Board 9: Measuring Change: Research Updates Helping Engineering Students Tackle Complex, Sustainability Problems

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Dr. Elise Barrella is an Assistant Professor and Founding Faculty Member of the Department of Engineering at Wake Forest University. She is passionate about curriculum development, scholarship and student mentoring on transportation systems, sustainability, and engineering design. Dr. Barrella completed her Ph.D. in Civil Engineering at Georgia Tech where she conducted research in transportation and sustainability as part of the Infrastructure Research Group (IRG). In addition to the Ph.D. in Civil Engineering, Dr. Barrella holds a Master of City and Regional Planning (Transportation) from Georgia Institute of Technology and a B.S. in Civil Engineering from Bucknell University. Dr. Barrella has investigated best practices in engineering education since 2003 (at Bucknell University) and began collaborating on sustainable engineering design research while at Georgia Tech. Prior to joining the WFU faculty, she led the junior capstone design sequence at James Madison University, was the inaugural director of the NAE Grand Challenges Program at JMU, and developed first-year coursework.

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Dr. Mary Katherine Watson is currently an Assistant Professor of Civil and Environmental Engineering at The Citadel. Prior to joining the faculty at The Citadel, Dr. Watson earned her PhD in Civil and Environmental Engineering from The Georgia Institute of Technology. She also has BS and MS degrees in Biosystems Engineering from Clemson University. Dr. Watson's research interests are in the areas of engineering education and biological waste treatment.

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Executive Summary

Real-world engineering challenges are open-ended, multi-faceted, and exist within a societal context, requiring knowledge from multiple domains (technical, environmental, economic, and social) to be adequately addressed. Students gain knowledge in each of those domains from a variety of undergraduate classes (both engineering and non-engineering) and need guidance for drawing on that knowledge and integrating it when they are faced with new, complex problems. Faculty often observe that students have difficulty connecting knowledge from across classes or domains to fully analyze problems and evaluate trade-offs. The primary goal of this project is to improve students' abilities to apply sustainable engineering design concepts across different problems or design contexts and improve assessment of the learning gains using direct measures. The theoretical framing for this project is Cognitive Flexibility Theory (CFT), which Spiro et al suggested as a means to help students learn in complex and ill-structured domains [1]. While there has been recent discussion of CFT in the literature, there is no clear consensus on a definition of cognitive flexibility or how it is directly measured, particularly in complex problem-solving situations such as engineering design. One common definition of cognitive flexibility is the ability to switch between thinking about two different concepts and being able to think about multiple concepts simultaneously (for example, multiple design criteria or constraints in an engineering problem or multiple dimensions of sustainability). Accordingly, some researchers have used time spent on tasks in relation to performance on tasks as indicators of cognitive flexibility. Another definition is the "selective use of knowledge to adaptively fit the needs of understanding and decision-making of a particular situation" [1, p. 548]. The latter definition seems appropriate for describing cognitive flexibility in engineering problem-solving but does not seem to be fully captured by measures of time spent on task and performance.

The research goals guiding this NSF-REE project include: (1) Identify appropriate measures of knowledge transfer/cognitive flexibility/adaptive expertise that apply to engineering design tasks and other open-ended tasks; (2) Develop and adapt instructional materials and assessments to measure and help students improve ability to transfer knowledge to/across sustainable design problems; (3) Explore differences in students' responses to the interventions between different types of engineering programs.

The poster will share progress related to each of the goals through methods and results from two types of studies: (1) exploring neuroscience theories and measures related to cognitive load, efficiency, and flexibility for complex problem-solving; and (2) developing and testing a Sustainable Design rubric for use with multi-disciplinary engineering capstone design projects. New analysis and findings from the two studies are briefly summarized in the following sections, including specific objectives for the work and results, and in recent publications [3, 4, 5].

Neuroeducation Study

After a successful pilot project with an electroencephalogram (EEG) to measure cognitive load during a statics problem-solving session, we initiated a pilot study using EEG and self-report data to investigate engineering undergraduate students' cognitive activities when completing

different tasks related to sustainability problem contexts. Following a brief demographic survey, systems thinking survey, and benchmarking tests with the EEG, each participant completed two listing and two concept mapping tasks in one of four randomly assigned sequences. Each task related to a sustainability issue: climate change, food systems, renewable energy, or water availability. After finishing all of the tasks, participants completed the NASA-TLX instrument (a validated self-report measure of cognitive load) and a brief post-survey on the experience. Twenty-seven participants at a large public university completed the study, and data analysis is being conducted in a variety of ways to explore individual variables and combinations of variables, and to triangulate results from different types of data. In particular we are comparing cognitive functions and activation during linear thinking (i.e., listing) tasks and systems thinking (i.e., concept mapping) tasks. We hypothesized that (1) concept maps allow individuals to organize their thoughts within a systems thinking framework, and thus result in a more complete and holistic response than a linear thinking equivalent (i.e., listing task) and (2) creating a concept map is a more complex cognitive process than writing a list of terms and thus students (at least initially) would experience greater cognitive load while completing the concept mapping tasks. For each participant, we recorded over forty pieces of data including demographic data, responses to the Revised Systems Thinking Scale, order effects, EEG performance variables, NASA-TLX scores, performance on listing tasks, and scores on concept maps.

