrollment in engineering degree programs occurs between the first and second years. Because engineering programs receive few transfers from other majors [3, 4], first-year courses are critical to retention in engineering degree programs. If the goal of engineering education, as Dym and colleagues [5] suggest, is to produce engineers *who can design*, then providing students with early opportunities to engage in authentic engineering design work may improve graduation rates and retention in the profession. In support of this claim, research on engineering education [6–10] has shown that students who have *meaningful experiences of authentic engineering practice* are more likely to persist beyond the first year of an engineering degree program than students who have not had such experiences.

In this paper, we review one method of providing authentic experiences for students—virtual internships. We examined students' attitudes towards engineering as well as their performance in virtual internships. To assess performance in engineering, we used epistemic network analysis, a tool for modeling and measuring complex thinking as it develops over time. Our aim is to show that using virtual internship programs together with epistemic network analysis allows for the implementation of authentic engineering experiences for students with real-time feedback on their development of engineering thinking early in their undergraduate education, laying the foundation for life-long professional development for 21st century practice.

II. Virtual Internships for Engineering Education

In recent decades, many engineering programs have developed first-year cornerstone design courses in order to increase retention, but these design projects are typically not based on authentic practices or real-world problems. In most cases, it is too difficult, too dangerous, or too expensive for first-year students, who lack the requisite training and experience, to solve such problems. Similarly, internships, cooperative research programs, and other work-based learning opportunities, which help students begin to form the identity, values, and habits of mind of professional engineers, are often inaccessible to first-year students because they do not yet have the skills and knowledge to contribute to professional engineering work. Even when internships are available, the quality of mentoring is variable, some do not provide students with opportunities to do authentic engineering work, and there are not enough high-quality internships to go around [11]. Furthermore, in both cornerstone design courses and internships, it is difficult to assess whether students are learning to solve engineering design problems in the way professional engineers do [12, 13].

Our prior research [10, 14–22] has shown that engineering virtual internships, which are online simulations of authentic engineering design practice, can address these challenges. For example, in the virtual internship *Nephrotex* [20] first-year students work as materials engineers at a fictitious biotechnology company to design an ultrafiltration membrane for hemodialysis equipment. Students work both individually and in teams, performing tasks that they would do in an ideal internship: reading and analyzing research reports, designing and performing experiments, responding to client and stakeholder requirements, writing reports, and proposing and justifying design prototypes, all within a self-contained workplace simulation.

The activities and team interactions all take place through the web platform that supports the internship. Students begin by logging into the company website, which includes an email and chat interface. Acting as interns, they send and receive emails to and from their supervisor (a non-player character) and use the chat window for instant messaging with other team members and their assigned design advisor.

After conducting background research within the Nephrotex website, interns examine company research reports based on actual experimental data with a variety of polymeric materials, chemical surfactants, carbon nanotubes, and manufacturing processes. After collecting and summarizing research data, interns begin the actual design process using the simulated engineering drawing tool (figure 1a). First individually and then in teams, students develop hypotheses based on their research, test these hypotheses in the provided design space, and analyze the results provided. The design space in Nephrotex contains four inputs and five outputs (figure 1b).

