Transitions: From Conceptual Ideas to Detail Design

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Abstract

In previous meetings, we presented preliminary work on coding student design journals as part of an effort to better understand how design processes affect design outcomes. We have also conducted a number modeling efforts on a dozen student mechanical engineering projects that correlate key process variables to design quality, client satisfaction, and designer productivity measures. One of the main patterns across the different analyses is that system-level design, which falls between concept design and detail design, consistently appears as a strongly significant variable distinguishing strong performing projects from weaker performing projects. In this paper, I briefly summarize the results of three analyses on the coded journal data. I then explore what "system level design" is, illustrated with a case example, and how it serves to bridge the gap between concept and detail design. These results have important implications for engineering problem-solving in general (not just design), which are also discussed.

1. Introduction

> *…over the years I've become increasingly frustrated with the belief that more ideas alone mean better results. If you're serious about encouraging creativity in yourself or others and if you want to deal with change effectively, then implementing ideas is at least as important as generating ideas…. Creativity requires that ideas be implemented, and it is in the pragmatic details of implementation that creativity often fails, relegating the ideas to occasional hindsight discussions at cocktail parties.* [1]

Creativity is certainly a very important part of innovating clever solutions to problems encountered as part of the human endeavor, what we call engineering design. However, as James Adams[1] points out in the introduction to his book on creative problem-solving, good ideas are not very useful if never implemented.

All authors of engineering design texts implicitly recognize this same notion when they propose design process models. These models intend to provide the designer with guidance in how to proceed from recognition of a need to preliminary, abstract ideas on how that need could be met, and on to detailed, concrete solutions. Many authors recognize that design proceeds roughly (though not strictly) in stages or phases. And while no two design process models are exactly alike, they all seem to explicitly include a problem definition/information gathering/need recognition phase, a concept design phase, and a detail design phase. Most also include a transition phase of some kind between concept and detail design. For example, Ulrich and

Eppinger[2] define concept, system-level, and detail design phases of product development; Dym and Little[3] present concept, preliminary, and detailed design as key stages; Pahl and Beitz[4] identify concept design, embodiment design, and detail design as distinct design phases. Interestingly, many tools and techniques exist for concept design (e.g., brainstorming techniques, attribute analysis, and selection matrices), and for detail design (e.g., CAD and CAE tools), but the transition from the vague and abstract to the detailed and concrete has received little attention.

In counterpoint, prior work on product development processes in the automotive industry found that this transition phase receives substantial attention and resource at Toyota Motor Corporation, but comparatively little among US competitors.[5] Interestingly, Toyota has consistently outperformed its US competitors over the last two decades by nearly all measures. This motivated a study of design processes that explicitly included system level design in the slate of research parameters to answer the question: just how important is this transition phase?

This paper summarizes a trio of analyses that correlates design process characteristics to design outcomes in mechanical engineering capstone design projects. A theme from those studies is that, even though system-level design activity typically constitutes a small portion of design effort among student design teams, it associates strongly with higher performing teams. I then describe what we mean by "system-level design" and discuss implications for teaching design.

2. Background

In 1999 we embarked on a study to better understand student design processes by collecting and characterizing design process data from student capstone projects, measuring the "goodness" of the products of these projects, and modeling the data to see how the process parameters associate with the outcome measures. We collected process data from mechanical engineering capstone projects via design journals kept by the students. We trained the students in journaling, then periodically evaluated the journals for thoroughness throughout the semester to increase the quality and quantity of data recorded.[6] Students were required to put time and date stamps on all journal entries, which gave us a means to quantify the processes. Journals were retained at the conclusion of the semester.

A subset of the projects was selected from among those with usable journal records for coding. We developed a coding scheme that identified four categories of design activity (problem definition, idea generation, engineering analysis, and design refinement) and three design levels (concept, system, and detail).[7] Of particular interest for this paper is system-level design—"defining subsystems for a particular concept, and defining their configuration and interfaces"—in contrast to concept-level design ("addressing a given problem or sub-problem with preliminary ideas, strategies, or approaches") and detail-level design ("quantifying specific features required to realize a particular concept").

