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

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An engineering workforce of sufficient size and quality is essential for addressing significant global challenges such as climate change, world hunger, and energy demand. Future generations of engineers will need to identify challenging issues and design innovative solutions. To prepare young people to solve big and increasingly global problems, researchers and educators need to understand how we can best educate young people to use engineering design thinking. In this paper, we explore virtual internships, online simulations of 21st-century engineering design practice, as one method for teaching engineering design thinking. To assess the engineering design thinking, we use epistemic network analysis (ENA), a tool for measuring complex thinking as it develops over time based on discourse analysis. The combination of virtual internships and ENA provides opportunities for students to engage in authentic engineering design, potentially receive concurrent feedback on their engineering design thinking, and develop the identity, values, and ways of thinking of professional engineers.

Keywords: design thinking; engineering design; assessment; online learning; learning sciences; virtual internship

1. Introduction

We are faced with significant global challenges, such as finding alternative energy sources, addressing climate change, and securing cyberspace. At the same time, the development and use of new technologies is accelerating. In just a few decades, products and systems have been developed that efficiently harness solar energy, rapidly purify water, and allow us to network with billions of people around the world.

With the industrial changes that this century will bring, future generations of engineers will need to develop a form of *engineering design thinking* that allows them to understand and solve the complex social and physical relationships that enable modern technologies to function. If the goal of engineering education, as Dym and colleagues [1] suggest, is to produce engineers who can design, then providing students with early opportunities to engage in authentic engineering design work may help students develop innovative design skills such as problem formulation, need identification, prototype creation, concept analysis, and documentation [2, 3]. Additionally, modern engineering design thinking requires empathy, meaningful social interactions with others [4, 5], and a comprehension of the social and economic consequences of certain design choices [6].

In this paper, we review one method of providing authentic experiences for students, i.e., teaching engineering design thinking: *engineering virtual internships*. We examine students' attitudes towards engineering as well as their performance in virtual internships, which simulate engineering design problems and practices in an online learning environment. To assess engineering design thinking, we use *epistemic network analysis* (ENA), a tool for modeling and measuring complex thinking as it develops over time. Our aim is to show that using virtual internships allows for the implementation of authentic engineering experiences for students. Using ENA to assess student work during these experiences can potentially provide students with real-time feedback on their engineering thinking, laying the foundation for life-long professional development and the ability to provide innovative solutions to current and future global challenges.

2. Virtual internships for engineering design education

In recent decades, many engineering programs have developed first-year cornerstone design courses in order to expose students to design thinking earlier in their engineering careers. However, 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 design work, and there are not enough high-quality internships to meet the needs of the engineering undergraduate population [7]. 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 [8, 9].

Our prior research [10–19] 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* [17], first-year students work as materials engineering interns at a fictitious biotechnology company to design an ultrafiltration membrane for hemodialysis equipment. Interns 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. Thus, a key aspect of this particular engineering virtual internship is the ability to participate in several iterations of the engineering design process in the context of a real-world design problem.

The activities and team interactions all take place through the web-based platform that supports the internship. Interns begin by logging into the company portal, which includes email and chat tools. They send and receive emails to and from their supervisor and use the chat window for instant messaging with other team members and their assigned design advisor. The design advisors are trained engineering senior undergraduate students, graduate students, or instructors playing the role through the company portal. These players log on to the system during the scheduled class sessions, mentor interns via chat, and monitor the interactions between interns and characters in the virtual internship that are automated by the system (non-player characters). Outside of scheduled class sessions, interns can log on to do work outside of class and design advisors can log on to assess interns' in-class and out-of-class work. There is one design advisor assigned to every 25 interns.

Interns at Nephrotex prepare for the design task by examining company research reports based on actual experimental data on a variety of polymeric materials, chemical surfactants, carbon nanotubes, and manufacturing processes. After collecting and summarizing research data, they begin the actual design process using the simulated engineering drawing tool (Fig. 1a). First individually and then in teams, interns develop hypotheses based on their research, test these hypotheses in the provided design space, and analyze the results provided. The design space in *Nephrotex* is constrained, meaning that interns choose from a fixed (and predetermined) set of design inputs. The space contains four input categories and five output categories (Fig. 1b); there are 570 devices with unique performance results that can be designed in *Nephrotex* [20]. The design space is also fully mapped, meaning that performance criteria exist for all 570 device options available. Importantly, however, students cannot access performance criteria for all devices; each student can only query the system for performance criteria for twenty-five unique device designs.

