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HOW PROCESS AFFECTS PERFORMANCE: AN ANALYSIS OF STUDENT DESIGN PRODUCTIVITY

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ABSTRACT

In this paper, we analyze journal data from twelve student projects to help identify design processes that achieve higher quality in less time. Journal data are coded for the number of engineering hours spent on different design activities at three design levels. Each project's outcome is independently assessed for client satisfaction and design quality. We use factor analysis to group common variability into factors. A multivariate linear regression model of three factors explains 91% of productivity variance within the study sample. The factor scoring coefficients are then used to translate the regression model coefficients back to activities and design levels. Results indicate that generating ideas and defining the problem at a system level are the key discriminating variables between more or less productive design teams in our sample, while conceptual design at the front end and detail-level work at the back end are not associated with productivity.

Keywords: Engineering Design, Design Process Attributes, Design Process Productivity, Design Quality, Design Process Model.

INTRODUCTION

Product development organizations are under increasing pressure to provide innovative products at a lower cost in shorter time. To simultaneously increase quality and throughput while reducing cost requires a better understanding of the underlying principles of design. Also, from an educational standpoint, a deeper understanding of the design process will enable educators to better equip engineering graduates to work productively and thereby supply industry with more capable designers.

In an effort to better align accredited institutions with the needs of industry, ABET increasingly focuses on the outcomes of the education engineers receive in accredited programs. Specifically, ABET sets as a criterion that students should have “an ability to design a system, component, or process to meet desired needs” and thus contribute their knowledge, skills, and abilities to increasingly competitive fields such as product development [1]. Academic programs will need to continue improving design education to preserve ABET accreditation.

An objective of our current research effort is to better understand the role that *process* plays in engineering design. To accomplish this, mechanical, industrial, and electrical engineering students at Montana State University keep journals as part of their capstone course. The journals serve the dual purpose of instructional aid and data source. The present study analyzes journal data from mechanical engineering projects in order to identify patterns associated with productive processes.

To characterize the process data, we define design process attributes along two dimensions [2]. First, we delineate four broad categories of *activities*: problem definition, idea generation, engineering analysis, and design refinement. Second, we distinguish three *design levels*, namely concept, system, and detail design, to indicate the progression of design work from ambiguous to specific, with a middle step focused on system architecture. Table 1 lists these attributes and their definitions. Journals are coded for the amount of time spent doing each activity at each design level.

The objective of the present study is to provide empirical support for Costa and Sobek's framework for design iteration [3], specifically the recommendation to transition from concept to detail design without skipping intermediate design levels. The transition between conceptual and detailed work should involve spending time at an intermediate design level that considers solution structure and interfaces between modules or subsystems. This intermediate level is defined as system-level design in this work [2].

Table 1: Activity and Design Level Definition

Activity	
Problem Definition	Gathering and synthesizing information to better understand a problem or design idea
Idea Generation	Qualitatively different approach(es) to a recognized problem
Engineering Analysis	Evaluation of existing design/idea(s)
Design Refinement	Modifying or adding detail to an existing design/idea
Design Level	
Concept	Addressing a given (sub)problem with preliminary ideas, strategies, and/or concepts
System	Defining subsystems for a particular concept, and defining their configuration and interfaces
Detail	Quantifying specific features required to realize a particular concept

LITERATURE REVIEW

A number of engineering design researchers have used quantitative approaches to better understand design process. Some examples include Steward's Design Structure Matrix (DSM) [4, 5], Markov chains, and fuzzy logic.

Design structure matrices have been used widely to decompose and integrate components in a design, team members in an organization, activities in a process, and parameters in design decisions [6]. Specifically, DSM has helped model design iteration [7, 8], assess the probability of rework [9], and predict system interactions [10]. Smith and Eppinger [11] combine DSM with a Markov chain model to study sequential versus parallel iteration in design. The applications of DSM to engineering design and product development continue to grow.

Fuzzy logic techniques, such as the Method of Imprecision, have been used to model uncertainty in early design stages [12]. The method is designed to mathematically represent uncertainty in design, which helps deal with uncontrollable noise factors to achieve a more robust design, select better alternatives based on customer and designer preferences, or reduce overall performance uncertainty [13, 14].

