EXPERIMENTS ON SYSTEM LEVEL DESIGN

by

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ABSTRACT

The goals of this study are three-fold. First, previous studies involving student design journals have indicated that engineering effort aimed at system-level design (SLD) issues can be associated with design outcome quality. This relationship will be empirically demonstrated in this thesis. Second, a SLD method is developed to address how SLD can be leveraged to improve design outcomes. Finally, a merger of educational and empirical research objectives to aid in the further development of design process research is proposed.

These goals are addressed in the context of three empirical studies involving mechanical engineering students from Montana State University. The pilot study was developed as a tool to teach the process of conducting experiments and to empirically demonstrate the association between SLD and design outcome. The baseline study demonstrated the significant positive impact that the SLD method has on design quality. The follow-on study addresses detailed questions about how the SLD method affects design outcome. Based on these results a series of recommendations to inform education and practice are presented.

CHAPTER 1

INTRODUCTION

Engineering design is widely applied as a creative, iterative and often open-ended process. A designer must conceive and develop components, systems and processes through the integration of engineering and mathematical sciences. Constraints such as economic considerations, user health and safety, social and environmental factors, codes of practice, and applicable laws must all be taken into account.

Design provides the link between the science of how things work and the application of science to problems that are faced in the every day world. The challenge of design is combing the reservoir of available knowledge about a topic and then finding and implementing a solution that satisfies all of the requirements and constraints of the customer. Because design provides this essential connection between a customer and the technology, it is one of the most important aspects of engineering.

The process of design in engineering is very important to education because the skills required to produce a good design are not necessarily those that are developed by learning general engineering tools and methods. One’s ability to produce a detailed CAD drawing of mechanical devices does not translate directly into being able to specify the requirements and needs of that device. Specifications might include details about how that device operates as a subsystem including power sources, setting, and life-cycle decisions. Because design decisions encompass so many considerations, it is important for educators to expose novices to the design process early and often. By taking advantage of the tools and methods that have been developed to aid in design, these novice engineers are able to fit their skills into the whole picture of the process better than if their skills are taught in isolation of the bigger picture.

What is System Level Design?

The design process can be broken into multiple stages. They are commonly noted as: problem definition, exploration of existing ideas and constraints, conceptual ideation, evaluation and concept selection, preliminary design, and finally detailed design. Problem definition is the first stage in laying out what is needed to address the shortcomings in current designs or to produce a new design. Exploring existing ideas and constraints shapes the possible solutions to the problem and generates ideas for how existing ideas can be adapted. Conceptual ideation merges the problem, constraints and existing ideas, and seeks to provide potential solutions that can serve as a starting point for further development. The conceptual ideas are then evaluated and the best option is fleshed out with more details until finally the nuts and bolts of the design are finished.

All of these stages have been written about and described in detail. Tools and methods to aid designers in problem definition, conceptual ideation and decisions, and detailed design are plentiful. However, the transition from conceptual design to detailed design is not as well specified as the other stages. This transition is called system-level design (SLD), defined as *exploration of and decisions about components and subsystems, and their configuration*. SLD includes functionality, location, orientation, grouping, interfacing, and connectivity in relation to other components/subsystems and to the operating environment. SLD activities often relate to decisions about product architecture, product planning, and defining an assembly scheme. It starts with the solution path laid out in the conceptual design and expands the particulars of that concept. For each particular, whether it is a subsystem, a component, or an interface, options and alternatives can be researched and developed. Any alternative chosen must meet the criteria of the overall problem. The criteria might be “hard” engineering requirements, such as space or power, but could also fall into “softer” areas of concern such as economic or ethical requirements. The evaluation and selection of subsystems is extremely important to the overall success of a design project, and it occurs in SLD.

These vitality important ideas typically rely on a designer’s experience to solve. Heuristic models based on designer’s experiences with specific system level problems do exist but are not commonly used. More general design models primarily call system-level design an iterative process and do not provide a specific method for doing system-level design. A general design model that includes widely applicable system level design tools is needed.

Research Objectives

The objectives of this thesis are 1) to experimentally verify the importance of system-level design practices within the design process, and 2) to formalize a tool or method that can be used to aid in system-level design practice. The first step toward realizing these objectives grew out of the need to test whether SLD could be experimentally associated with design outcome measures. To do this, an experiment to test for significance of a single design stage was required. Since no standard for design experimentation exists, the study had to be designed from scratch.

