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FROM JOURNALS TO VALIDATED TOOL: RESULTS OF EMPIRICAL RESEARCH ON STUDENT DESIGNERS

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ABSTRACT (250 WORDS MAX)
This paper reviews a multi-year design research project that illustrates a general design research framework. Researchers collected detailed design process information from student mechanical engineering projects via design journals. They then coded the data and statistically modelled the relationship between design process variables and outcome measures of the student projects. Results of analyses revealed a set of design process variables that seem to differentiate higher versus lower performing teams. One of those was system-level design. Research effort then focused on the development of a design tool and method to aid students in this particular design phase. A controlled experiment verified the tool and method's usefulness to student designers. This paper presents the key outcomes of each research phase in relation to a previously published general design research methodology.

Keywords: empirical research, research methodology, design education, design tools

1 INTRODUCTION
Numerous design approaches, methods, and tools have been proposed over the years. Yet few have been rigorously tested or empirically validated. In recognition of this growth area in the design research field, Blessing et al. propose a general methodological framework for design research [1]. The framework starts with a clear definition of what we are trying to improve, followed by a "Descriptive I" phase involving observations of what seems to lead to successful design. The results of this phase should lead to a "Prescriptive" phase where new tools and methods are developed. The new tools/methods should then be validated in what the authors call the "Descriptive II" phase. The framework also includes iteration, where results from one step may lead one to return to an earlier phase.

Blessing et al. acknowledge that no one study would be expected to cover all the steps, but that every study should be positioned in the context of the general framework. They also indicate that, in much design research, several key linkages are weak, notably the linkage between Descriptive I and Prescriptive phases since few tools or methods are based explicitly upon descriptive studies.

In this paper, the author provides an overview of a multi-year design research effort that illustrates Blessing et al's general framework in the context of engineering design education. An in-depth empirical study (Descriptive I phase) resulted in insights regarding the importance of intermediate phases of the design process; that is, the activities and decisions that bridge conceptual design and detailed design. These insights led to the development of a design tool and method (Prescriptive phase) which was validated through a series of designed experiments (Descriptive II phase). The experiments resulted in a number of improvements to the design tool and method, and also determined that the tool was useful for junior and senior level students but not necessarily for truly novice student designers.

The remainder of the paper is organized as follows. The next section briefly reviews some of the literature related to the current work. Section 3 reviews the data collection and coding procedures used in the Descriptive I phase, while Section 4 reviews the statistical analyses results most pertinent to the present discussion. The following section presents a design tool and method developed as part of the Prescriptive phase along with experimental results of its usefulness. The concluding section summarizes a few observations of the overall project.

2 RELATED LITERATURE

The growing body of empirical work on engineering design has led to a number of insights on the nature of design processes. But as the work on design expertise has pointed out, it is not clear how to help novices (such as students) become experts [2]. It is further not clear that characteristics observed among expert designers are suitable for novice, i.e., student, designers. For example, researchers have observed that experts are often opportunistic in their approach to design problems, frequently deviating from structured or top-down approaches [2]. Yet one study of student designers found that reading a design textbook associated with improved design performance [3]. Similarly, an early study of mechanical designers concluded that mechanical design relies more on a richness of knowledge than on problem-solving techniques [4]; yet most engineering students are in the process of acquiring a rich knowledge base—how can we help them now? Thus the study of student design processes appears a critical piece to improving design education.

In recent years, a number of researchers have conducted empirical studies of student engineering designers, though their frequency relative to studies of practicing designers is sparse. One of the earliest [5] found a strong tendency among student designers to fixate quickly on initial concepts, and a comparable reluctance to let go of that concept even in the face of contradicting evidence (a tendency, interestingly, also observed among expert designers [2]). They also found satisficing behavior to be more prominent than optimizing behavior. In another study, verbal protocol analysis of senior and freshman engineering students led to a number of compelling observations [6]. They found that better design quality was associated with: more time spent gathering additional information, cycling through design steps multiple times rather than spending a long time on a given step before moving to the next and not returning, and going through all the design steps defined in the study. A more recent study found that training in design methodology did not help novice students initially; but that training did bear fruit once the students gained enough experience with the methodology to apply it flexibly [7]. These studies suggest a relationship between design process and the quality of what that process produces, but additional insight into the nature of those relationships would be useful for improving design instruction.

The literature on engineering design also contains numerous articles that describe new design methods or tools. Some of these have found their way into design textbooks. However, consistent with Blessing et al.'s [1] observation, it is rare to find a proposed design tool or method that has been rigorously tested and validated, and rarer still to find one that has been specifically validated for educational purposes. Thus a significant gap still exists between the descriptive research of the ilk described in the previous paragraph, and the development of validated tools and methods appropriate for engineering students. It is further unclear how well the prescriptive methods work for students outside of anecdotal evidence that providing some structure to the design task seems to be better than no structure at all. The research project outlined in the following sections provides one example for developing an empirically grounded and validated design tool suitable for engineering student designers.