Our study differs from previous work in three important ways. First, our approach uses data from 12 actual design projects, in contrast to design process models based on stylized versions of the design process. Second, we use designer productivity as our primary dependent variable. Productivity combines quality and development cost (that is, the level of quality achieved for expended effort) as opposed to treating either measure alone. Third, unlike many studies of actual design processes, we use powerful statistical analysis tools to gain insight into the data rather than qualitative, case-based techniques.

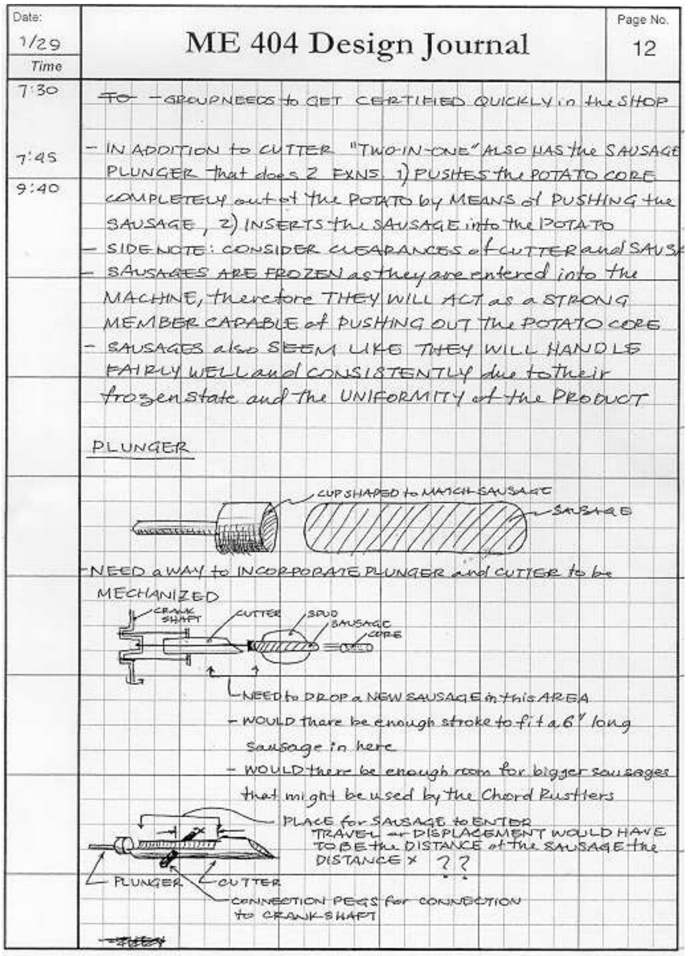
RESEARCH METHODOLOGY

Our analysis approach uses factor analysis on 12 process variables (total times spent at each activity at its design level) to group common variability and assign it to factors. The factor scores for each of the projects become the predictor variables in a multivariate linear regression analysis with productivity as the dependent variable. The contribution each activity has to productivity can be inferred by multiplying the standardized scoring coefficients from the factor analysis by the regression coefficients.

The following paragraphs describe this analysis approach in greater detail, preceded by a discussion of the study sample and variables used in analysis.

Sample and Variables

The sample consists of twelve mechanical engineering capstone design projects, with each project involving three to four senior-level mechanical engineering students and having a duration of 15 weeks. Students were required to record their design activity on paper journals, indicating the date and beginning and end times of project related activities. Figure 1 presents a sample journal entry, followed by a brief explanation of how these entries were coded on design level and activity.