To this end, a pilot study was conducted to test the effect of SLD on design outcomes and serve as an exercise in creating design experiments. The pilot study provided many lessons on designing an experiment, but also verified that SLD had an affect on design outcomes, although a causal relationship could not be established. The most important lesson learned was that directly leveraging SLD (i.e., including it in the experimental group but not in the control group) was not possible. The limitations of the design process protocol used in the pilot study were addressed in a second experiment.

The baseline study attempted to demonstrate that a SLD tool could systematically direct SLD effort and produce a higher quality outcome than a design process that does not include the tool. The baseline experiment was successful; the SLD tool did produce higher quality outcomes. It also answered the question of whether testing for the applicability of a specific design tool would be possible. However, the baseline study did not show what aspects of the SLD tool were the effective leverage points for the design outcome.

In order to address questions unanswered in the baseline study, a follow-on study was designed to answer the following three questions:

1. Is the tool sensitive to changing complexity in the design question?
2. Does implementing the SLD tool before concept selection result in higher quality outcomes than using it after concept selection?
3. Which of the two SLD elements used in the baseline study (Morphological System Design Tool or Interface Walk-Through) most significantly affected design outcome?

Thesis Outline

The thesis details the series of three experiments, including the results, conclusions, and lessons learned. Chapter 2 briefly explains SLD's role in the design process and examines the importance of SLD, especially in terms of design outcome and improving the design. Existing literature about research related to SLD and accepted methodologies in design research are presented. Chapter 3 addresses the pilot study: the objectives, experimental design, results, and post-analysis. Chapter 4 covers the baseline study: how the tool performed, the experimental design and the results. Chapter 5 details the follow-on experiment: objectives, experimental design, analysis methods, results and discussion. Chapter 6 concludes the thesis with a discussion of what was learned about SLD, the effect of the SLD methodology, what was learned about conducting design experiments, possible future work, and finally recommendations to inform practice and education.

CHAPTER 2

LITERATURE REVIEW

Design is what separates engineering from mathematics and other sciences. Mathematics and sciences often seek to describe or model a phenomenon that has been observed. Engineering seeks to apply descriptions and models to find a solution to a problem. Engineering design is the decision-making process by which descriptions and models are applied to meet a stated objective. Historically, engineering design was thought of as an art or an imprecise science. Only recently has engineering design been recognized as a discipline in its own right (Andreasen, 2001). As a discipline, it is important for designers to model the patterns in the design processes they observe (Horváth, 2004).

System Level Design in the Design Process

Numerous attempts have been made to describe the sequence of events that make up the design process. Haik (2003) compares three of these attempts: Johnson (1978), Dym (1994) and Pahl and Beitz (1996). These three descriptions of the design process emphasize different aspects of engineering, have different names for many of the sequence steps, and often require decisions to be made at different locations of the process. However, Haik points out that each process description leads to the same identification of the design process stages. Examining other design process descriptions from Otto and Wood (2001), Pugh (1991), Ullman (2003), Christopher (1980), Sherwin

(1982), and Hubka (1982) yields similar design process stages, even though the order and significance are represented differently.

The commonly identified design stages are: identifying needs, defining goals, market analysis, establishing functions, task specifications, conceptualization, evaluating alternatives, analysis and optimization, experimenting, and marketing. Every author presents these steps as highly iterative and requiring numerous decisions to progress the design. Each stage may be visited and revisited multiple times until an acceptable form is reached. Haik (2003) proposes the general process shown in Figure 1.

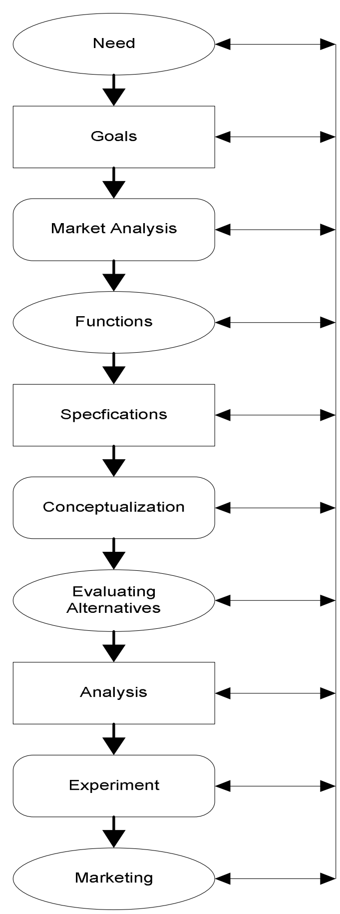


Figure 1 - Haik's (2003) General Design Process Model

Each author presents a view that focuses on different areas of the design process. For example, Johnson (1978) emphasizes the need for searching past designs and then synthesizing those views into feasible alternatives. The optimal configuration is chosen from among the feasible alternatives, and then materials and dimensions are determined by various optimization and prototype, trial and error techniques. Once a workable design is identified, it is evaluated theoretically and experimentally. If a design passes the evaluation, it moves on to the production cycle.