3 DATA COLLECTION AND CODING

All mechanical engineering students at Montana State University complete a capstone design project in the final year of study. Teams of three to four students interface with a project sponsor to define the client's needs, generate and research alternative solutions, conduct engineering analyses, and present the project deliverables (written and oral reports, drawings, and in some cases a prototype) to meet the client's needs. Thus, every project has a unique set of design goals. Faculty advisors supply technical guidance through weekly team meetings over the 15 week semester.

Each student must document their project related activities in the form of a design journal. Over the four years that student journals were retained, the principal investigator trained the students in journaling by: a) providing an initial training session, and b) periodically collecting and evaluating the student journals, and giving feedback. Furthermore, members of the research team observed advisor meetings for a sample of projects to help verify that the data captured in the design journals were representative. The current sample of coded journals, selected at random from those collected, includes 19 projects representing 67 individual journals and over 7,000 pages of documentation.

3.1 Journal coding

Authors in the area of engineering design often characterize the design process through multiple lenses. Two of the more common are to view the process as series of overlapping phases (e.g., Ulrich and Eppinger's [8] generic product development process has 6 phases: problem definition, concept design, system-level design, detail design, test and verification, and production) and as an interactive set of activities (e.g., Atman and Bursic [9] identify 9 design activities for their protocol analysis: gathering information, generating ideas, modeling, evaluation, and so forth). Given that design participants work at different levels of abstraction throughout the project, theoretically engaging in similar types of activities at different abstraction levels, we developed the dual coding-scheme displayed in Table 1 [10].

Table 1: Coding Matrix

	Concept Design	**System-Level Design**	**Detailed Design**
Problem Definition	C/PD	S/PD	D/PD
Idea Generation	C/IG	S/IG	D/IG
Engineering Analysis	C/EA	S/EA	D/EA
Design Refinement	C/DR	S/DR	D/DR

Project Management	PM
Delivery	RW, PP

The coding scheme categorizes journal entries into three levels of design to capture high, medium, and low levels of abstraction as follows:

- Concept Design (C) – addressing a given problem or sub-problem with preliminary ideas, strategies, and/or approaches.
- System-level Design (S) – defining subsystems for a particular concept, and defining their configuration and interfaces
- Detailed Design (D) – quantifying specific features required to realize a particular concept.

The coding scheme also defines four types of design activity that capture the heart of the engineering problem-solving process:

- Problem Definition (PD) – gathering and synthesizing information to better understand a problem or design idea.
- Idea Generation (IG) – qualitatively different approach(es) to a recognized problem.
- Engineering Analysis (EA) – evaluation of existing design/idea(s).
- Design Refinement (DR) – modifying or adding detail to existing design/idea.

Each design-related journal entry received a design level code and a design activity code. Three additional designations describe activity not bearing directly on the design problem, yet essential to successful project completion: project management (PM), report writing (RW), and presentation preparation (PP).

After the journal entry had been coded by activity type and design level (or PM/RW/PP), time was allocated to each code according to the start and end times recorded. For entries with more than one code or dual-code, time was allocated in proportion to the space taken up by that activity on the page.

Journal coding proceeded in two stages. First, research assistants familiarized themselves with the projects by reading the final written reports, then coded entries and captured times by walking through team members' journals in lock step, considering all the members' entries for a given day before assigning codes and times, and before moving to the next recorded day. Simple rules were devised for resolving discrepancies among the different journal accounts. The principal investigator then reviewed the coding as a crosscheck on accuracy and consistency. Disagreements were resolved through discussion and the process continued until mutual agreement was reached. The code and time data were then entered into a database, and aggregated for the project by combining individual journal data.

3.2 Design quality measures

Arguably the effectiveness of a design process should be measured by the quality of what the process produces. To measure the "goodness" of the students' end products, we developed, validated and deployed two instruments for measuring the client satisfaction and design quality quantitatively: the Client Satisfaction Questionnaire (CSQ) and the Design Quality Rubric (DQR) [11, 12].

The CSQ, created by adapting pieces of previously developed surveys [13, 14, 15], consisted of 20 questions that used a five-point Likert scale for recording responses. The survey was validated prior to implementation using content and face validation techniques. Analytical hierarchy process [16] was used to determine weights for the measures comprising each metric. Project clients were faxed a copy of the survey, then a research assistant walked them through the questions by telephone and filled in the responses by hand. Next, the survey data were analyzed for statistical reliability using the Cronbach's alpha coefficient. Two metrics exhibited adequate inter-metric consistency, and were subsequently used to calculate a client satisfaction index:

- Quality – The percentage of the design objectives the client thought the team achieved, and the closeness of the final outcome to client's initial expectations.
- Overall – Design's feasibility in its application and fabrication; client's likeliness to implement the proposed final design; client's opinion on students' knowledge of math, science and engineering in developing solutions; and overall satisfaction with the design outcome.