Each journal entry received an activity code and a design level code in order to distinguish, for example, concept-level problem definition from system-level problem-definition, or concept-level analysis work from detail-level analysis. Table 1 summarizes the dual coding scheme, which will be used extensively in the next section. Time values for each code were estimated from the journal time stamps, and entered into an electronic database by date. Data were then aggregated to the project level to increase the reliability and representativeness of the data. (See Sobek[7] for more detail on the codes and coding protocol.)

Design Activities	*Design Levels*		
	Concept (C)	**System (S)**	**Detail (D)**
Problem Definition (PD)	C/PD	S/PD	D/PD
Idea Generation (IG)	C/IG	S/IG	D/IG
Engineering Analysis (EA)	C/EA	S/EA	D/EA
Design Refinement (DR)	C/DR	S/DR	D/DR

TABLE 1: CODING MATRIX

To measure the outcomes of the student projects, we developed a client satisfaction questionnaire and a design quality rubric.[8] The client satisfaction questionnaire measured the degree to which the project's client was satisfied with the final product. Two composite measures based on a 1-5 scale were summed into a 2 to 10 satisfaction score, with ten being high. The client responses were collected via telephone to ensure a 100% response rate. During those discussions we learned that client satisfaction was relative to the client's initial expectations coming into the project. Thus, to get a more objective comparison of the quality of student products relative to one another, we contracted four professional engineers to evaluate the final reports (which included engineering drawings and analyses) using a design quality rubric. The rubric asked the evaluator to score the project along 5 metrics on a scale of 1-7 (seven being high), which were averaged to obtain a quality score for the project. A minimum of two practicing professionals evaluated each project. (See Sobek and Jain[8] for details on the instruments and their development.)

To date we have coded journals from 19 projects, although the analyses reported in the next section where done at a point when only 14 projects had been coded; work to incorporate the additional five projects is ongoing. Journals from the 14 projects represent over 5,000 pages of documentation from 47 individual journals and thousands of hours of student work.

3. Modeling Efforts and Results

To date, the modeling efforts have focused on total accumulated time for each of the 12 activity/design-level parameters, e.g., the number of person-hours spent on concept-level problem definition for the entire semester. This section summarizes the results from three analyses on these data.

The first analysis used a step-wise reverse elimination technique to create two multiple linear regression models: one using client satisfaction score as the response variable, the other using design quality score.[9] The independent variables were the number of person-hours spent on each design-level/activity combination over the course of the project as. Table 2 displays the final models. Both models show excellent fit as measured by R-squared, and interestingly, show little overlap in the statistically significant variables. Other parameters were also included in the analysis, such as team size, effort level, amount of report writing, project management, and presentation preparation; but none of these improved the model or provided a better fit.

Independent Variables	Client Satisfaction Model	Design Quality Model
Intercept	4.203 **	1.899 **
Conceptual Problem Definition (C/PD)	0.085 **	
Conceptual Idea Generation (C/IG)		
Conceptual Engineering Analysis (C/EA)	-0.110 **	
Conceptual Design Refinement (C/DR)		-0.159 **
System Problem Definition (S/PD)		
System Idea Generation (S/IG)		0.060 *
System Engineering Analysis (S/EA)		
System Design Refinement (S/DR)		0.117 **
Detailed Problem Definition (D/PD)	0.027 **	
Detailed Idea Generation (D/IG)		
Detailed Engineering Analysis (D/EA)	0.020 **	0.018 **
Detailed Design Refinement (D/DR)	-0.006 **	
R^2	0.957	0.908
Standard Error	0.377	0.369
Degrees of Freedom	8	9
n	14	14

* $p \leq .05$, ** $p \leq .01$

TABLE 2: REGRESSION MODELS FROM WILKENING AND SOBEK[9]