In contrast, Dym (1994) and Pugh (1991) heavily emphasize the need for detailed specifications for the product environment, technical requirements, costs, and specified functions. Dym then proceeds to map the overall function structure of the design. After comparing actual and specified functions, the detailed forms and materials are selected and production design begins. Pugh emphasizes an additional step, called conceptual design, after having detailed the specifications. During this step many potential solutions are created and are applied to the total design, sub-systems level and even the component level. All of these potential solutions must meet the requirements outlined during the specification stage. The potential solutions are then analyzed and the best design is selected for detailed and production design.

Pahl and Beitz (1996) use a similar process as Pugh, but rather than emphasize the conceptual design, they focus on what they call embodiment design (see Figure 2). After having selected a concept, Pahl and Beitz seek to develop preliminary layouts and form design, and evaluate them against the technical and economic criteria specifications before moving to detailed design. The best preliminary design is then optimized and reevaluated in terms of cost and production feasibility. After this step, the design is then passed along for the definitive layout and detailed design. Otto and Wood (2001) borrow heavily from Pahl and Beitz, but maintain Pugh's emphasis on specifications. More frequent evaluations occur during the embodiment design stage, where, rather than returning to the conceptual level to evaluate design decisions, decisions are made at the relevant level of abstraction.

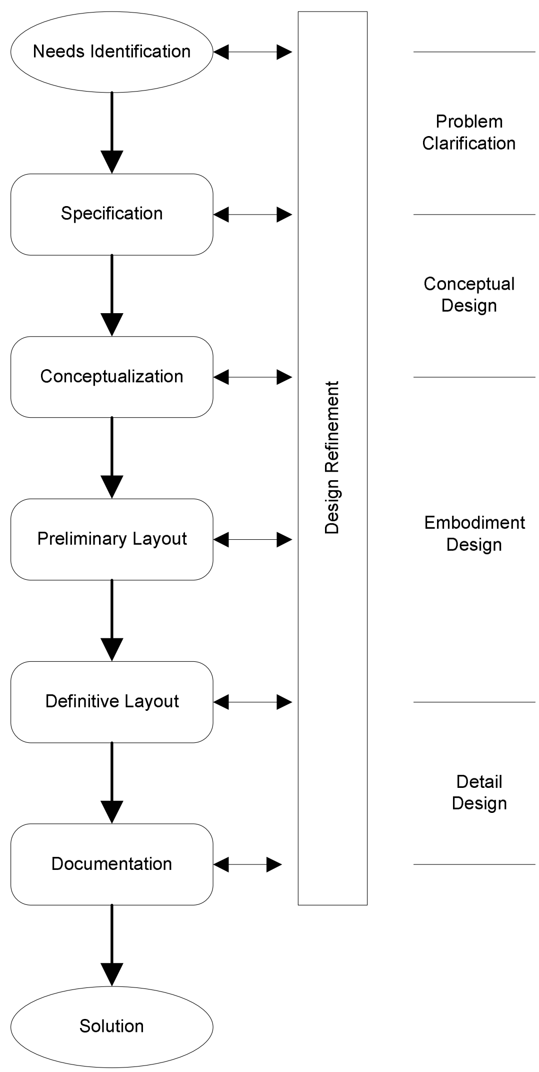


Figure 2 - Pahl and Beitz's (1996) Design Process Map

Given that SLD is defined as the *exploration of and decisions about components and subsystems, and their configuration*, it is easy to see that each of the above process models includes and even emphasizes many aspects of system level design. This is most apparent in Pahl and Beitz's design process model where the whole of the embodiment design process can be classified as SLD. For Pugh, SLD is included in many of the conceptual level decisions and the evaluations of subsystems and components against the specifications. Dym explicitly includes SLD in the determination of feasible design function structures, while Johnson speaks of systematic configuration techniques.