The client satisfaction index was then calculated by summing these two metrics, resulting in scores on a scale of 2-10 with 10 being the highest (each metric having a 1-5 scale). For more details on CSQ development, see Jain and Sobek [11].

To develop the DQR, we first obtained evaluation schemes from mechanical engineering capstone course instructors at 30 top ranking mechanical engineering programs in the US, and from several design contests [17, 18, 19, 20]. From the evaluation schema, we extracted 23 metrics common to the evaluation schema used to rate a design project, and aggregated them into six broad categories: requirements, feasibility, creativity, simplicity, aesthetics and professionalism. Since aesthetics is not a requirement in many of our projects, and professionalism deals more with report/presentation quality attributes than design quality directly, we grouped them with an "overall impression" question to capture the reviewer's overall assessment, which could include professionalism and aesthetics if appropriate. The final DQR metrics and their definitions are:

- Requirements – the design meets the technical criteria and the customer requirements.
- Feasibility – the design is feasible in its application and fabrication / assembly.
- Creativity – the design incorporates original and novel ideas, non-intuitive approaches or innovative solutions.
- Simplicity – the design is simple, avoiding any unnecessary sophistication and complexity, and hence is: practical, reliable, serviceable, useable, ergonomic, and safe.
- Overall – overall impression of the design solution.

A seven-point scale was used for each question/metric and three anchors provided (1-poor, 4-acceptable, 7-outstanding).

Four engineering professionals were hired to evaluate the project outcomes as presented in the students' final reports. All four evaluators assessed two of the reports in order to determine inter-evaluator consistency; the remaining projects reports were each assessed by at least two evaluators.

The quality index for each project was calculated by averaging the scores of the individual metrics, then averaging across evaluators. For more details on DQR development, see Sobek and Jain [12].

4 JOURNAL DATA ANALYSES

A series of analyses using different statistical modelling approaches related the quantified design process variables to the outcome measures, as summarized in Table 2. The analyses resulted in different results, in part because they were done at different stages of the research, in part because the response variables differ, and in part because the different modelling approaches employ different methods to study the relations among the variables. What seems to be instructive here is not that any one of the analyses is "correct" and the others wrong, but the overall trends.

Table 2: Summary of Statistical Analyses

Reference	**Modelling Approach**	**Response Variable**	**Significant Design Process Variables**
[21]	Linear Regression	Client Satisfaction	+ Conceptual Problem Definition + Conceptual Idea Generation + Detailed Engineering Analysis - Detailed Design Refinement
[21]	Linear Regression	Design Quality	+ Conceptual Design Refinement + System Engineering Analysis - System Idea Generation
[11]	Virtual Design of Experiments	Client Satisfaction	+ Conceptual Problem Definition + Conceptual Idea Generation + System Problem Definition + System Engineering Analysis - Conceptual Engineering Analysis - Conceptual Design Refinement - System Design Refinement - Detailed Idea Generation - Detailed Engineering Analysis - Detailed Design Refinement
[12]	Virtual Design of Experiments	Design Quality	+ Conceptual Problem Definition + System Problem Definition + System Idea Generation + System Engineering Analysis - Conceptual Idea Generation - Conceptual Design Refinement - Detailed Problem Definition - Detailed Design Refinement
[22]	Factor Analysis	Design Team Productivity*	+ System Problem Definition + System Idea Generation - Conceptual Design Refinement - System Engineering Analysis - Detailed Idea Generation

* Productivity calculated by averaging the project's client satisfaction and design quality measures and dividing by total person-hours of team effort.

Upon inspection of the significant design process variables, it is clear that all three levels of abstraction are important to project outcomes. Further, more time/effort spent at detailed levels appears to have the most negative associations, while more time/effort spent at the system level appears to have the most positive association. Time/effort spent at the concept level was roughly evenly split.

A similar inspection of design activities reveals that problem definition garners the most positive associations, while design refinement sees a preponderance of negative associations. Idea generation and engineering analysis activities were more evenly divided between negative and positive associations across the design levels.

Putting the design levels and activities together, it appears that the design level-activity combinations that receive the most positive associations with desirable project outcomes are: concept level problem definition and idea generation, and system level engineering analysis. Those combinations receiving the most negative associations were any activity at the detailed level, and design refinement at any level. This qualitative evaluation is displayed graphically in Figure 1. Project management, report writing, and presentation preparation time/effort measures were also evaluated, but no significant associations were found.