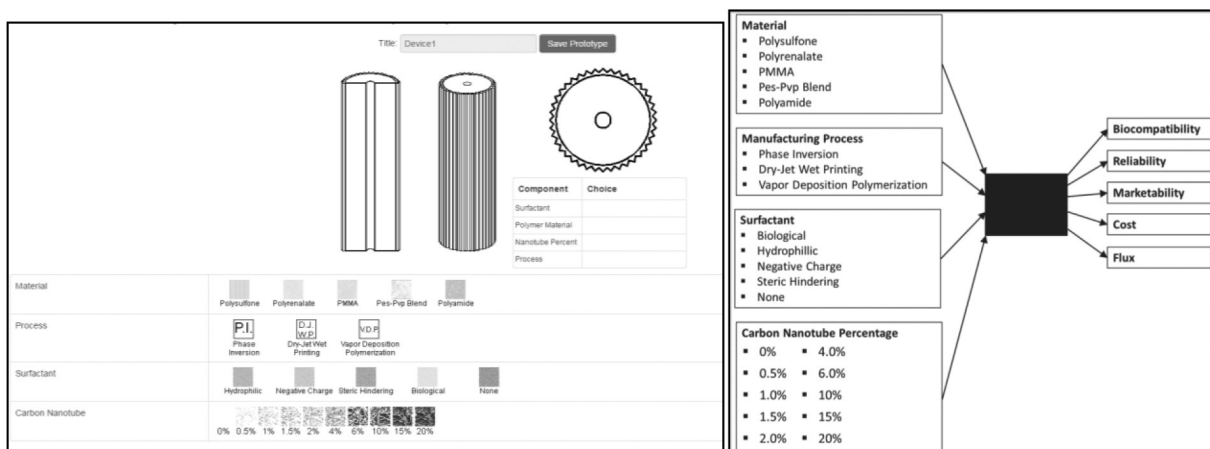Interns also learn about internal consultants within the company who have a stake in the out-

Fig. 1 (a) The simulated engineering design tool in *Nephrotex*. (b) A representation of the design space (the inputs and outputs) in *Nephrotex*; from the perspective of the interns, the relationships between inputs and outputs are initially opaque.

come 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, while 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.

In the first half of the internship, students in teams test five devices. During the second half of the internship, interns switch teams and inform their new team members of the research they have conducted and results they have obtained thus far. In the new teams of five, interns test five more devices (for a total of twenty-five devices tested), analyze the second iteration of results, and decide on a final prototype. During the final days of the internship, interns present their prototypes and justify their design decisions. They then complete an exit interview, which includes survey questions about their attitudes towards the engineering profession.

Virtual internships such as *Nephrotex* thus enable first-year undergraduates to experience authentic engineering design practice, with professional mentoring and real-time feedback, in a realistic, collaborative learning environment. Although the design spaces are fully mapped, students work with authentic design problems with many feasible design choices. In turn, students must justify their particular design choices and tradeoffs.

Participating in a virtual internship give students the opportunity to (a) engage in meaningful, consequential engineering design practice; (b) frame, investigate, and 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.

3. Developing and assessing engineering design thinking

Assessing the development of engineering design thinking is a significant challenge. Existing education standards, such as the ABET [21] 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). In one study centering on ABET standards, McKenzie and colleagues [22] developed and implemented a large-scale survey interviewing senior capstone course instructors about their engineering design assessment methods. Faculty members expressed that ABET criteria are not well assessed in capstone courses and wanted assistance developing assessment tools. Regarding their practices in the classroom, faculty responded that "they lacked information and know-how to develop assessments for all users, write clear and appropriate course objectives, and determine whether assessments used in courses are as fair as desired" (p. 17).