What Makes SLD Important to the Design Process?

Conceptual design, including ideation and selection, is often considered the most important phase of decision making in the design process. Methods and tools such as concept selection charts, morphological analysis and systematic idea generation techniques have been developed to support conceptual design. Similarly, techniques to aid in detailed design have been developed such as analytical and numerical modeling tools, physical prototyping tools, and drawing aids. The goal of detailed design activities is to establish the final dimensions, tolerances or materials of a component or a subsystem. SLD activities aim to configure multiple subsystems together or define the way in which the subsystems interface. While these design aids for conceptual and detailed design exist and are widely used, changes to the existing design doctrine are slow to be adopted in practice, primarily due to the complexity of implementing different models (Eder, 1998).

Very few methods exist to aid decision-making for SLD. SLD is a critical bridge between conceptual and detailed design, where important, often vital, decisions in the design process are made. These decisions require design development just as challenging as conceptual level problems (Ulrich & Eppinger, 2004), but typically involve trade-offs that are difficult to evaluate, especially in terms of conceptual specifications or problem definition (Ulrich, 1995). These trade-offs are not adequately explored by existing decision support tools, particularly in the realm of interfacing couplings between systems or across boundaries (King & Sivaloganathan, 1999).

Perhaps the reason so few tools exist to support SLD is that SLD itself remains the least studied and least understood stage of the design process. While many design process models go into great detail about conceptual or detailed design, little is actually said about how to implement SLD. Pahl and Beitz suggest that formalizing the "flexible approach with many iterations and changes of focus" when approaching SLD issues could eliminate wasted effort. Their approach includes many rules and guidelines for improving the embodiment design process, but this prescriptive checklist fails to provide a satisfactory general method to approaching system level design.

Pahl and Beitz are not alone in their view of SLD. Many of the authors already mentioned note that wasted design effort occurs during system level decision-making. Marshall & Leaney (2002) claim that such wasted effort might be a side effect of dealing with highly-complex system-level decisions; in that light, they view SLD as an attempt to provide a structured approach to dealing with complexity. Unfortunately, most of the models used to provide structure to SLD are based on heuristics rather than empirically validated studies.

Current Ideas about SLD

Standardizing the way SLD decisions are informed is important to the development of useful SLD tools and methods. At a systems level, function interactions, functional schemata, and function criteria determine the physical "chunks" or subsystems that make up a product. Each of these subsystems can be constructed of a physical architecture and physical interactions, then analyzed and improved to meet whatever measure of design success is appropriate (Rouse, 1991). Identifying the systems and subsystems of a design problem is considered by many of these heuristic models as the first step in addressing system level issues. Once the product is aggregated systematically, the question of when and where to apply system level design methods becomes increasing important (Sridharan & Campbell, 2004), as critical interactions and interfaces will have to be addressed in a consistent and systematic manner to complete the design process. This view of SLD is popular because, while function structures, interfaces, couplings, layouts and other aspects of system level design rarely have repeatable solutions (Gershenson, Prasad & Zhang, 2004), dealing with the design in terms of chunks makes it more readily adapted to computer software tools and does not rely as heavily on designer experience as other views.

As this kind of functional partitioning becomes more popular, methods for accomplishing the partitioning are under increasing scrutiny. Holtta and Salonen (2003) tested three methods for functional partitioning to measure their repeatability on similar problem types. The three methods were the heuristic method, design structure matrix and modular functional deployment. While each method performed well for repeatability, the functional partitions determined by the methods differed greatly. Thus, the authors conclude that none of these models are capable of operating as a stand-alone model for determining a useable functional partition, contrary to accepted practice.

Another attempt at standardization of a SLD tool was presented by Sered & Reich (2003). The study compared existing design structure matrix techniques for multi-generation products with the goal of lowering overall development costs by improving product design efforts. The study also represents an initial attempt at formalizing an approach which would allow for more empirical testing in the area of design methodology.

Kurfman et al. (2003) directly address the question of whether existing design methodologies represent a contribution to the field of design engineering. They created three experimental protocols to test whether different designers would produce repeatable functional models when using the functional model derivation method. The first protocol they used asked their participants to construct a functional model of a device based upon "Pahl and Beitz-inspired function structure generation methods." The models were then compared to control models created by the research team. For the second protocol, participants follow a "how-to" manual for creating structures, which were again compared to control models. Finally, the third protocol asks the participants to create a function structure of an original design problem. While the results of this experiment do indicate that the functional model derivation method does produce repeatable functional models with a high degree of success across a number of cases, this experiment is of primary interest in that it represents an explicit testing of design methods.

