Work in Progress: Quantifying the Differences Between Professional Expert Engineers and Engineering Students Designing: Empirical Foundations for Improved Engineering Education

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Design is recognized as the critical element of engineering thinking that differentiates engineering from other problem solving approaches (Dym, et al. 2005). One of the primary goals of engineering design education is to equip students with the capability of becoming expert design engineers. To develop this capability in students, educators require a detailed knowledge of the cognitive behavior of both undergraduate students and expert design engineers. However, there is insufficient information known about the cognitive behavior of expert design engineers, since most studies focus on engineering students or engineers early in their professional careers. While the significant differences between expert behaviors and novice behaviors have been studied in many other STEM fields ranging from biology to medicine to mathematics, it has been notably understudied in engineering. There is a gap between competencies developed in universities and those needed to become an expert in the field; the process to quantify and verify how students acquire "the ability to do expert work" is inadequately studied in engineering. *By using the function-behavior-structure (FBS) ontology methodology from design science, we can begin to develop more complete models to articulate and quantify the differences between the cognitive behaviors of novice and expert engineering designers.* This will provide the foundation for educational interventions that move novices along a cognitive trajectory towards expert behavior.

The ***purpose*** of this research is to begin to characterize engineering learning so that we may begin to identify potentially novel pathways to approach the cognitive transformation from novice to expert in engineering education. This project measures and compares the design thinking of dyads of freshmen engineering students, dyads of senior engineering students, and dyads of professional expert engineers through a study of their cognitive processes while designing. It uses tools and processes developed in previously funded NSF projects to provide a uniform basis for comparing students and professional experts that is independent of the educational and experiential background of the participants.

Outcomes of this research provide a cognitive foundation to inform and improve engineering education models while expanding our understanding of how students evolve to acquire expert-level design skills. The results inform leaders in engineering education and developers of instructional materials and curricula, as well as teachers and designers planning classroom strategies, of initiatives in formal engineering education. The development of educational strategies are explored and developed through a workshop of engineering design educators to move students along a trajectory towards expert design behavior. Table 1 presents an overview of the problem, approach, and potential outcomes of this project.

Background and Significance of Related Work

There has been a significant impediment in providing quantitative empirical evidence about the cognitive behavior of designers. Design cognition has been difficult to measure in ways that are both independent of the designer and produce results that are commensurable with results from previous experiments. Much of the empirical work carried out in studying engineering design has focused on the meta-cognitive level (Atman, Adams, et al, 2007). In order to measure design cognition empirically this project makes use of a method of determining and describing design cognition, based on the FBS ontology (Gero, 1990), that is independent of the design task, the designer's experience and the design domain. Hence, it produces commensurable results from different experiments (Gero, 2010; Gero & Kannengiesser, 2014; Jiang, 2012; Kan, 2008).

Table 1. Overview of problem, approach, and potential outcomes

PROBLEM	OUR APPROACH	POTENTIAL OUTCOMES
Design cognition of students and professional expert designers is inadequately characterized.	From video protocols of experimental sessions, recent developments in cognitive science are used to characterize design cognition of dyads of students and professional experts while designing.	A commensurable description based on a method that is independent of designer and allows comparisons within this project and with results of previous projects.
Design cognition of teams of students with and without minority membership is inadequately characterized.	From video protocols of experimental sessions, recent developments in cognitive science are used to characterize design cognition of dyads of student teams with and without minority membership.	A commensurable description based on a method that is independent of designer is produced that allows comparisons between teams of students with and without minority membership.
Design cognition needs to be described quantitatively.	From the distributions of design issues and design processes quantitative models of design cognition are derived.	Design cognition of students and expert designers are characterized through empirically-based quantitative models.
Need to measure differences between students and professional experts.	Use empirically based quantitative models of design cognition as basis for difference measurement.	Lay empirically-based foundation for education to move engineering students' towards professional expert-like behavior.
Need to reduce gap between student and professional expert design behavior.	Workshop of engineering educators to formulate classroom practice founded on results from this project.	Interventions proposed that move students along trajectory toward expert-like design skills.