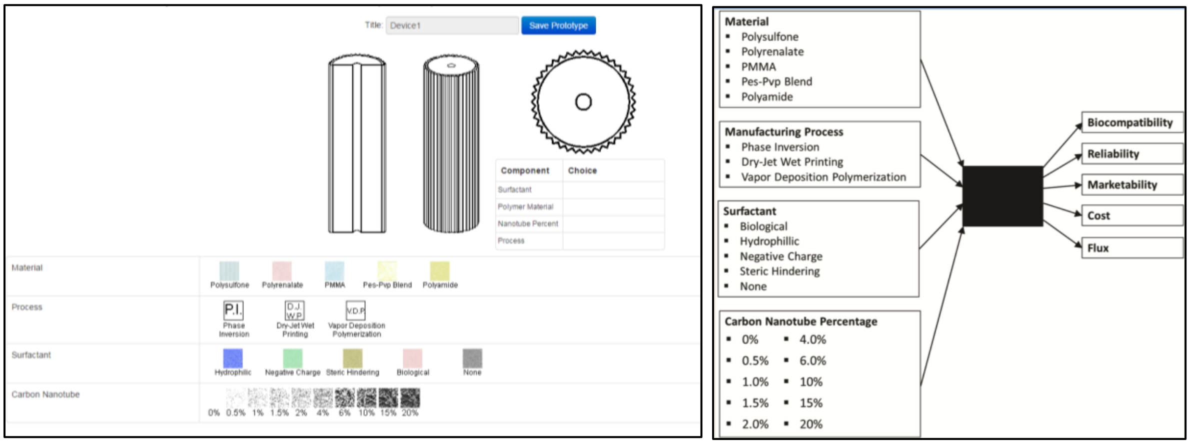

Figure 1: (a) The simulated engineering drawing tool in *Nephrotex.* (b) A representation of the design space (the inputs and outputs) in *Nephrotex.*

Interns also learn about internal consultants within the company who have a stake in the outcome of their prototype design. These consultants value different outputs, which are essentially performance criteria. Each of the five internal consultants in Nephrotex prioritizes two output parameters and identifies specific threshold values for each output. For example, the clinical engineer would like a high degree of biocompatibility and high flux, and the manufacturing engineer would like a device with high reliability but low cost. The consultants' concerns are often in conflict with one another (e.g., as flux increases, cost also increases), reflecting the conflicting demands common in professional engineering design projects.

During the second half of the internship, students switch teams and inform their new team members of the research they have conducted thus far. In the new teams, students test more devices, analyze the second iteration of results, and decide on a final prototype. During the final days of the internship, students present their prototypes and justify their design decisions to the class and instructor. They then complete an exit interview with survey questions about their attitudes towards the engineering profession.

Virtual internships, such as *Nephrotex*, thus enable first-year students to experience authentic engineering design practice, with high-quality mentoring and regular feedback, in a realistic, collaborative learning environment. In general, virtual internships give students the opportunity to (a) engage in meaningful, consequential engineering design practice; (b) solve a complex engineering design problem; and (c) begin to see themselves not as engineering students but as student engineers. Because all student and mentor actions and interactions occur in a closed system, they can be automatically recorded in log files, allowing for analysis of learning outcomes and processes and of the extent to which students are developing, in addition to core engineering knowledge and competencies, the identity, values, habits of mind, and other attributes of professional engineers.

III. Developing and Assessing Engineering Thinking

Although virtual internships allow for the collection of student actions and interactions, using these data to assess the development of engineering design thinking is a significant challenge. Existing education standards, such as the ABET [23] standards, offer little help. ABET criterion 3c, for example, states that students, upon completing a bachelor’s degree in engineering, should display “an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.” Typical of existing standards, this provides guidance neither on how to help students develop this competency (i.e., curriculum design) nor on how to determine if students have met this goal (i.e., assessment). Effective educational assessments classify what students say, do, or produce in a particular setting to make broader inferences about their abilities. Developing criteria for assessment purposes thus requires consideration of the social setting in which the assessment is developed and applied and of how evidence of learning will be defined and measured.

To characterize learning in virtual internships, we developed a model based on the learning science theory of *epistemic frames* [24–26]. Epistemic frame theory suggests that the characteristics of engineering professionals’ design thinking are denoted by specific patterns of connections among the knowledge, skills, values, identity, and ways of making decisions (the epistemic frame elements) that characterize authentic engineering practice. In other words, realistic engineering practice is characterized not by a collection of isolated elements but by a network of them, an epistemic frame, that makes the individual elements meaningful, actionable, and persistent. The associations that a person makes among elements in an epistemic frame can be modeled with epistemic network analysis (ENA) [27–32], a psychometric tool that can assess evidence from student participation in virtual internships to characterize how they think while solving a complex design problem. ENA creates a network model in which the nodes of the network represent the key components from a domain. The links between these nodes quantify how often a person has made connections between these elements at some point in time. In this way, ENA models the development over time of an individual's epistemic frame and, in turn, quantifies and assesses their ability to think and work like professionals.