When to address SLD design issues in the design process becomes more important as more tasks are relegated to computational techniques. Sosa, Eppinger, and

Rowles (2003) have identified 7 types of interfaces that are often not addressed explicitly in design team work. These interfaces are often defaulted to the detailed design stage. However, even small adjustments to existing designs during the detailed design phase results in tremendous loss of efficiency for the designer (Flemming, et al., 1997). Placing SLD before detailed design still leaves a wide range of options within the design process. While most authors agree that "architectural decisions made in early phases (of the design process) plays a lead role" in the success of a design (Ulrich, 1995), the most effective task sequencing, particularly in regard to SLD issues, remains unanswered.

Why Study SLD?

Despite the availability of computational software to aid in some SLD issues, the key ingredient to most SLD methods is designer experience. This represents a significant shortcoming to SLD methods because the design experience and judgment on which many heuristic models rely requires a great deal of time to develop (Holt, 1997). Novice designers, such as students, do not have the reservoir of experience or judgment that professional designers have, making many of the available models that rely on designer experience of debatable use. Novice designers exposed to effective tools and methods for design processes gain experience in good design practice while maintaining high quality design outcomes (Verma, 1997). For this to happen, tools and methods that are based on planned or validated research rather than on the experience of authors must be developed (Wallace & Burgess, 1995; Zhu & Kazmer, 2001).

Recently, design researchers have attempted to validate existing design models through empirical testing. Their attempts have met with some success, but because this testing is new, a uniform empirical process does not exist. Issues regarding what constitutes an acceptable study in this area have yet to be addressed (Bender, 2003). Among these issues are: what constitutes an empirical test of validity, should students or experts be the subject of research, and how broadly should the design methods be tested. Unvalidated SLD models exist, but is SLD an area of the design process worth pursuing?

During prior research on student design journals our research group identified a statistical correlation between SLD activities documented in student design journals and project outcomes. This correlation was found during analyses of design process elements that contribute to good designs (Costa and Sobek, 2004; Jain and Sobek, forthcoming; Sobek and Jain, forthcoming; Wilkening and Sobek, 2004). Of the themes that emerged from this work, perhaps the strongest was that design activity that occurs at a system level strongly correlates with both design team productivity and outcome quality. This research indicated that it might be possible to show a causal relationship between SLD and design outcome. In light of this correlation, the work reported in this thesis seeks to show the effects of SLD on design process outcome and thereby validate SLD as a critical phase of the design process.

CHAPTER 3

PILOT STUDY

The pilot study was designed to test whether the results of the student journal analyses, namely, the correlation between SLD and design outcomes could be established as a causal relationship. If a causal relationship could be demonstrated in a laboratory setting, it would justify further research into the development of SLD tools or methods. This study was the present author's first attempt at experimenting on the design process.

This chapter details the initial experimental design, data collection, analysis and results. The experiment was designed to test whether a causal relationship between SLD and design outcome could be determined. Interestingly, the differences between the control and the experimental group were insignificant. However, a post-experimental analysis suggests that the insignificant results may be due to the experimental protocol, which failed to sufficiently constrain the design team's activities. Further analysis created a measure of a design team's SLD activities and compared that measure to design outcome. The results provide additional evidence of the relationship between SLD and design outcomes, but are not strong enough to claim a causal relationship.

Objectives

The first goal of the pilot study was to learn how to conduct experiments on the design process. The second goal was to demonstrate a causal relationship between system level design and quality outcomes. To experimentally demonstrate a causal relationship between SLD activity and design outcomes, it was necessary to implement a design process protocol that distinguishes between a design process that uses SLD and one that does not. If a causal relationship exists between design process (specifically SLD) and design outcome, we expected teams that included SLD in their design process would produce better performing designs.

Experimental Design

The experimental participants were randomly assigned to either an experimental or a control group. The experimental group was asked to follow a design process that included SLD while the control group followed a design process that did not explicitly mention SLD. A design-build format was chosen for the experiment because it would produce easily measurable results and would accommodate a variety of design processes. A comparison of the control and the experimental groups' design outcomes would indicate the better design protocol, which according to the hypothesis, would be the protocol that included SLD.