Date: 1/29

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Time

7:30 ~~TO~~ – GROUP NEEDS to GET CERTIFIED QUICKLY in the SHOP

7:45 – IN ADDITION to CUTTER "TWO-IN-ONE" ALSO HAS the SAUSAGE PLUNGER that does 2 FXNS 1) PUSHES the POTATO CORE

9:40 COMPLETELY out of the POTATO by MEANS of PUSHING the SAUSAGE, 2) INSERTS the SAUSAGE into the POTATO

– SIDE NOTE: CONSIDER CLEARANCES of CUTTER and SAUS

– SAUSAGES ARE FROZEN as they are entered into the MACHINE, therefore THEY WILL ACT as a STRONG MEMBER CAPABLE of PUSHING OUT the POTATO CORE

– SAUSAGES also SEEM LIKE THEY WILL HANDLE FAIRLY WELL and CONSISTENTLY due to their frozen state and the UNIFORMITY of the PRODUCT

PLUNGER

– NEED a WAY to INCORPORATE PLUNGER and CUTTER to be MECHANIZED

NEED to DROP a NEW SAUSAGE in this AREA

– WOULD there be enough stroke to fit a 6" long sausage in here

– WOULD there be enough room for bigger sausages that might be used by the Chord Rustlers

PLACE for SAUSAGE to ENTER

TRAVEL or DISPLACEMENT WOULD HAVE TO BE the DISTANCE of the SAUSAGE the DISTANCE x ??

Figure 1: Sample Journal Entry

In this sample journal entry, the initial text was coded as detail problem definition and the top sketch as detail idea generation because in the text the student notes the plunger's function with its constraints and then visualizes an aspect of the plunger's design to better perform its function. However, the sketch that illustrates the relation between the cutter, the potato, the sausage, and the core was considered system design refinement. It was not considered idea generation because the same idea appears earlier, only now the student considers the layout again before exploring possible design problems at a detailed level. The notes on the sketch were coded as detail problem definition and the sketch at the bottom as detail idea generation as the student asks some questions on the design's constraints and then sketches a possible solution.

Students were free to include any design activity they considered necessary and were not conditioned to record using a particular representation. The journals were retained at semester's end. Research assistants coded the journals to indicate the activity they performed and the corresponding design level for every journal entry. The principal investigator (second author) reviewed the coding to ensure both internal and inter-evaluator consistency. Input to the journals was monitored throughout the course of the project to ensure students followed minimum form and content requirements. The recorded activity is limited to the paper journal, and any record of computer use has the form of printouts and explanations of purpose and outcome of the computer work.

The coding for individual journals were entered into a database, then aggregated to the project level by summing the data from individual journals for that project. The variables for factor analysis are the total number of person hours spent on each of the twelve activity / design level combinations (see Table 2).

Table 2: Codes for Activity at a Design Level

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

To evaluate a project's outcome, Jain [15] developed two validated outcomes assessment instruments. Practicing engineers evaluated the final reports for each project in the sample and assigned scores using a carefully designed rubric intended to measure the overall quality of the design (*Q*). Two basic metrics (requirements and feasibility), two advanced (creativity and simplicity), and a metric of the overall impression of the design solution compose the rubric. Each metric is on a scale of 1 to 7, with 7 being the best. The quality score (Q) is the average of the five metrics across evaluators.

In addition, Jain [15] administered a client satisfaction questionnaire and computed a customer satisfaction score (*S*) for each project using two metrics: quality and overall. The quality metric relates to design objectives and customer expectations, while the overall metric addresses feasibility of implementation, willingness to implement, and overall satisfaction with the design outcome. Each metric is on a scale of 1 to 5 (5 being best). The client satisfaction score (S) is the sum of the two measures.

The present study uses a productivity measure (*P*) calculated by:

$$P = \frac{(S+Q)/2}{\sum t} \qquad (1)$$

where $\sum t$ is the total number of student engineering hours spent on design activities in the project. Productivity measures in the sample range from 0.0012 to 0.0035.

Factor Analysis and Multivariate Linear Regression

Factor analysis isolates latent constructs that explain the common variance among a set of variables. Using the factors as substitutes for the variables helps reduce dimensionality and allows more error degrees of freedom for the subsequent analysis. Factor analysis of the 12 predictor variables resulted in four latent constructs. The standard scoring coefficients for each construct were multiplied by the corresponding variable value for each project and summed to obtain one score for each factor for each project.