Previous research including prior NSF-funded projects have supported the development of methods, techniques and tools to measure the cognitive behavior of designers and have developed quantitative measures of cognitive design style, a measure of design strategies (Gero, Jiang & William, 2012; Lee, Gero & Williams, 2012; Williams, Gero, Lee &Paretti, 2011). These quantitative measurements provide a robust empirical foundation for the development of educational strategies and a basis for measuring the success of subsequent educational interventions.

This project builds on previous NSF-funded projects that looked at the longitudinal development of design cognition of undergraduate engineering students across two contiguous years (Williams, Lee, Gero & Paretti, 2013). Results from a pilot study at Utah State University show there is a significant gap between the cognitive behavior of novice and professional expert engineering designers (Song, 2014). This project makes use of those results and focuses on gaps. It brings together the beginning of engineering education (freshmen), works with students completing engineering education (seniors), and completes the longitudinal development of engineering design by studying professional experts.

Expert engineers are those who have at least 10 years and 10,000 hours of professional experience (Cross, 2004; Dufresne, Gerace, et al, 1992; Ericsson, Charness, Feltovich, &

Hoffman, 2006; Kaufman, & Kaufman, 2007; Kavakli, & Gero, 2002). The design cognition of expert design engineers is inadequately characterized. The focus of previous studies on expert design behavior have been on case studies that produced qualitative results (Ahmed 2001; Ahmed, Wallace and Blessing 2003; Baird, Moore, et al, 2000; Marsh, 1997). A meta-analysis of design cognition studies indicated that there are commonalities as well as differences between students and professional designers (Gero, Kannengiesser & Pourmohamadi, 2012). Understanding difference between novices as developing learners and expert target performance is essential to identify appropriate learning experiences to reduce this performance gap.

Design Theory: The FBS Ontology

In order to compare the design cognition of different designers with varying education and experience backgrounds, and designing for a variety of requirements under different conditions, a means of characterizing designing in a uniform way that is independent of the designer, the design task and the design situation is necessary. Thus, what is needed is a set of irreducible foundational concepts of design and designing. These irreducible foundational concepts should cover the acts of designing and the representation of the design. The Function-Behavior-Structure (FBS) ontology (Gero, 1990; Gero & Kannengiesser, 2004; Gero & Kannengiesser, 2014; http://en.wikipedia.org/wiki/Function-Behaviour-Structure_ontology) was developed to distinguish what the design was from, how it worked and from what its intended purpose was.

The FBS ontology (Gero, 1990; Gero & Kannengiesser, 2014) models designing in terms of three classes of ontological variables: *function, behavior, and structure*. The goal of designing is to transform a set of functions, driven by the client requirements (R), into a set of design descriptions (D). The *function* (F) of a designed object is defined as its intended purpose or teleology; the *behavior* (B) of that object is either derived (Bs) or expected (Be) from the structure, where *structure* (S) represents the components of an object and their relationships. The requirements (R) and the description (D) are expressed in terms of FBS so new ontological variables are needed to cover them.

Designers decide which behaviors (B) are significant and needed to assess the designs they produce. So, B can be subdivided into two sub-categories: the behaviors the designer expects the design to have (Be) and those that are measured from the design (S) itself and called behavior from structure (Bs).

Different functions for the same design produce different expected behaviors that generate different structures. An example of two different functions invoking different behaviors and different structures for the same design using a cell phone is show in Figure 1.

A design description is never transformed directly from the function, but is a consequence of a series of processes among the FBS variables. These processes include: *formulation,* which transform functions into a set of expected behaviors (process 1 in Figure 2); *synthesis*, where a structure is proposed to fulfill the expected behaviors (process 2); an *analysis* of the structure produced by the derived behavior (process 3); an *evaluation* process which acts between the expected behavior and the behavior derived from structure (process 4); *documentation*, which produces the design description (process 5). There are three types of reformulation: *reformulation I* – reformulation of structure (process 6), *reformulation II* – reformulation of expected behavior (process 7), and *reformulation III* – reformulation of function (process 8). Figure 2 shows the relationships among the eight transformation processes and the three basic classes of variables, which claim to be the fundamental processes for designing.