The design problem required the design teams to move a golf ball between locations on a variable-terrain course (see Figure 3) using Lego™ Technics parts. The problem is similar to the Bodiometer Design Exercise (Carrizosa & Sheppard, 2000). The problem statement given the teams was:

> *Move a golf ball from a stand still in the starting area so that it comes to rest on the target ring as close to center as possible using only the materials provided. The only energy that can be applied to the ball must be stored in the materials.*
>
> *Points will be awarded based upon the final resting location of the golf ball in relation to the target area. The objective is to score the most points possible while using a minimum number of parts.*

Participants were required to design, build a prototype, and test their design during a two hour period. A score was assigned based upon the accuracy of their final design and the number of component parts used.

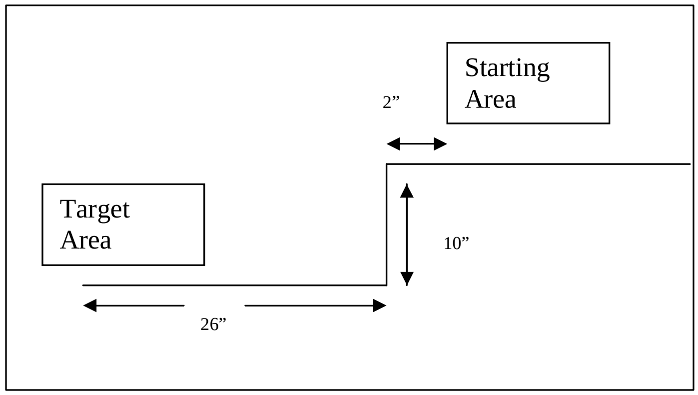


Figure 3 - Golf Ball Problem Course

The protocols followed by the control and experiment groups were designed to be as similar as possible. The only difference between the groups was the inclusion of SLD. Appendix A gives a side-by-side comparison of the protocols. The protocol began with a brief 15-minute familiarization exercise to introduce the design teams to the capabilities of the materials provided so that teams would not have an advantage due to prior exposure to Legos. After the familiarization, both the control and experimental groups were given 75 minutes to design and build their product. Ten minutes of the experimental group’s design time was allocated for the SLD activities assigned. During that ten-minute segment, the control group was allowed to begin prototyping their design. Our expectation was that the difference in time allocation would not negatively affect the experimental design because work done on system level issues allows for a more efficient convergence to a solution.

The participants in the exercise were students enrolled in ME 403: Mechanical Engineering Design I. This course is structured as a design project emphasizing use of a formal design process, presentations, and documentation. The course also includes coverage of industry machining and welding practices. Fifteen teams of two, seven in the control group and eight in the experimental group, participated in the exercise. Table 2 displays the participant demographics.

Table 1 - Pilot Study Participant Demographics

	Number of Participants	**Average Age**	**Average GPA**
Male	30	22	2.82
Female	2	21	3.2
Cumulative	32	22	2.84

The exercise was implemented according to the script attached in Appendix B. The script was followed rigorously with no significant deviations from the planned protocol other than that some of the groups did not need the full five minutes to read the problem statement and examine the set-up. Groups were encouraged to ask for clarification on rules or the problem constraints at any time, but typically they only asked when called upon for questions.

Written and verbal announcements were given to the groups announcing the start of each design phase. Time remaining was updated at five minute intervals and a verbal warning of five minutes accompanied a reminder of the deliverables required at the end of the period. With two minutes remaining, a final verbal warning was issued. When time expired, all activity was brought to a halt.

The accuracy score was gathered using the final resting location of the ball during the final test. The location of the ball was judged based upon its contact point with the surface of the target, or if the design precluded the ball's contact with the target, the ball's center of mass projection down onto the target. Once the final test began no pieces could be added to or removed from the design. After the completion of the three consecutive runs, the pieces were counted twice with both team members and the experimenter present.

Results

The outcome variable for analysis was constructed by normalizing the accuracy and piece count scores on a 0 to 1 scale, with 1 being the best score, and then averaging them. The composite, accuracy and piece count scores were then used as response variables in 2^2 ANOVA analyses. A 10% level of significance was chosen due to the interaction with human subjects.

Model adequacy was checked by testing for normality and outliers. A normal probability plot was used on the accuracy scores, the piece count score, and the composite score. No outliers were found and the lowest R-squared value from the regression test was 0.96. From this we conclude that the normality assumption is reasonable.