In response to these issues, many design researchers have developed assessment tools that include surveys, pre-post tests, and rubrics for final designs and portfolios [23–26]. For example, Safoutin and colleagues' *design attribute framework* [27] consists of a detailed list of standards that transforms the imprecise ABET learning outcomes into information that instructors could use in curriculum and assessment development. The framework provides descriptions of the various stages of the design process and identifies what is required of students at each step. For instance, they identify one component as *needs recognition*, and detail several subcomponents, such as identifying needs to be served by the design, evaluating societal needs, evaluating the cost associated with a product, and identifying target customers and markets. Safoutin and colleagues generated the design attributes from a large number of engineering design process models and from verbal protocol analysis studies, in which students were observed while engaging in a design task.

Although Safoutin and colleagues' framework and other rubrics provide items to identify design thinking, they may not accurately identify the *authentic design process*. Design thinking doesn't always follow a direct, straightforward pathway and thus, assessments that follow a linear model may not accurately capture authentic design activity or thinking. Adams and colleagues [28] agree that static, stepwise, and fixed models of learning progressions may not be useful, and instead favor dynamic and interconnected models that articulate how variations in an embodied understanding of

practice reveal multiple trajectories of interconnected ways of thinking, acting, and being in the world. Saffer [29] has claimed that design thinking involves a focus on customers/users, finding alternatives, ideation and prototyping, dealing with wicked problems, possessing a wide range of subject knowledge, and exhibiting emotional understandings. He continues, "Other disciplines, I'm sure, do one or more of these at any given time. But I think it's the combination of these that mean—or should mean—when using the phrase 'design thinking."

Based on the value of interconnectedness in design thinking, we approach complex design thinking from the learning science theory of *epistemic frames* [30–32]. 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 design practice. In other words, realistic design 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 ENA [33–38], 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 epistemic frame elements 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 in the domain.

4. Methods

In the fall semester of 2014, we implemented *Nephrotex* in a new introductory engineering course in which students participated in two virtual internships. Each internship lasted 7 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.

To examine the design processes that students used, we developed a coding scheme based on Safoutin and colleagues' [27] design attribute framework. The coding scheme consists of seven elements that were relevant for *Nephrotex*: 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 *nCoder* [39, 40], a validated, automated discourse coding system.

The original coding scheme consisted of fourteen elements: need recognition, problem definition, planning, management, information gathering, idea generation, modeling, feasibility analysis, evaluation, selection/decision, implementation, communication, documentation, and iteration. We selected and modified 7 of the 14 codes that were applicable to *Nephrotex* (Table 1). We removed need recognition and modeling because students are given the needs statement and the modeling tools within the internship program. We removed idea generation and implementation because students do not create a novel design or a physical prototype—all designs are virtually produced. Finally, we removed iteration and communication because students are required to iterate through two design cycles and to use the chat tool to communicate.

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. 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 the median value 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- or low-quality designs, we examined the ENA results for each team. The technical details of ENA have been provided elsewhere [10, 36, 39], but 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.

More specifically in ENA, for any two codes the strength of their association in a network is computed based on the frequency of their co-occurrence in discourse. For example, the window in Fig. 2a would be coded for "planning" and "selection/

Table 1. Design coding scheme based on Safoutin and colleagues' design attribute framework applied to Nephrotex discourse