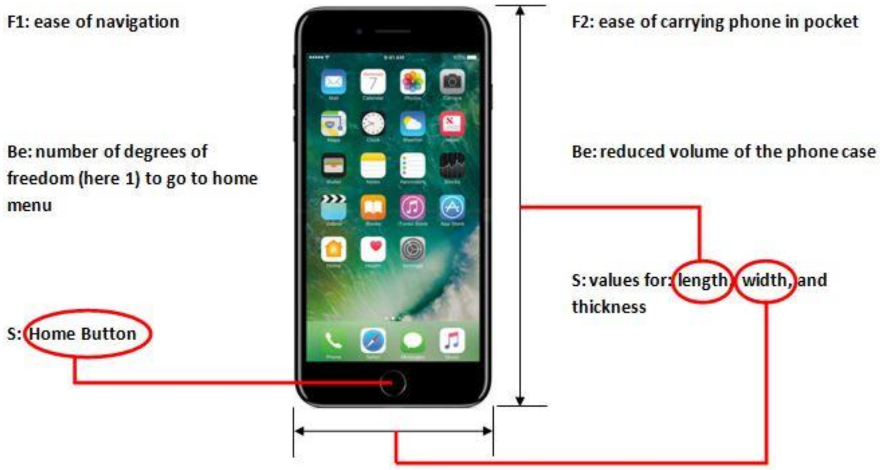

Figure 1. An example of functions (F), expected behaviors (Be) and structures (S)

The FBS coding scheme is based on the FBS ontology of designing and is used in protocol studies of designers (Gero, 2010; Jiang & Yen, 2009; Kan, 2008; Lammi, 2011; Lee, et al., 2012; Song, 2014; Williams, et al., 2013).

The FBS ontology of designing that has been used in multiple disciplines and one that transcends individual designers, the design task, the design environment, and whether designing individually or in teams (Branki, 1995; Hofmeister, et al., 2007; Jiang, 2012; Kruchten, 2005; Robin, et al, 2007; Van Wie, et al., 2005;Visser, 2006).

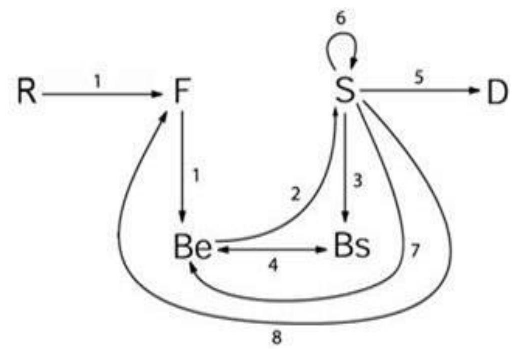

Figure 2. The FBS ontology

Design Cognition Research

Much of engineering education research in design is dominated by explorations of design teaching, although recently there have been cognitive studies of designers that have been aimed at elucidating design-thinking behavior. These studies have fallen into five methodological categories: questionnaires, interviews (Cross & Cross, 1998); input-output experiments (where the designer is treated as a black box which produces the behaviors in the outputs for changes in inputs) (Purcell, Williams, et al, 1993), anthropological studies (Lopez-Mesa & Thompson, 2006), and protocol studies. While each of these methods produced interesting results, the most promising method is protocol studies. It has become the basis of the current cognitive study of designers (Atman, et al. 2008; Badke-Schaub et al 2007; Becker & Mentzer, 2012; Christensen &Schunn 2007; Gericke, et al 2007; Gero, Kan & Jiang, 2014; Kavakli & Gero, 2002; McDonnell & Lloyd, 2007; McNeill, et al, 1998; Song, 2014; Suwa, et al, 1998; Suwa, Gero & Purcell, 2000; Williams, et al, 2013).

Given the demonstrated value of protocol studies, this project uses the approach as the tool, but applies a design ontology-based coding scheme derived from recent innovations in design science and cognitive science to a longitudinal study of design development to enrich our current understanding of design learning. This coding scheme is based on the Function-Behavior-Structure (FBS) ontology (Gero, 1990) and its extension, the situated Function-Behavior-Structure (sFBS) ontology (Gero & Kannengiesser, 2004) as a design-based coding scheme.

The broad applicability of this coding scheme (described in more detail in the Research Design and Methodology section below) is paramount in its value as a tool to analyze design cognition across education, experience and domains. Such cross-education, cross-experience and cross-domain analyses, including not only within engineering but between engineering and other fields, is critical if engineering education researchers hope to develop approaches to design thinking that are grounded in a deep understanding of student learning.