We then created a multivariate linear regression model to determine whether the factors can predict productivity. The independent variables are the factor scores, with team productivity as the dependent variable. Thus, each factor's regression coefficient represents the contribution to a unit increase in productivity.

In order to relate the regression model back to the original variables, the regression coefficients were multiplied by the factor scoring coefficients to arrive at a productivity coefficient for each of the original variables.

ANALYSIS RESULTS

Factor Analysis on Total Times

Factor analysis resulted in four factors that combined explain 84% of the total variance in time spent on activities at the three design levels. Table 3 presents the breakdown of variance explanation for each of the factors. Factors are independent from one another, so there is no covariance. Factors 1 and 2 explain substantially more variance than factors 3 and 4.

Table 3: Variance Explanation by Factor

Factor 1	28.5 %
Factor 2	26.5 %
Factor 3	17.0 %
Factor 4	12.0 %

Table 4 lists the communality estimates of the twelve variables in descending order. The communality estimates represent the percentage of a variable's variance that is common, i.e., explained by the four factors. The remaining variance for each variable is unique and not explained by the factors. The degree of communality ranges from 92 to 68%, which means these variables have well over half of their variance common with at least another variable.

Table 4: Communality Estimates

Design level and Activity	% Common Variance
Conceptual problem definition	92
Conceptual design refinement	92
Detail idea generation	91
System engineering analysis	89
System design refinement	87
System idea generation	85
Conceptual engineering analysis	85
Detail design refinement	84
Conceptual idea generation	84
System problem definition	79
Detail engineering analysis	72
Detail problem definition	68

Each project's factor scores were derived by multiplying the original variable values and the corresponding standardized scoring coefficients, then summing. This transforms the data set from 12 observations of 12 independent variables, to 12 observations of four latent process attributes, or factors.

Multivariate Linear Regression on Factor Scores

As a preliminary step before regression analysis, the factor scores were analyzed to identify possible outliers that would distort the results. This preliminary analysis identified one project which obtained a score for Factor 3 that, assuming normality, lay outside of the 95% t-distribution confidence interval. The possible outlier score may be explained by the nature of the project, which involved equipment selection rather than the design of a mechanical device.

After removing this project from the sample, linear regression for all variable combinations resulted in a best-fit model that includes factors 1, 3, 4 and explains 91.5% of the variance in productivity (see Table 5). Factor 2 had a p-value of 0.83 and was removed from the model. The intercept was set to zero, which added an error degree of freedom. The extremely low p-values indicate the coefficients differ significantly from zero at any reasonable confidence level. Also, the high R-squared value suggests the model is an excellent fit for the data. The model has 8 error degrees of freedom, which is satisfactory given the small sample size but is still under the 10 considered desirable.

The regression coefficients indicate the contribution of one factor to a unit increase in productivity while holding all others constant. The coefficient's sign indicates whether the factor relates to increased or decreased productivity.

Table 5: Multivariate Linear Regression Statistics

Regression Statistics – linear model intercepts at the origin	
Multiple R	0.9567
R^2	0.9153
Adjusted R^2	0.7691
Standard Error	0.0025
Observations	11

ANOVA	Degrees of Freedom	Sum of Squares	Mean Square	F	P-value
Regression	3	0.00056	2E-04	28.84	0.00026
Residual	8	0.00005	6E-06		
Total	11	0.00061			

	Coefficients	Standard Error	t Stat	P-value
Factor 1	-0.003807	0.000145	-26.3	4.8E-09
Factor 3	0.001474	0.000089	16.56	1.8E-07
Factor 4	-0.001413	0.000093	-15.2	3.5E-07

Productivity Coefficients

To translate the factor coefficients back to the twelve activity / design-level combinations, we simply multiplied the regression coefficients of the three remaining factors by the standardized scoring coefficients from the factor analysis. The resulting productivity coefficients shown in Table 6 indicate the expected contribution from a given variable to a unit increase in productivity holding all others constant. The productivity coefficient is multiplied by 10^4 for scaling purposes.