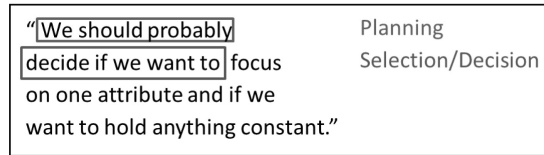| Code	Description	Actions	Examples
1. Problem Definition	Determining design objectives and functional requirements based on needs statement, identifying constraints on the design problem, and establishing criteria for acceptability and desirability of solutions.	• Transform statement of need to statement of design objectives (functional requirements). • Identify or reference constraints on the design problem.	*This material maximizes flux which is very important to the design because it allows patients to have a shorter treatment time.* *yes because some consultants wanted to maximize flux while others wanted to minimize cost*
2. Planning	Development of an initial design strategy, including an overall plan of attack, decomposition of design problem into subtasks, prioritization of subtasks, establishment of timetables and milestones by which progress may be evaluated.	• Develop a design strategy. • Decompose problem into subtasks where appropriate.	*How about everyone describes what the strengths and weaknesses are of the material they worked with based on their previous designs?* *Yes, we should each contribute one prototype containing our material, but we should keep the other variables of each design somewhat constant, so that we can easily compare the results of the different designs.*
3. Management	Guidance of course of action during design and in response to changing conditions.	• Manage time and resources to meet timetable and milestones.	*I think the deliverable is due at 5 so I don't think that would work.* *okay, guys.... I think the personal deadline we should set is midnight tonight.*
4. Information Gathering	Gathering information about the design problem, including the need for a solution, user needs and expectations, relevant engineering fundamentals and technology, and feedback from users.	• Gather or reference data to verify the existence of a problem including data on customer perceptions and desires. • Gather or reference relevant engineering fundamentals and technological state-of-the-art.	*The graphs made all of the options easily comparable in a side to side format.* *We would need to make sure all toxins can pass through the membrane and anything that needs to stay in the blood does not get filtered out.*
5. Feasibility Analysis & Evaluation	Evaluating feasibility of alternatives or proposed solutions by considering stated constraints as well as implied constraints such as manufacturability, compatibility, cost, and other criteria. Objectively determining suitability of alternatives or proposed solutions by comparing actual performance to evaluation criteria.	• Evaluate feasibility of multiple alternatives in terms of constraints. • Recognize unstated constraints such as manufacturability or assemblability in evaluating designs. • Use evaluation criteria to objectively judge acceptability, desirability of alternatives.	*That sounds good but if we wanted a true base model/cheapest we would have to do no surfactant or CNT.* *I suppose for the patient, Christopher's may be better, but Scottland's is the only prototype that met all the requirements.* *I think mine would be a good choice too actually because it still meets the internal consultants requests and is at least a little less expensive.* *I think Prototype 3 on this last testing batch gave the best results, covering the most aspects, most equally.*
6. Selection/Decision	Selection of the most feasible and suitable concept among design alternatives.	• Discern feasible solutions or partial solutions. • Use evaluation to select feasible alternative that best satisfies objectives.	*I think that prototype would probably be the best option.* *Okay, so then our prototype would be PESPVP, Dry-jet wet, hydrophilic, 20%CNT.* *Then yes let's use that device.* *So we each pick the one that we think will perform the best, and then compare them?* *I think mine would be a good choice too actually because it still meets the internal consultants requests and is at least a little less expensive.*
7. Documentation	Production of usable documents of record regarding the design process and design state, including decision history and criteria, project plan and progress, intermediate design states, finished product, and use of product.	• Document decisions and decision criteria. • Keep a journal or other record of design development. • Create and maintain planning documents and status assessment reports. • Document the finished product or process as appropriate for the discipline according to standard practice.	*We can also include a nice 3 sentence justification.* *Alright I can post my notebook after in the shared area.* *I have 4 designs and 3 justifications in my notebook.* *We created a google document to work in and we divided tasks among the group members.*

"We should probably decide if we want to focus on one attribute and if we want to hold anything constant."

Planning
Selection/Decision

Fig. 2a. Example window coded for two design codes.

- Documentation
- Feasibility Analysis & Evaluation
- Management
- Information Gathering
- Planning
- Selection/Decision
- Problem Definition
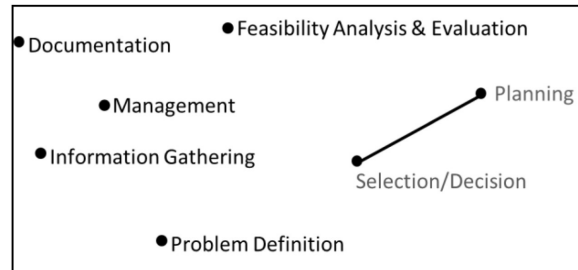
Fig. 2b. Example stanza represented as a network.

	Planning	Selection/Decision	Documentation	...
Planning	0	1	0	...
Selection/Decision	1	0	0	...
Documentation	0	0	0	...
...	..	...	...	..

Fig. 2c. Example stanza represented as an adjacency matrix.

decision," but not for "documentation," "feasibility & evaluation," "management," "information gathering," or "problem definition." Fig. 2b shows this stanza represented as a network, where the elements that co-occurred in that stanza are now connected while elements that do not co-occur are not connected. Fig. 2c shows this stanza as a symmetric adjacency matrix, where the codes are represented both as rows and columns. Elements that co-occurred are represented by a one where they intersect, and elements that did not co-occur are represented by a zero. Not all codes are included in this representation for visual clarity.