Research Design and Methodology

This project synergistically brings together methodologies from different disciplines to characterize and model the effects of education and experience on engineering students' and expert designers' design cognition. The methodologies are drawn from:

- design theory: design ontologies
- cognitive science: protocol analysis and cognitive style
- statistical modeling: standard statistical analysis, Markov modeling, problem-solution index.

Figure 3 shows the research design including *inputs, the process, analysis* and *outputs*. Using the function–behavior–structure (FBS) ontology, empirical research is collecting data from the verbal protocols of 60 (teams of two) undergraduate engineering students, and 20 (teams of two) professional expert engineers while designing. In order to capture a diverse population of undergraduate engineering students, 30 student teams include mixed populations. A cohort of 30 is sufficient to provide a statistically reliable dataset to measure any differences. Expert engineers are selected from a design companies in Seattle, Washington and Salt Lake City, Utah. Having the expert team members come from across the country gives a representative cross-section of the US.

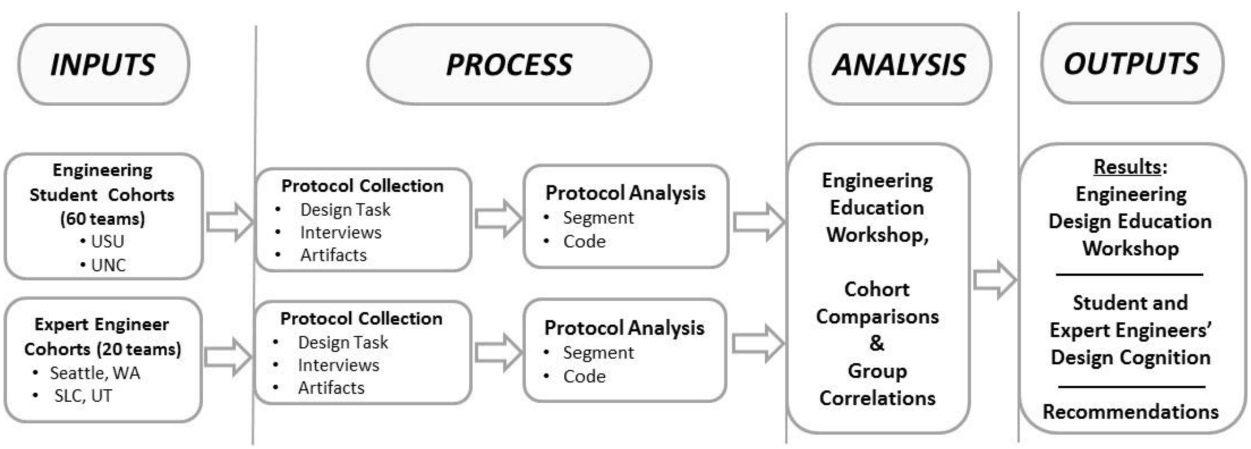

Figure 3. Research design showing inputs, process, analysis and outputs

Design Task
In this research, all teams complete the same functional-level engineering design task. Student participants are drawn from the freshmen year and senior year of engineering. The task is one that is not familiar to either the students or the experts.

The design task is a device for a double-hung window opener that assists the elderly with raising and lowering windows. This design task has been extensively used in studies involving high school students and college freshmen students (Atman, Kilgore, & McKenna, 2008; Gero, 2010). Students in high school and college freshman do not have enough related knowledge to solve complex design problems and the window opener task is appropriate for their knowledge level.

Participants are given a specified time to complete the engineering design task. Participants are requested to submit design proposals as their outcomes. There are no instructions about the form or the content of the proposals they will submit. All cohorts are given the same design task.

Cognitive Science: Protocol Analysis
Protocol analysis is a rigorous methodology for eliciting verbal reports of thought sequences as a valid source of data on thinking. It is a well-developed, validated method for the acquisition of data on thinking (Ericsson and Simon 1993; Van-Someren, et al 1994). It has been used extensively in design research to assist in the development of the understanding of cognitive behavior of designers (Atman et al 1999; Badke-Schaub et al 2007; Christensen and Schunn 2007; Gericke et al 2007; McDonnell and Lloyd 2007; Mentzer, Becker &Sutton 2015;McNeill et al 1998; Purcell and Gero 1998; Suwa, et al 2000; Tang and Gero 2002).