Table 6: Productivity Coefficients by Design Level and Activity

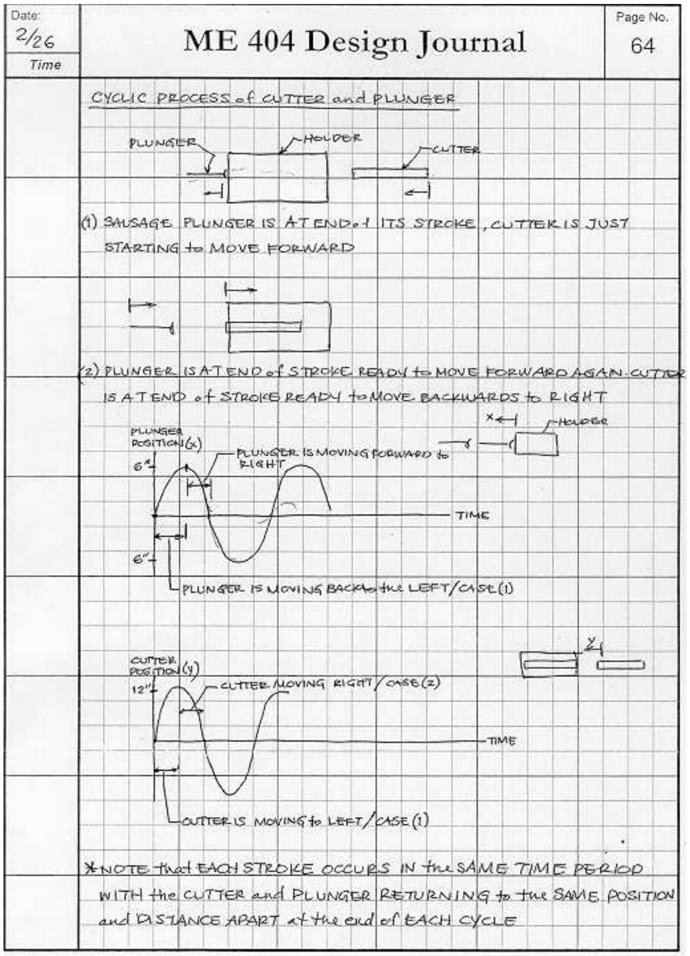
Design and Activity	Productivity Coefficient (x 10,000)	Characteristic Phase
System idea generation	31	Transition
System problem definition	11	Transition
Detail problem definition	5	Transition / Back End
Concept engineering analysis	4	Transition
System design refinement	1	Transition
Detail engineering analysis	1	Back End
Detail design refinement	0	Back End
Concept idea generation	0	Front End
Concept problem definition	-1	Front End
System engineering analysis	-10	Transition
Detail idea generation	-12	Transition / Back End
Concept design refinement	-19	Transition

The data in Table 6 indicate that system-level idea generation strongly relates to increased productivity, far more than any other activity, with system-level problem definition following at about one-third the contribution. Only two other activities contribute positively to productivity — detail-level problem definition activity and concept-level analysis.

At the other end of the scale, refining the design at a conceptual level is associated with lower productivity. This seems to indicate that, rather than spending time refining the concept, designers that improve the state of information [16] by transitioning to the system level—that is, increasing the amount of detail on interfaces and product structure—achieve quality designs in less time. System-level engineering analysis and detail idea generation also relate to decreased productivity, but to a lesser degree.

In the middle are activities that seem to have little effect on productivity. These are: conceptual level problem definition and idea generation, detailed level engineering analysis and design refinement, and system-level design refinement.

To put these results in perspective with respect to the data, Figures 2 and 3 present two sample entries related to the same project but from different student journals.