The technical details of ENA have been provided elsewhere [10, 30, 33]. In short, ENA measures the connections among discourse elements, or codes, by quantifying the co-occurrence of those elements within a defined window of utterances. These windows are defined such that the utterances within a given window are assumed to be closely related topically. In virtual internships, we typically define windows in terms of the activities in the internship, such as background research or team design discussions.

We have explored the implementation of virtual internships and ENA in several studies. In 2010, we implemented *Nephrotex* as part of a first year introductory engineering course. Based on this preliminary implementation, Chesler and colleagues [34] described the design criteria for creating a virtual internship in engineering and provided proof-of concept data on the engineering learning that occurs with use of Nephrotex for first-year engineering education. We continued the implementation of Nephrotex in courses at several national institutions. After collecting data from these implementations, Arastoopour and colleagues [10] demonstrated that women who participated in an engineering virtual internship felt more confident in and committed to engineering than women who participated in a first-year engineering course with no design component. Arastoopour and colleagues also showed, using ENA, that men and women whose chat discourse within the virtual internship was focused on engineering design self-reported increased commitment to an engineering career. These positive results motivated us to design a second engineering virtual internship, *RescuShell*, that is similar in length, activities, scope and structure to *Nephrotex*. The development of this second virtual internship allowed us to implement a new first-year undergraduate introductory engineering course that was entirely based on simulations of authentic engineering practice [35], which offered new opportunities to explore ENA as a design assessment tool.

IV. Results

In fall 2014 we implemented the two virtual internships, Nephrotex and RescuShell, in a new introductory engineering virtual internship course. Each internship lasted 8 weeks. We collected data in two forms: (1) chat logs from teams of students during the second half of the simulation in which they made their final design decisions and (2) each team's final design specifications. The data presented here were collected from two instances of Nephrotex. Both instances contained five teams of three to five students each, for a total of 10 teams and 46 students overall.

To examine the design processes that students used, we developed a coding scheme based on Safoutin and colleagues' [21] design attribute framework, which stems from ABET student outcome criterion 3c. The coding scheme consists of seven elements: problem definition, planning, management, information gathering, feasibility analysis and evaluation, selection/decision, and documentation. We coded chat discourse utterances from student teams in Nephrotex using the AutoCoder [33, 36], a validated, automated discourse coding algorithm.

To investigate the relationship between the teams' design discourse networks and the quality of their final designs, we calculated a quality score for each team's final device. Quality was measured in terms of how many consultant thresholds were met by a team's final device. We assigned a quality score for each team's final device based on the number of consultant thresholds the device met. Student teams that scored below the median value were categorized as low scoring, and student teams that scored above were categorized as high scoring (1 = high scoring, 0 = low scoring).

Then, to determine what sorts of connections between design attributes were made by teams that generated high and low quality designs, we examined the ENA results for each team.

The first two dimensions of ENA results for this study (Figure 2) show that there is some distinction between the groups with low-quality devices (green) and the groups with high-quality devices (blue). In particular, the groups with low-quality devices have lower values on dimension one, and the groups with high-quality devices have higher values on dimension one.