The second analysis involves a more sophisticated modeling technique: virtual design of experiments (VDOE).[10] In this technique, two principle components neural network models were developed relating the 12 process variables to client satisfaction[11] and design quality[12] respectively. In this case, the process variables were expressed as a proportion of total design time (rather than raw hours, as was done in the previous analysis). Both neural network models had six principle components and one hidden neuron layer. Then, using the neural networks to predict project outcomes, two 2^{12-4} fractional factorial design of experiments were conducted, one on client satisfaction and the other on design quality, to see the effects of the different independent variables. The data were analyzed using analysis of variance (ANOVA). The results of the two ANOVA models were then used to determine the relative importance of the significant factors by dividing the slope of the variables versus the response variable by the absolute value of the lowest magnitude slope (D/DR in both cases). These are displayed in Table 3.

Factor	Relative Slope Estimates	
	Quality Model	*Satisfaction Model*
Conceptual Problem Definition (C/PD)	4.96	8.20
Conceptual Idea Generation (C/IG)	- 36.50	8.16
Conceptual Engineering Analysis (C/EA)	*	- 4.09
Conceptual Design Refinement (C/DR)	- 48.97	-11.83
System Problem Definition (S/PD)	40.46	9.46
System Idea Generation (S/IG)	31.61	*
System Engineering Analysis (S/EA)	114.51	21.06
System Design Refinement (S/DR)	*	- 4.13
Detailed Problem Definition (D/PD)	-14.82	*
Detailed Idea Generation (D/IG)	*	- 7.71
Detailed Engineering Analysis (D/EA)	*	- 6.06
Detailed Design Refinement (D/DR)	- 1.00	- 1.00

* Insignificant at $p \leq 0.05$

TABLE 3: RELATIVE FACTOR SLOPE SCALING FROM SOBEK AND JAIN[10]

The third analysis used a productivity measure as the response variable.[13] Productivity was calculated by averaging the client satisfaction and design quality scores of each project (seeing that students are, in theory, trying to optimize both), then dividing by the total number design hours dedicated to the project. The independent variables were the number of person hours spent at each design-level/activity, as in the first analysis. To analyze the data, we conducted a factor analysis on the independent variables resulting in four factors that explained 86% of the variance of the original variables. These factors were then fit to the productivity scores using a linear regression model. One of the factors was insignificant and was removed. The remaining factors were significant at levels much lower than 1%. We then multiplied the vector of regression coefficients and the matrix of factor loadings for these factors to obtain an estimate of the strength of association each of the original variables has with productivity. These productivity coefficients, as we termed them, are displayed in Table 4.

Design and Activity	Productivity Coefficient
Conceptual Problem Definition (C/PD)	-1
Conceptual Idea Generation (C/IG)	0
Conceptual Engineering Analysis (C/EA)	4
Conceptual Design Refinement (C/DR)	-19
System Problem Definition (S/PD)	11
System Idea Generation (S/IG)	31
System Engineering Analysis (S/EA)	-10
System Design Refinement (S/DR)	1
Detailed Problem Definition (D/PD)	5
Detailed Idea Generation (D/IG)	-12
Detailed Engineering Analysis (D/EA)	1
Detailed Design Refinement (D/DR)	0

TABLE 4: PRODUCTIVITY COEFFICIENTS BY DESIGN LEVEL AND ACTIVITY FROM COSTA AND SOBEK[14]

Each of these analyses takes a different look at the data, so we would expect to see differences in each despite being based on the same underlying data set. One of the themes that became apparent as we conducted these different analyses is how often system level design crops up as significant, often in the positive direction. The regression analysis found that system-level idea generation and design refinement were significantly associated with design quality, in the positive direction. In the VDOE analyses, system-level problem definition, idea generation, and analysis were positively associated with quality while system-level problem definition and engineering analysis were positively associated with client satisfaction. In the factor analysis, system-level problem definition and idea generation were moderately to strongly associated with productivity. In contrast, though, the VDOE analysis found system-level design refinement associates negatively with customer satisfaction and the factor analysis found a moderately negative association between system-level engineering analysis and productivity.