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CYCLIC PROCESS of CUTTER and PLUNGER

(1) SAUSAGE PLUNGER IS AT END of ITS STROKE, CUTTER IS JUST STARTING to MOVE FORWARD

(2) PLUNGER IS AT END of STROKE READY to MOVE FORWARD AGAIN. CUTTER IS AT END of STROKE READY to MOVE BACKWARDS to RIGHT

PLUNGER IS MOVING FORWARD to RIGHT

PLUNGER IS MOVING BACK to the LEFT/CASE (1)

CUTTER MOVING RIGHT/CASE (2)

CUTTER IS MOVING to LEFT/CASE (1)

*NOTE that EACH STROKE OCCURS IN the SAME TIME PERIOD WITH the CUTTER and PLUNGER RETURNING to the SAME POSITION and DISTANCE APART at the end of EACH CYCLE

Figure 2: Sample Entry for System Problem Definition

The sample entry for System Problem Definition shows how a student attempts to determine the constraints derived from the synchronization of two functions in the design (cut and plunge) refraining from introducing possible solutions, while the System Idea Generation entry presents a student's idea of how the complete system would look like and includes the interfaces between the different functional sub-systems.

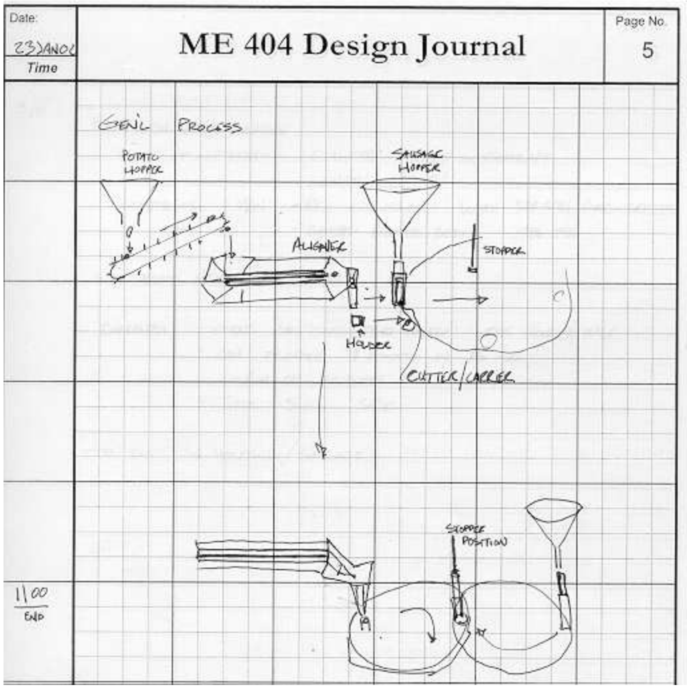

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Figure 3: Sample Entry for System Idea Generation

DISCUSSION

Project Phases

Engineering design research often characterizes design as a process composed of phases, with particular emphasis placed on the initial concept creation and selection steps. For example, Ulrich and Eppinger [17] define problem definition, concept design, system-level design, detail design, and production phases in product development. In a similar fashion, Pahl and Beitz [18] consider design as a highly iterative process through three stages: concept, embodiment, and detail design. However, as Otto and Wood point out [19], there is no clear transition between concept and embodiment design. By the same token, Ulrich and Eppinger discuss system-level design, but the discussion revolves around degrees of modularity in the system architecture, and the relationship with concept design is left unstated. In fact, it can be a bit confusing as "modularity" can be a concept-level objective. It seems therefore that there is no clear definition of the design process during the transition from concept to detail design.

Observation of timing patterns in our design journal data has uncovered affinities among certain activities that allow grouping them into phases. Conceptual problem definition and idea generation dominate the first three weeks in our sample, thus defining the first phase – the *front end* (see Figure 1). Other activities at different design levels are present in the first three weeks, but do not show up consistently or in significant amounts in the sample.

At the other end, detailed engineering analysis and design refinement dominate the last seven weeks, and can be used to define the *back end* phase of the project. Together, these activities represent the single most important productivity predictor because they correspond heavily with total project hours but not to quality. However, their predictive power is less actionable because they appear at the last stage of the project.

Weeks														
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Front End			Transition			Back End								
C/PD, C/IG			S, C, D			D/EA, D/DR								

Figure 4: Design Process Phases and their Main Activities

In between the front and back ends is a transition phase, where concept-level problem definition and idea generation begin to phase out and detail-level engineering analysis and design refinement begin to pick up. No single activity or design level dominates this phase, although most of the system-level activity for the project can be observed during these three weeks.