ENA constructs an adjacency matrix for every stanza. The adjacency matrices are summed for every team of students and normalized so that groups with more discussion in chat are not weighted more heavily than groups who had less discussion but used the same configuration of connections in their discourse. Finally, the matrices are represented as vectors in a high-dimensional space, and a singular value decomposition is conducted to rotate the vectors so as to show the greatest variance among the matrices. This approach is mathematically similar to a principal components analysis. In this rotated space, each team's adjacency matrix is represented as a point in high-dimensional space that roughly corresponds to the network's centroid. Each dimension in this space can be interpreted by examining the loadings (rotation) matrix, which, again, is similar to the interpretation in a principal components analysis.

In sum, ENA can be used as a tool for examining the complex links and connections between key skills and ways of making decisions that occur during the authentic engineering design process. However, ENA is just one method for measurement and analysis of learning; modern approaches include a range of techniques. While each technique has its particular strengths in measuring learning, each also has limitations. For example, diagnostic classification and latent class models can be used to make statistical inferences about latent variables and their relationships to problem-solving tasks. However, current techniques require very large datasets to analyze even small numbers of latent classes; moreover, such models are not well suited to the analysis of data in ill-formed problem settings, such as authentic engineering design problems. At another end of the spectrum, techniques from dis-
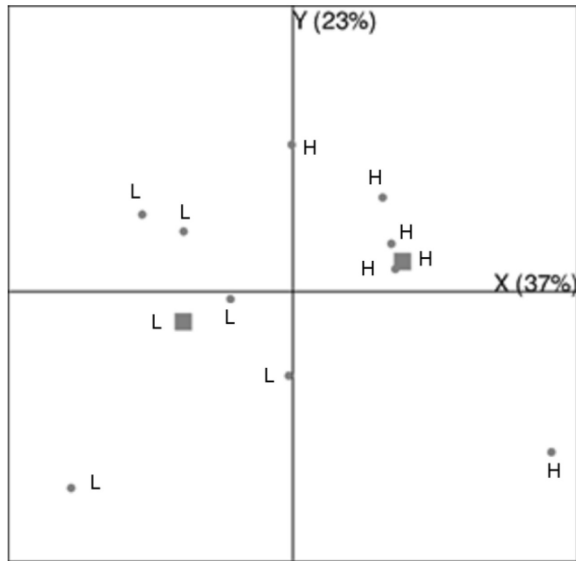
Fig. 3. First two dimensions of ENA results for student groups that generate low-quality devices (labeled with L) and student groups that generate high-quality devices (labeled with H). The points represent the centroids of each group's network. The squares represent the means of the points. The first dimension (X) accounts for 37% of the variance in the data, and the second dimension (Y) accounts for an additional 23%. A higher score on dimension 1 indicates more connections to management and a higher score on dimension 2 indicates more connections with selection/decisions.

course analysis are designed to investigate rich sets of data about problem solving; however, extant methods are not well suited to large data sets or large numbers of students. Additionally, ENA examines the co-occurrence of elements within a given segment of time and is able to model the co-

occurrences across these time segments. Other methods may not consider the connections within each time segmentation or allow for network representations of the discourse.

By providing a quantitative model of engineering design thinking that measures connections between critical design skills, ENA provides more than merely a technical advance in the science of measurement and assessment. It lays the foundation for analyzing creativity and innovation in design tasks by providing an approach to quantifying expertise in ill-formed problem domains, such as engineering design.

In a previous study, we used similar methods with a preliminary coding scheme [39]. In this current study, we revised the coding scheme and present the refined results.

5. Results

The first two dimensions of ENA results for this study (Fig. 3) show that there is some distinction between the groups with low-quality devices and the groups with high-quality devices. 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.