	Problem Definition	Idea Generation	Engineering Analysis	Design Refinement
Concept	+ + +	+ + –	–	+ – –
System Level	+ + +	+ + –	+ + + –	–
Detail	–	– –	+ –	– – –

Figure 1: Graphical Depiction Statistical Analyses Results

These results suggest a number of possible avenues for further research. The one that intrigued this author the most, however, was the strongly positive significance of system-level design activities across many of the analyses. Compared to some of the other variables in the analysis, such as idea generation and problem definition, relatively little has been written about system-level design. Also, in our sample, system level design activity accounts for less than 10% of all design team effort; and yet it frequently appears as significantly positive, and often the strongest predictor or effect observed. Thus the research effort turned towards a deeper understanding of this set of design activities.

5 TOOL DEVELOPMENT AND EXPERIMENTATION

System-level design in this work is defined as all design activity related to defining the subsystems required to realized a given concept, their configuration and (perhaps most importantly) their interfaces. While the results reported in the previous section indicated a positive association between system level design activities and project outcomes, we had not yet established a causal relationship. To attempt to demonstrate this causality, we conducted a human subjects pilot experiment in the context of an introductory design course taken by third and fourth year mechanical engineering students [23]. In the experiment, students were asked to solve one of two design problems in a laboratory setting, randomly assigned. In the first run, teams followed a specified protocol (a very basic design process) that did not mention system-level design. In the second run, student teams solved the other design problem with a protocol very similar to the first, except it specifically prompted system-level design tasks. Design quality was assessed by combining a performance score for the main functional requirement with a score for design simplicity (based on a simple part count—fewer parts used meant a simpler design).

The experimental results were indeterminate, but we learned that merely instructing students to do system-level activity was insufficient. A tool was needed. However, some students did system-level design even when not instructed to do so. A secondary analysis of the documents students created in the experiment provided further evidence that system-level design associated with better design quality. Based upon this empirical result, the research team developed a design tool to aid student designers specifically in system-level design as a literature search turned up no tools to help with this phase of design.

5.1 Tool and method

The tool developed is an extension of morphological analysis applied to the system architecture. The design method that employs the tool instructs the design team to apply the tool before concept selection. Then, for each concept under consideration, the design team:

1. Identifies the key functions of that concept needed to realize the design objectives
2. Generates 2 or more options to accomplish each function
3. Identifies which function options cannot be used with other options (exclusions)
4. Identifies which function options require inclusion of another option (dependencies)
5. Generates a list of alternative configurations for the concept alternative
6. Investigates interface feasibilities
7. Selects the most promising configuration

The tool is simply a matrix of functions and option alternatives. It also prompts the design team to list exclusions and dependencies, and record alternative configurations in spaces provided. The result of the system-level design exercise is a set of alternatives going into concept selection, where a 'best' configuration has been initially identified for each concept alternative.

5.2 Experiment and results

Another crossover design experiment was conducted, where the main experimental variable was using the tool and method, or not [24]. The sample consisted of a different set of students in the same class the following semester. Again, two runs were conducted, the first one without using the system-level design tool and method, and the second requiring its use. In between the runs, the experimenter ran a training exercise in class with the student participants.

The experimental results confirmed our hypothesis that using the system-level design tool and method improves design quality, as measured by the experimental protocol, among engineering students. A post-experiment survey of the participants yielded triangulating results that the students generally found the tool helpful, and that a majority would use the tool on a future design project.

A third experiment was conducted to try to better understand a few questions that arose in the second experiment:

- Is the tool or the method more important? Or are both needed?
- Is it more effective to apply the tool before or after concept selection?
- Does the tool's usefulness increase with problem complexity?

We conducted a 2^4 designed experiment, and because of sample size needs, used freshman engineering students as subjects. It turned out that no effects were observed, even between those using the tool and method and those using neither (as opposed to one or the other). Thus it appears from this experiment that the tool is not very useful for very novice designers (a.k.a., freshman) who are still learning fairly elementary problem-solving skills.

6 CONCLUSION

The overview just described thus illustrates a general design research methodology [1]. Basic empirical work on the design processes of engineering students identified a set of design activities that seem to strongly associate with positive design project outcomes (client satisfaction, design quality as determined by practicing professionals, and design team productivity). The set of design activities centers on the design and development of system architecture and related issues, a topic that has not received much attention in the design literature relative to others. This motivated the development of a design tool and method targeted at that specific phase of the design process. The tool was validated among 3rd and 4th year engineering students, but failed to precipitate a similar effect among freshman students. Thus the tool and method are grounded in empirical research, and validated for use in upper division engineering students.

As Blessing et al. [1] acknowledge, not all design research should be expected to complete every phase of the general design research methodology. However, it is possible to do so, and doing so can lead to robust, rigorously tested enhancements to design methods. Future work will seek to further understand the intricacies of system-level design, and its relations to preliminary (or conceptual) design and detail design. We also hope to test the usefulness of the tool in industrial settings.

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