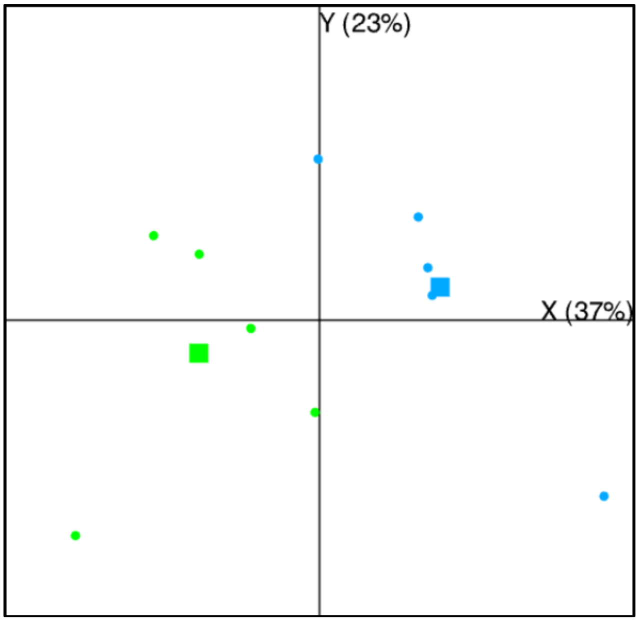

Figure 2: First two dimensions of ENA results for student groups that generate low-quality devices (green) and student groups that generate high-quality devices (blue). The points represent the centroids of each group's network. The squares represent the means of the points. The first dimension (X) accounts for 37% of the variance in the data, and the second dimension (Y) accounts for an additional 23%.

To gain more insight into the differences between student groups that generate low- and high-quality devices, we plotted the mean network connections for each group (Figure 3). The connections distinguishing the low- and high-scoring groups are connections to management. That is, the discourse of student teams that generated high-quality devices on average showed more connections between management talk and other elements of engineering design than the discourse of student teams that generated low-quality devices.

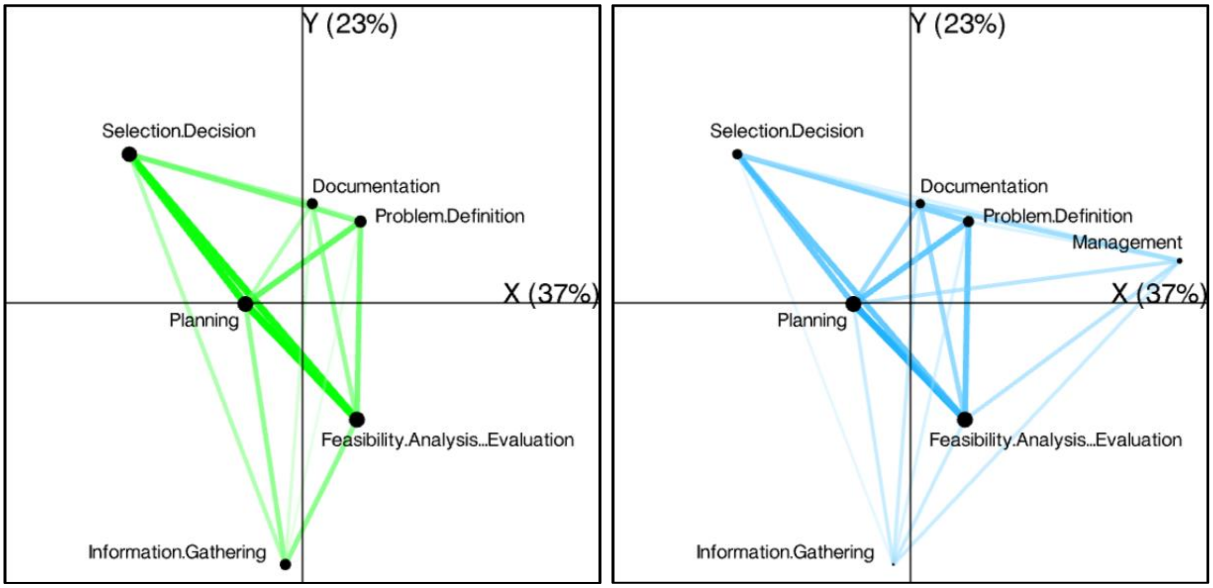

Figure 3: Mean network representations of student teams that generate low-quality devices (green) and teams that generate high-quality devices (blue). Thicker lines indicate stronger and more frequent connections between elements.

As reflected in the discourse networks, students that generated high-quality devices engaged in discourse that involved managing their decision making and planning (table 1).

Table 1: Chat discourse of one student team that generated high-quality devices.