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 (Fig. 4). The connections distinguishing the low- and high-scoring groups are connections to management. That is, the discourse
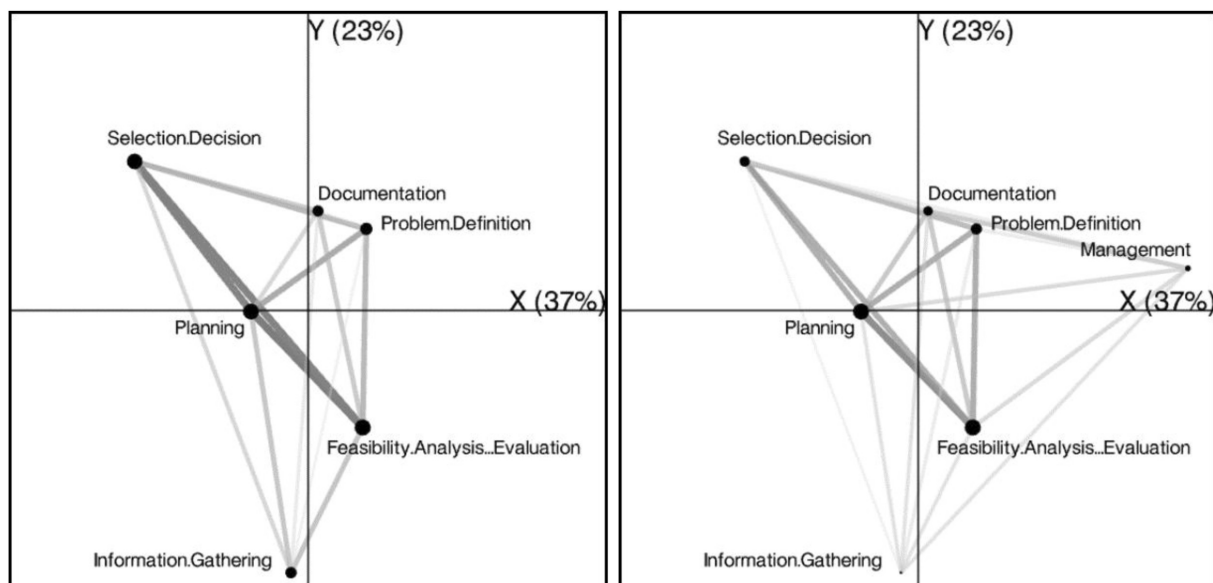

Fig. 4. Mean network representations of student teams that generate low-quality devices (left) and teams that generate high-quality devices (right). Thicker lines indicate stronger and more frequent connections between elements. Teams that generate high-quality devices have networks with more connections to management, which is why the centroids in Fig. 2 are plotted higher on the first dimension than teams with low-quality devices.

of student teams that generated high-quality devices on average showed more connections between management talk and other elements of engineering design thinking than the discourse of student teams that generated low-quality devices.

As reflected in the discourse networks, student teams that generated high-quality devices engaged in discourse that involved managing their decision making and planning (Table 2).

Because student teams that made more connections with management in their networks are mostly located on the right in Fig. 3, 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 aspects of engineering design thinking*.

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 = 0.168, SD = 0.14) and student teams that produced low-quality designs (M = –0.168, SD = 0.12 t(10) = 3.9, p < 0.01). The effect size, Cohen's d, was equal to 1.0, which indicates a large difference between the two groups.

6. Discussion

The results above show that ENA can be used to quantify student teams' qualitative discourse in *Nephrotex*, a virtual internship program for first-year undergraduate engineering students. 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 to assess the extent to which students make connections among critical design components and to make 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 design 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 frame, investigate, 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 fully mapped, meaning that students are making design choices from a database [10, 17]; (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 [17, 41].

Second, assessing student data from virtual internships with ENA offers a model for measuring engineering design thinking and 21st-century engineering skills. To date, ENA has been used as a form of summative assessment and as not yet been integrated into virtual internships as a form of formative assessment. However, these results show that ENA could potentially allow for assessment of student thinking *as the student is performing tasks*. In turn, the assessment can provide 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 most importantly, using virtual internships and ENA together provides 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 different students' design thinking, and measure students' design thinking against standards of design thinking that could 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.

7. Conclusion

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, skills, and practices, and they begin to form the epistemic

frames of professional design engineers—that is, they learn to think like designers. 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 design in the way professional engineers do. The combination of these approaches offers significant potential for improving learning outcomes in cornerstone engineering design courses and standardizing assessment of engineering design thinking.

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