In comparing these observations with the results reported in Table 6, an interesting pattern emerges. The amount of time spent in the activities that dominate the front and back ends (concept-level problem definition and idea generation, and detail-level engineering analysis and design refinement) does not affect productivity, positively or negatively. On the other hand, those activities most closely associated with positive or negative productivity coefficients are found in greatest abundance in the transition phase. The right-most column of Table 6 displays this information. It seems, then, that the transition between concept and detail design is much more critical to designer productivity than either the front or back end design effort, at least in terms of distinguishing among the projects within our sample. This supports Costa and Sobek's [3] proposition that skipping design levels can be detrimental to project outcomes. In addition, these results suggest that system-level problem definition and idea generation are more fruitful during this transition phase than refining conceptual ideas or generating new ideas at the detail level.

Limitations

While the variable values represent a great deal of data (for instance, 12 data points represent 400-500 pages of journal data and hundreds of hours of student work for one project), the number of projects in the sample relative to the number of variables of interest results in few degrees of freedom. The analysis results should be interpreted in this light. In addition, the numerical values used are to a significant extent based on subjective assessments.

We took great pains to minimize this effect by aggregating to the project level, performing 100% cross-check of all coding work, validating the assessment instruments, and in the case of the external quality assessment, obtaining multiple scores for each project. We also coded the projects before performing the outcomes assessment, and obtained the outcomes data without the evaluators' knowledge of the process results. However, bias in the study is still possible.

Our sample is limited to mechanical engineering students at Montana State University. MSU does not have an ethnically diverse engineering student population, and has only about 10% female representation in mechanical engineering (about the national average). Thus, our results may not be applicable to other settings, such as an urban population or an experienced professional engineering organization.

CONCLUSIONS

Our results indicate that the transition phase is the distinguishing factor in a design team's productivity. Neither front nor back end activities associate with productivity, probably because the data does not present much variability in either phase. On average, student teams spend 79% of the front end's design effort on conceptual problem definition and idea generation, and 75% of effort at the back end on detailed engineering analysis and design refinement. Given the variability in the sample, we are 99% confident that the true means of these effort allocations are greater than zero. The processes differ the most at the transition phase.

In an earlier paper, we recommend that design iterations should not skip design levels [3]. This relates to the importance of the transition phase in the process and specifically to the role that system-level work plays. This study provides empirical support for the recommendation because generating ideas and defining the problem at system level present the highest positive association with increased productivity. These results are consistent with Jain [15], who identified system-level activities as one of the most significant factors contributing to higher design quality and customer satisfaction in a virtual designed experiment performed based on a comparable data set.

Future Work

We have not yet looked at the factor loads, or patterns, for the original variables (see Table 7). Interpreting these factors may yield additional insight into how these design activities affect overall performance. For instance, Factor 2 clearly separates detail-level engineering analysis from the rest of the activities, which might indicate that this factor captures spending time on detailed calculations to the detriment of all other activities. The rest of the factors are not as readily interpretable.

Table 7: Factor Loading Matrix

		Factors			
		1	2	3	4
Concept	problem definition	-0.67	0.63	0.25	0.14
	idea generation	0.49	0.74	0.18	0.13
	engineering analysis	-0.76	0.25	0.44	0.10
	design refinement	0.30	0.69	-0.39	0.44
System	problem definition	-0.34	0.82	-0.07	0.09
	idea generation	-0.61	0.22	0.56	-0.32
	engineering analysis	0.36	0.19	0.78	0.34
	design refinement	0.33	0.73	-0.47	-0.07
Detail	problem definition	0.59	0.34	0.14	-0.44
	idea generation	0.56	0.19	0.32	-0.68
	engineering analysis	0.36	-0.51	0.25	0.52
	design refinement	0.73	0.03	0.51	0.21

Future efforts will focus on interpreting the meaning of these factors, as they are powerful predictors of design team performance. The predictive power of these factors will become more attractive if the meanings relate to “a priori” conditions of the design team or controllable factors. Also, the model can be validated by predicting the productivity of projects not used to create the model.

ACKNOWLEDGMENTS

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