Protocol Analysis Methodology: The basic methodology of the protocol analysis method consists of the following sequence of tasks.

- *Coding development*. In typical protocol analyses the researchers commence with a pre-existing coding scheme and modify it based on the task and events in the current protocol. In this project we use a principled coding scheme based on the FBS ontology. The FBS coding scheme can be summarized, using the design terminology embodied in Figure 2. This produces six codes for the design issues (segments) and those six codes can be combined to produce eight design processes, Tables 2 and 3.

Table 2. FBS Codes

Code
R
F
Bs
Be
S
D

Table 3. FBS Processes

Design Process	
Formulation	R>F, F>Be
Synthesis	Be>S
Analysis	S>Bs
Documentation	S>D
Evaluation	Be<>Bs
Reformulation I	S>S
Reformulation II	S>Be
Reformulation II	S>F

- *Videoing of participants*. This involves capturing voice, sketching and gestures. Experience demonstrates that all three of these need to be captured to have a robust data source for the later segmentation and coding. The result is a time-stamped video of the design session. The camera used focuses on the participants and the design surface (white board) at the same time.
- *Transcription of verbalization into text*. Transcription of the utterances in a design session results in a time-stamped, text version of the verbalizations in a session. The transcription also includes design activities such as drawing and notation in addition to the utterances.
- *Segmentation of the verbalization as text*. Segmentation involves collecting into a single unit those verbalizations that cohere with each other. There are a number of possible bases for segmentation. The simplest is based on time, i.e., all segments have the same length of time. In this project, segmentation is based on individual design issues represented by the FBS codes. Each segment can contain only one code, Table 4. This harmonizes all segmentation when using this coding scheme, since there is now an *isomorphism between segments and codes*. This is a critically important advance in protocol analysis since the two separate processes of segmentation and coding of segments are now linked. The segments can be connected to time through the time-stamped text constituents of the segments.

Table 4. Example segmentation, with 6 segments based on the FBS coding.

R	(reads requirements) it need only be temporary
F	Does it need to be storable?
Be	It should be able to rotate.
S	If we have a ball joint
Bs	That will be expensive
S	What about a hinge?

- *Arbitration of segmentation/coding.* Two segmenters/coders are used to produce the final segmented/coded protocol in order to have robustness, which is measured by inter-coder reliability against the final, arbitrated protocol. Typical inter-coder reliability obtained by this method is above 75% and in this project was in the range of 80–90%. Agreement between coders is obtained using the Delphi method (Linstone & Turoff 1975; Rowe & Wright 1999). The result is the final, arbitrated protocol. This final protocol is the first data set available for analysis. The final protocol for a 60-minute design session may generate between 500 and 1500 segments. This provides a rich and statistically significant data set. The coders (doctoral students and researchers) are trained in the coding methodology using training documents from previous projects.

- *Producing the protocol's linkograph.* Linkography is a technique used in protocol analysis to study the structure of reasoning processes of designers (Goldschmidt, 1990). A link maps directly onto a design process and is the way in which design processes are captured from the empirical data. A linkograph can be constructed by connecting adjacent segments to produce a "syntactic" linkograph (Kan, 2008). This automatically generates the design processes since each segment is a design issue and the links are the transformations between one design issue and another, Table 3.

Cognitive Design Style
Cognitive style describes the way a person thinks. Cognitive design style is one characterization of a designer's design thinking. The differences between novices and experts are able to be characterized by the differences in their design styles. A cognitive style is further distinguished as consistent individual differences in the ways people experience, perceive, organize, recall and process information (Allinson & Hayes, 1996; Goldstein & Blackman, 1978; Messik, 1984; Riding, 1997). It is reflected in the organization of information in memory, the speed and accuracy of decision-making under uncertainty, the global or macro approaches to dealing with problems, and the preference for different problem solving strategies (Messik, 1976, 1984; Sternberg & Grigorenko, 1997).

Two measures of cognitive design style are used in this project, the first is the problem-solution index and the second is design patterns based on the transitions of design issues and design processes. These provide quantitative measures of design styles. Cognitive design style is measured at the meta-level by dividing the entire design activity into two cognitive spaces: problem space and solution space. A problem-solution index has been proposed and tested as a quantitative measure of the cognitive effort distributed between these two spaces, Table 5 (Jiang, 2012; Jiang, et al, 2012). This measure is called the "problem-solution index" or the P-S index.