That system-level design is significant at all is especially striking given that system-level design work accounts for less than 10% of total design time in this data set. In some cases system-level activity was the strongest indicator in the model (i.e., S/EA in the VDOE quality analysis, S/IG in the factor analysis of productivity). This suggests that the transition phase between concept and detail design certainly is important, and could be a significant contributor to higher design team performance along multiple dimensions, but especially design quality and designer productivity. Further, that some variables (e.g., system-level engineering analysis) have a positive association with quality and a negative association with productivity is provocative and suggests further investigation is needed. Do design teams get a good "bang for the buck" with this activity, or is there some other dynamic going on that we do not yet understand?

4. What is System-Level Design?

To define system-level design more fully, I briefly explore how a number of authors have proposed to transition from concept to detail design, then revise our own definition taking the literature and our own research into account. Pahl and Beitz[4] identify the transition phase as an overall layout design (general arrangement and spatial compatibility), preliminary form design (component shapes and materials), the production process, and solutions to auxiliary functions. Embodiment design, as they call it, consists of a series of analysis-synthesis iterations to improve the layout for a given concept. This iteration is necessary due to the complexity and difficulty in foreseeing the consequences of change in a highly interrelated system. Dym[14] also focuses on layout design, which he defines as deciding the general arrangement of components and assemblies with respect to spatial compatibility, in transitioning from concept to detailed design. Otto and Wood[15] expand on Pahl and Beitz's concept of embodiment design, suggesting embodiment design as a way to develop and understand alternative concepts in greater depth when it is not clear that one alternative concept is superior. This suggestion recognizes that a complete assessment of an idea is not always possible at a conceptual level. The transition phase is then used to test preliminary designs of a concept.

Ulrich and Eppinger[2] emphasize product architecture decisions in the transition from concept design to detailed design. Specifically, they point out the need to identify the product's subsystems, define their functions, and decide how modular to make the design. The degree of modularity is determined by a) the separation of function among the components/subsystems, and b) the complexity of interface. In other words, how easily can a module be replaced or updated without impacting the rest of the system?

Pugh,[16] interestingly, does not distinguish a transition phase. Rather, he begins the detailed design phase with a step called "component design specification" (CDS). CDS involves defining the constraints for components to include not only functional performance parameters, but also interface and spatial constraints imposed by the system configuration. The interaction between the subsystems of the design should be considered as constraints imposed by those subsystems. Similarly, Ullman[17] does not define a distinct phase, but incorporates specific transition activities between concept design and component design at the beginning of a detailed design phase he calls the product development phase. These transition activities include configuration (or arrangement) of components and assemblies of components, keeping in mind spatial constraints, and defining interfaces between components that support their function.

Thus, the transition between concept level design and detailed level design seems to be characterized by exploration of and decisions about: what the components and subsystems are and what their function will be; how the different pieces will be arranged, including location, orientation, and grouping; and how the pieces will connect or interface. Often, it seems from our journal data, student teams assume a certain configuration in their conception of the solution concept, then proceed immediately to CAD tools to conduct detailed part design or detailed analysis. What these authors advocate, and what our data seem to show, is that taking project time to explicitly consider configuration as a design problem in its own right results in higher quality solutions and better use of designers' time.

To illustrate what might be considered system-level design, we pulled an example from one of the journals in our study. This team was designing a parachute release mechanism for a military application that would release upon water entry. One of the sub-problems they faced was how to activate the release mechanism. One of the concepts was to use a CO_2 gas cylinder, activated by a lanyard pull, which would pressurize a line to throw a piston. Figure 1 below illustrates what might be considered a rudimentary design study of the configuration of the different subsystems needed for this concept. The CO_2 gas cylinder is mounted underneath a lanyard assembly and the pressure is regulated by a combination of the tank and the timer with piston. This preliminary design begins to address how the different pieces will be located in relation to one another, and how they will interface (note the several callout labels on the diagram). Later in the same journal entry, we find notes-to-self the student has made to investigate "how to clean orifice," "how to replace CO_2 cartridge easily," and "how to attach CO_2 cartridge to copper line." Thus we see the student designer is clearly thinking about interface issues (broadly speaking) with respect to this concept.