Based on preliminary analysis, the cognitive load means were .757 for the systems thinking tasks and .752 for the linear thinking tasks. While, average cognitive load seems only slightly higher on the systems thinking task, the average systems thinking task took 522 seconds while the average linear thinking task took only 308 seconds. Thus, cumulative cognitive load is larger for the concept maps than the listing tasks. In addition, the NASA-TLX overall workload mean was 65.19 for the systems thinking task and 48.71 for the linear thinking task. Overall workload is a function of the various dimensions of the NASA-TLX that participants gave feedback on. The EEG and self-report data seem to suggest the concept map was a more complex task than listing. In terms of performance, on average, participants generated more concepts during the systems thinking task than the linear thinking task. All of the concept maps and lists are being further evaluated using quantitative and qualitative analysis to more completely understand performance on those tasks. In addition to calculating descriptive statistics, we are also conducting ANOVA and regression analysis as appropriate to explore relationships among different variables.

Rubric for Student Projects

Rubric work is focused on providing engineering educators and students with a learning and assessment tool to enhance sustainable design outcomes of projects. Ultimately, expert feedback substantiated parallel validation efforts using text mapping to established sustainable development frameworks; this work was reported and published previously and will be summarized on the poster. Guided by the analyses, we iteratively reduced the rubric to 14 criteria, which could be defined and thus rated using distinct language and examples, and identified three scoring dimensions (quantitative & qualitative evidence, long-term thinking and lifecycle, and formal methods/documentation) as important considerations for all of the criteria rather than stand-alone criteria. The criteria and their categories are:

Environmental Category

A1. Minimizes the use of non-replenishable raw materials; requires minimal energy input or uses renewable energy sources
A2. Minimizes quantity of consumable waste (e.g., water, materials) output; manages quantity and quality (benign, usefulness) of waste
A3. Protects or enhances natural ecosystems (water, air, soils, flora, fauna, etc.)

Social Category

B1. Identifies and engages stakeholders in the design process
B2. Addresses needs of diverse stakeholders, acknowledging culture and other differences among individuals and groups
B3. Protects human health and physical safety of users and society
B4. Promotes human well-being and enhances quality of life for users and society

Economic Category

C1. Evaluates economic impacts of environmental design criterion
C2. Evaluates economic impacts of a social design criterion
C3. Considers affordability for users and/or demonstrates cost competitiveness or cost reduction for client/sponsor
C4. Evaluates economic costs and benefits to inform decisions

Trade-off Category (consider project holistically)

T. Final design impacted by trade-offs among environmental, social, and economic criteria and reflects balance of dimensions

Bonus Category (consider project holistically)

X1. Uses and/or creates innovation(s) in its specific field to achieve sustainability
X2. Worked with experts from other disciplines to enhance process or final design

The rubric has been tested with students and their projects in order to iteratively complete substantive validation and begin structural validation of the Sustainable Design construct, following the Benson model [2]. The first structural study was conducted in Spring 2018 with 51 engineering student users for formative assessment of their preliminary capstone project work. In addition to individually scoring their projects, students also worked with their capstone teammates to arrive at consensus scores for each criterion and provide justification for the final scores. As a scoring example using the three previously mentioned dimensions, in order to earn full points for the first criterion ("minimizes use of non-replenishable resources"), a project would have to present quantitative and qualitative evidence of responsible natural resource use, consider all phases of a product or system's lifecycle, and clearly document how formal methods were used to evaluate the criterion and shape decisions. In general, students found that the social criteria were easiest to score (and also the category in which they scored themselves well) while economic criteria were the most difficult to score. Students were generally accurate with their

ratings, although some criteria seemed to receive inflated scores when compared to their justifications and a few criteria seemed to be double counting evidence (e.g., B1 and X2). We are completing a review of the quantitative and qualitative data in order to answer a few questions related to construct validation: (1) Is there a range of responses on the items? Are students using the full 0-3 scale? (2) Which items do we expect to be related? Which items perform as expected? (3) Where do we see the most variability in individual ratings – across individual items or across individual criteria? The primary objective of analyzing this data, including qualitative coding, is to improve the rubric in terms of content, structure, and implementation. Future rubric work will address other audiences and assessment purposes.

Observations across studies

Through the concurrent studies, we have made interesting and at times unexpected observations of how students conceptualize and apply the sustainability construct to engineering problems. For example, in both the EEG study and the rubric study we have seen evidence that students have a tendency to specialize or focus on one or two aspects of sustainability. While overall students are weakest with respect to economic aspects, some individuals over-represent social aspects and others environmental aspects. In the EEG study, this tendency is demonstrated by concept maps with a lot of depth in one or two categories and not a lot of breadth. To counteract this individual tendency and help students learn from each other (or at least appreciate the value of different aspects), teamwork and consensus-building, such as that employed in the rubric study, could be a valuable strategy for sustainable design. Our poster will explore additional connections across our studies which provide insights into how engineering students may develop cognitive flexibility and how we can better measure it.

Acknowledgement

References

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