Student	Chat Utterance	Design Attribute Code
1	first off, let's all pick our best design and provide a detailed justification.	Planning and Selection/Decision
2	so I guess I can help do that part	
3	yeah, yeah.	
3	I don't even think we need until 5 P.M. today	Management
3	if we get the FEEDS running in like 5 minutes.	Management
2	Yes But we still need to complete a notebook entry	Documentation
	Yes we should compete the new batch by 10:20 and everyone can submit their own notebooks by 5	Management & Documentation

Because student teams that made more connections with management in their networks are mostly located on the left in figure 2, we can interpret ENA dimension 1 as an Integrated Management score. A higher Integrated Management score (i.e., a rightward shift on ENA dimension 1) indicates that a team is making more connections between management and other design attributes.

There was a significant difference between design discourse networks on the Integrated Management dimension (ENA dimension 1) for student teams that produced high-quality designs (M = .168, SD =.14) and student teams that produced low-quality designs (M = -.168, SD = .12 t(10)=3.9, p<.01). The effect size, Cohen's d, was equal to 1.0, which indicates a large difference between the two groups.

V. Discussion

The results above show that ENA can be used to quantitatively measure student teams' qualitative discourse in Nephrotex, a virtual internship program for first-year undergraduate engineering students, and that the quality of student teams' final devices can be measured quantitatively. Taken together, the discourse networks and the device quality scores reveal that student teams that integrated management with all the design attributes were more likely to produce high-quality devices. Thus, ENA and device quality scoring can be used together as a form of assessing and making claims about student teams' design abilities. More broadly, the data suggest that ENA in coordination with other measures from activities within a virtual internship can reveal the development of students' engineering thinking and understanding.

The purpose in using virtual internships and ENA together is twofold. First, virtual internships offer theoretically-grounded engineering learning environments in which students can experience authentic ways in which engineers design and solve problems. We do not suggest that virtual internships should replace all other engineering design learning opportunities; there are clear advantages to working with real materials and real problems at different points in a student's learning trajectory. Rather, virtual internships have several key affordances: (1) the design space is constrained and fully mapped, so many elements can be automated or semi-automated with artificial intelligence, including individualized mentoring [10, 20]; (2) problems can be posed and scaffolded within the virtual internship such that no prior engineering knowledge is required without reducing the authenticity of the experience; and (3) rich data on student thinking can be captured for subsequent analysis [20, 37].

Second, assessing student data from virtual internships with ENA offers a model for measuring design thinking and 21st century engineering skills. ENA allows for assessment of student thinking as the student is performing tasks. In turn, the assessment provides instructors with real-time feedback while the student is interacting in the learning environment. Instructors can then intervene early in the student's learning trajectory. For example, in the results above, the quality of a design is positively correlated with integrated management skills. Using this measurement, an instructor can identify groups that are not managing their time and resources efficiently, and then mentor the students in terms of developing their management skills, which should ultimately lead to higher quality final designs.

Perhaps more importantly, using virtual internships and ENA together provide an opportunity to standardize assessment of engineering design abilities. Within the virtual internships, all students can be given the same real-world problem to solve and identical resources with which to solve it, providing a basis for standardized assessment. Using an assessment model that includes ENA and other outcome measures from the virtual internship, we can make assessment claims about students' design thinking, make valid comparisons among students' design thinking, and measure students' design thinking against standards of design thinking that can be developed from real-world practice. In other words, virtual internships and ENA provide a standardized test that actually measures what we value—engineering design thinking.

VI. Conclusion

In summary, virtual internships provide an environment in which students with no prior engineering training can engage in authentic engineering practices as they frame, investigate, and solve realistic engineering design problems. Through these internships, students learn basic engineering knowledge and competencies, and begin to form the epistemic frames of professional engineers—that is, they learn to think like engineers. Because all the activities occur in a fully mapped online learning environment, virtual internships produce rich data on student learning, and ENA allows us to assess the extent to which students learn to solve problems in the way professional engineers do. The combination of these approaches offers significant potential for increasing retention in engineering programs, improving learning outcomes in cornerstone engineering design courses, and standardizing assessment of design thinking.

VII. Acknowledgements

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