Interestingly, the team performed a similar design study in parallel on a competing concept involving a mechanical clutch. After conducting the two configuration design studies, the team was able to determine with confidence that the design they had originally favored based on their concept level work, the clutch, was inferior to the CO2 cartridge idea in terms of cost, complexity, part count, and anticipated design challenges and unknowns. It appears that an hour or two of system-level design work helped the team make a decision that potentially saved many hours of iteration in detailed design.

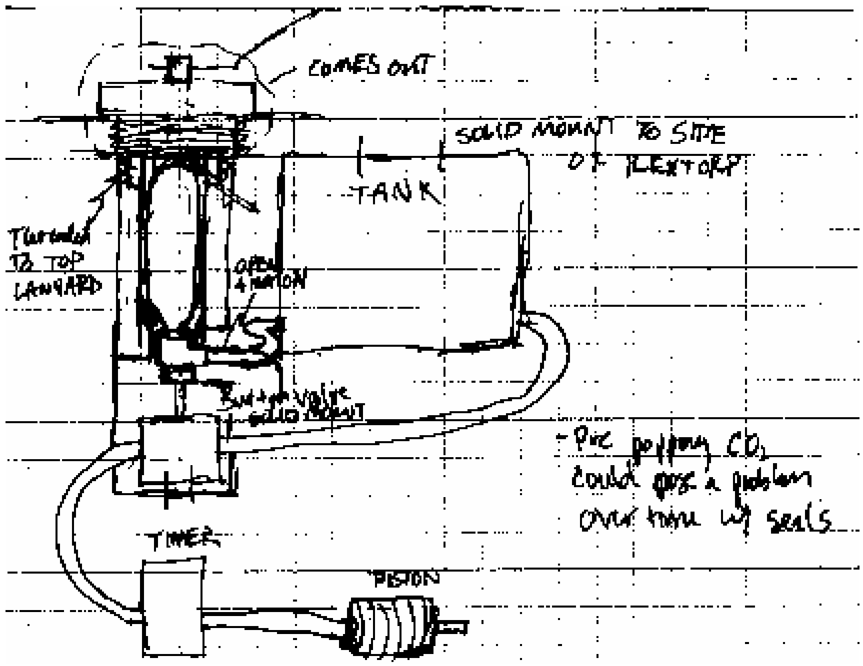

FIGURE 1: EXAMPLE OF SYSTEM-LEVEL DESIGN WORK FROM STUDENT JOURNAL

5. Summary and Implications

The data from these ME student capstone projects seem to indicate that concept-level design work and detail-level design work are both important to a successful design project; but equally important is the transition from concept to detailed problem-solving. As Adams indicates in the opening quote, implementation is as important as the idea itself. The usefulness of this design phase seems to be the ability to reason about design solutions in greater depth than one typically can with high-level, general concepts, but yet not have to expend the time and resource required for detailed design. It enables greater depth of understanding of a solution concept while keeping flexibility for alternative subsolutions. We've also observed that designs often fail at the interfaces, so design effort that explicitly considers interfaces within designed systems seems prudent.

One of the challenges we see is that system-level work does seem to involve detailed investigation, just not on everything. Good system-level work seems to entail knowing which details (the "vital few") are important at that stage of design and investigate those thoroughly, leaving the many, less significant details until later. Making this even more challenging is the fact that few if any tools exist to help with system-level design. We are given general guidance on what's needed, then told to "just do it."

Future work involves expanding the analyses above to the full data set we currently have (19 projects) to confirm the results of this first set of analyses. It will also focus on the development and validation of tools to assist the transition from concept to detail design is the subject of future work. I also hope to test these ideas in other engineering disciplines to test whether the transition from concept to detail design is equally important in other domains such as electrical systems design, transportation system design, structural design, or multi-disciplinary design. Another avenue of possible future work is to conduct a parallel study in industry to see if we observe similar effects.

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