Table 5. Mapping design issues and design processes onto problem and solution spaces

Problem/solution Space	Design Issue	Design Processes
Reasoning about Problem	Requirement (R) Function (F) Expected Behavior (Be)	1 Formulation 8 Reformulation II 7 Reformulation III
Reasoning about Solution	Behavior from Structure (Bs) Structure (S)	2 Synthesis 3 Analysis 4 Evaluation 6 Reformulation I

Problem-Solution index: A Measure of Cognitive Design Style
There are two P-S indexes: the P-S issue index, which measures the relative cognitive effort expended on design issues, or P-S process index, which measures the relative cognitive effort expended on design processes. The P-S index helps to characterize the overall cognitive style of a session, and is determined by calculating the ratio of the total occurrences of the design issues/processes concerned with the problem space to the sum of those related to the solution space, as shown in Equations (1) and (2). P-S indexes with a single value facilitate comparisons across multiple sessions and across sessions involving different situations.

$$\text{P-S index(cognitive issue)} = \frac{\sum(\text{Problem}-\text{related issues})}{\sum(\text{Solution}-\text{related issues})} = \frac{\sum(R,F,Be)}{\sum(Bs,S)} \quad (1)$$

$$\text{P-S index(syntactic cognitive processes)} = \frac{\sum(\text{Problem}-\text{related syntactic processes})}{\sum(\text{Solution}-\text{related syntactic processes})} = \frac{\sum(1,7,8)}{\sum(2,3,4,6)} \quad (2)$$

When the P-S index =1 the cognitive effort is equally divided between problem and solution. For values of P-S index < 1 more cognitive effort is expended on the solution than the problem and for values of P-S index >1 more cognitive effort is expended on the problem than the solution. The P-S index has been used to measure the effect of educational interventions in multiple environments and has been shown to be robust (Gero, Jiang & Williams, 2013; Jiang, 2012; Williams, et al., 2013).

Sequential P-S index as a time series: Designing is a dynamic activity. A single-value P-S index for an entire session will collapse any time-based changes into that single value. The sequential P-S indexes across different sections of a designing session generate a time-based "signature" of the cognitive style of the activity. When the session is divided into deciles, the P-S index for each decile is calculated, and used in a sequence of temporally ordered P-S indexes to represent the design style changes during the session. The P-S index provides an easily understood measure that can be used to compare the effects of educational interventions.

Design Patterns: A Measure of Learned Design Strategies
Design patterns, derived from the protocol data, represent learned connections between concepts that are re-used and become learned strategies. Experts have already developed their design strategies, while students are in the process of developing them. Finding design patterns provides an important means of measuring some significant differences between students and experts (Alexander, 1977; Erl, 2009; Kavakli & Gero, 2001; Smith, 2012). New methods have been developed to extract design patterns from the coded protocol data based on Markov models. These models automatically capture the transitions that form the basis of design patterns.

Statistical Modeling
Two classes of statistical analysis techniques are employed to obtain models from the two data sets of the final protocol and the final linkograph. Based on the information produced by these techniques, quantitative comparisons between the different levels of design experience can be made.

Standard Statistical Analysis: This generates the statistical distributions along with their variances of codes in segments in each of the final protocols and of the links in each of the final linkographs. This provides the foundation for the characterization of the design cognition of participants.

Markov Modeling: A Measure of Cognitive Design Strategies: Design styles and designer's strategies in terms of repeated processes can be assessed by building Markov models of the transitions between design issues and design processes (Kan, 2008). Markov models (Kemeny & Shnell, 1960) generates the probability of a particular design issue following another particular design issue. Markov models to represent cognitive design style have been used across multiple domains (Kan, 2008; Jiang, 2012; Pourmohamadi, 2013) and is one foundation for measuring quantitative differences between students and experts. Richer design patterns can be found using second- and third-order Markov analysis.

LINKODER (http://www.linkoder.com/) is a publicly available software tool that carries out the standard statistical analysis and Markov modeling on protocol data and is used for this project (Gero, Kan & Pourmohamadi, 2011).

Preliminary Results

The preliminary results reported here are derived from data collected from 26 freshmen engineering student volunteers drawn from Utah State University. They were presented with a design task to design of a device for a double-hung window opener that assists the elderly with raising and lowering windows. This design task has been used in previous research projects. The participants were formed into dyads and were given 60 minutes to complete the design task, during which time they were video recorded. As described above, the videos were transcribed, and then segmented and coded using two coders who then arbitrated the segmentation/coding to produce the final segmentation/coding for each design session. The distributions of the six design issues are presented in Figure 4.

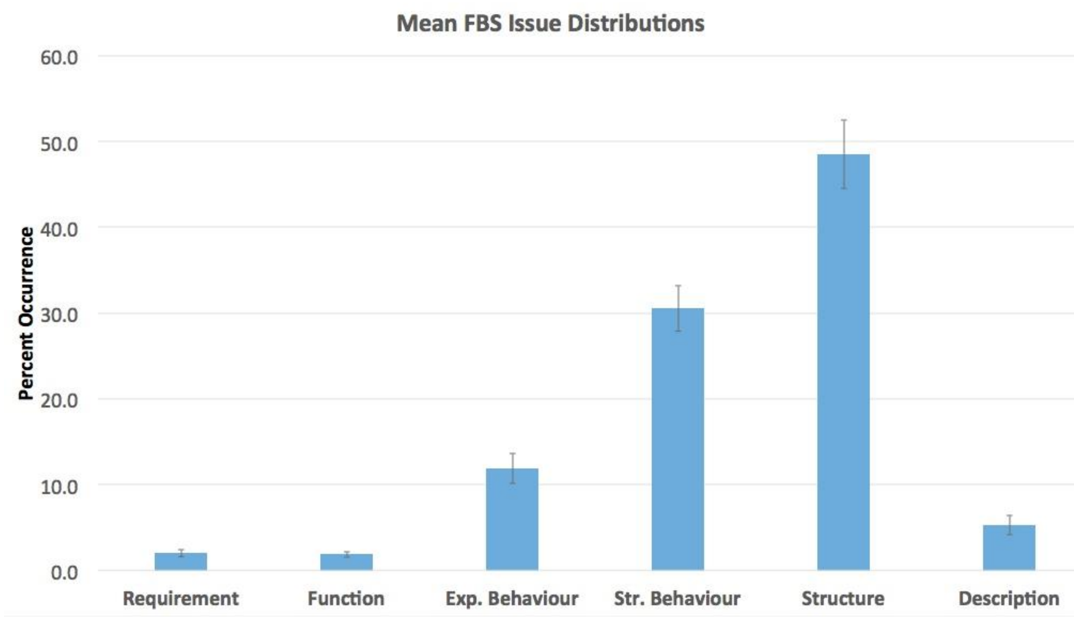

Figure 4. Distributions of the six design issues used to characterize design cognition for freshman engineering students.

From these results we can observe that almost 50% of the students' cognitive effort while designing is expended on the design issue of structure. Thirty percent of their cognitive effort goes into the design issue of structure behavior. While 12% of their cognitive effort is expended on the design issue of expected behavior. As a consequence freshmen expend 92% of their cognitive effort on three of the six design issues.

The distributions of the eight design processes are presented in Figure 5. These results indicate that these freshmen students allocate over 41% of the cognitive effort they expended on design processes to reformulation 1, i.e., on moving from structure to structure, and 22% of their process cognitive effort on analysis. With the 12% spent on evaluation, 75% of their effort can be accounted for by these three design processes.

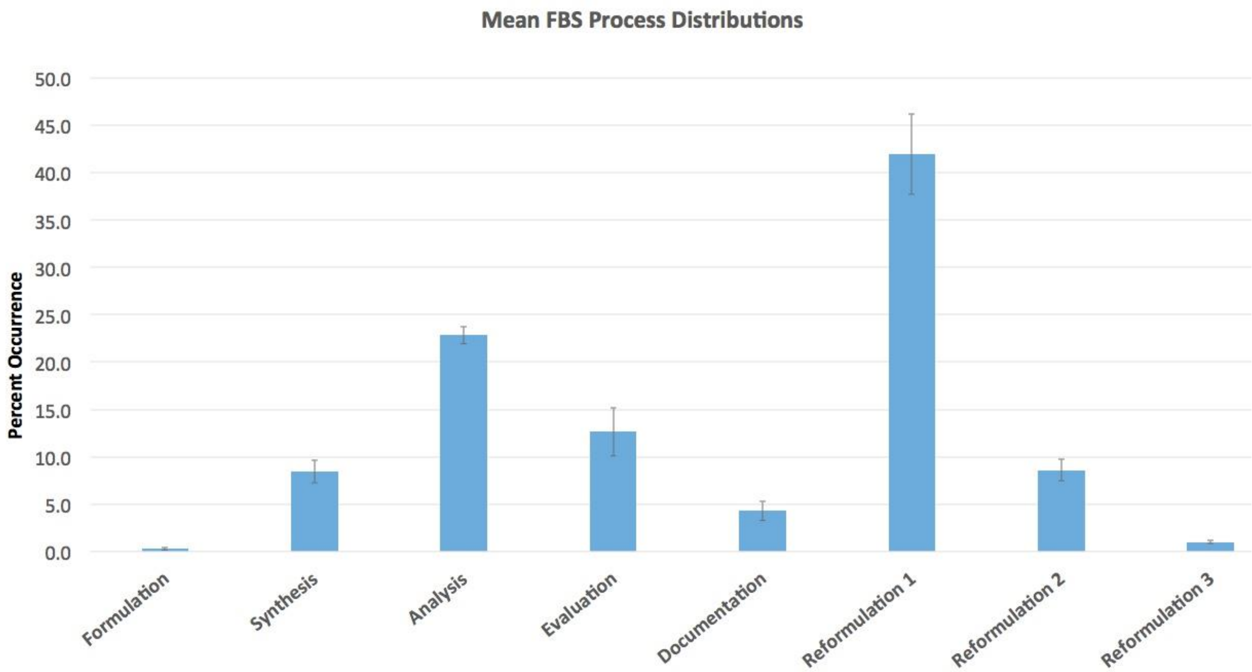

Figure 5. Distributions of the eight design processes that are used to characterize design cognition.

The P-S index across time is calculated for freshmen students and presented in Figure 6 as deciles. This shows that the P-S index reduces in value during the design sessions. This implies that these students increased their focus on the solution as the design session progressed.

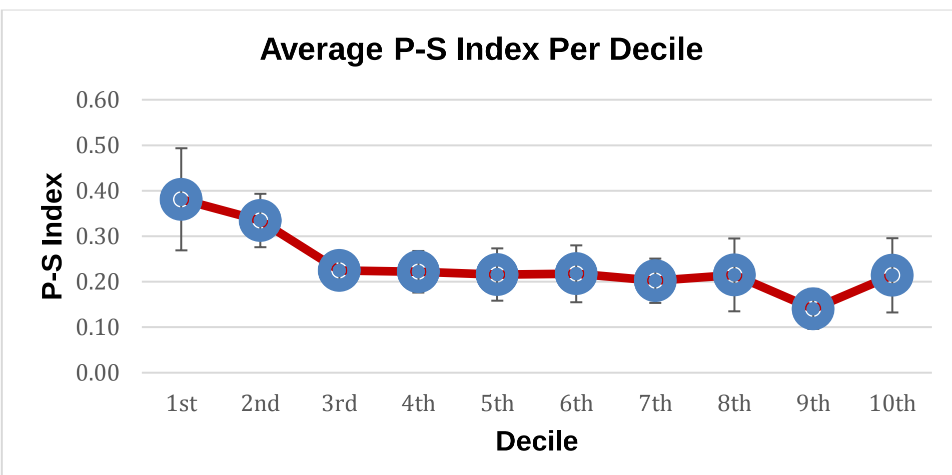

Figure 6. Average P-S Index per decile across all protocols.

Significance of Preliminary Results

These preliminary results form the control for the results of seniors and practitioners that are now being collected. They provide an evidence-based foundation for the effects of educational interventions between freshmen and senior years. Both the results of the design cognition of the freshmen and the seniors will be compared with those of the practitioners to determine learning trajectories across formal education and practice.

The results from this project motivate learning in upper-division courses, improve performance in capstone design courses, and have the potential to improve postsecondary cornerstone design experiences, which have been shown to enhance student interest and retention in engineering, especially among women, minorities, and underrepresented groups.

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