The equal variability assumption was tested using a two-sample F-test for variances. The p-value for the test on the composite score was 0.40 indicating that the variability between the control and experimental protocol was comparable. The response variable was deemed appropriate for testing the means for equality. Both the accuracy and piece counts scores also had equal variability and were tested for equality of means.

The equality of the means was tested using the standard two-sample t-test and the ANOVA test for means. The composite score Student t-test resulted in a p-value of 0.354 and the composite score F-test in a p-value of 0.397. These p-values indicate that no difference in mean composite score exists between the control and the experimental group. The accuracy and piece count means test results in Student t-test p-values of 0.559 and 0.283 respectively. This result indicates no difference in mean score between groups (see Table 2).

Table 2 - Two Sample Student t and F-test Results Summary

	Accuracy	**Piece count**	**Composite**
Control Mean	0.511	0.305	0.452
Experimental Mean	0.635	0.473	0.563
p-value t-test	0.559	0.283	0.354
p-value F-test	0.246	0.474	0.397

Since the experimental data showed no difference between the control and experimental groups' mean scores, it appears that system level design activity had no impact on the outcome of the exercise. However, a closer look at the deliverables collected during the exercise and the observations recorded by the experimenter revealed that many of the teams in the control group actually considered SLD issues even though they were not prompted to do so. Conversely, a number of teams in the experimental protocol, who were prompted to think about SLD issues, did not.

This means the protocol failed to sufficiently affect or limit the design process with regards to system level design. Because system level design activities were not limited to the experimental group, a new classification system was designed to determine which teams did SLD and create a measurable quantity that could be analytically compared to the design results.

Post-Analysis

Claiming that SLD activities are related to design outcomes is impossible based on the results of the analysis. However, because the experimental protocol failed, it is not possible to say whether the insignificant results are due to a failure of the protocol or a failure of SLD. The observation that control groups engaged in SLD activities indicates that a new measure of system level design effort is needed to adequately test the hypothesis of this experiment.

One measure of SLD effort is the number of system level issues that each group addressed during the design phase of the protocol. A further refinement included system level design work done on only the concept selected for prototyping. These two new measures of system level design effort might provide a means to correlate system level design and outcome.

First, all system level issues that groups addressed during the design phase were identified. The documentation collected from the students and the experimenter's notes was combed and four different design concepts were identified. They were: a dragging device, a rolling device, a sliding device, and a carrying device. For each of these concepts, four to six system level issues could be identified. Some of these issues were shared by all of the concepts, e.g., “Activating the device in such a way that starting the ball in motion will interface smoothly with other aspects of the concept.” But some concepts featured unique issues, such as the sliding concept: “Was the clearance requirement of the ball/device interface considered?” Appendix C presents all of the system level design index (SLDI) issues that were used in the analysis.

Once the criteria for system level design issues had been established, each group’s documentation was analyzed. The analysis was two-fold: system level design done on the selected concept and system level design done on any concept. Once the SLDI value had been determined for each group, a linear regression was computed for the composite score, the accuracy score, and the piece count score. The results are displayed in Table 3.

Table 3 - Results from Linear Regression Analysis on SLDI

	SLDI on Selected Concept		
	Composite Score	**Accuracy Score**	**Piece Count Score**
Intercept	-0.393 *	-0.713 ***	-0.073
Slope	1.239 ***	1.819 ***	0.659
R^2	0.589	0.720	0.166
N	15	15	15

	SLDI on All Concepts		
	Composite Score	**Accuracy Score**	**Piece Count Score**
Intercept	0.047	-0.346	0.441
Slope	0.062	0.131 ***	-0.007
R^2	0.170	0.428	0.002
N	15	15	15

*** p-value < 0.01
** p-value < 0.05
* p-value < 0.10

Table 3 reports R-squared values that offer an interesting insight into the association between system level design and design outcomes. Significant differences between groups that considered SLD issues on the selected concept and groups that did not consider SLD are detected for the composite and accuracy score. The regression for the piece count score is not significant. When considering groups that did SLD for all concepts, the variance in the accuracy score is significant (p-value < 0.01) but the piece count and composite scores are not (p-value > 0.10).

Post-Analysis Discussion

These R-squared values do not indicate a causal relationship between system level design activity and outcome as hypothesized. However, they are suggestive of correlation and support the need for further study. The primary question raised is why the SLDI associates with one measure of design performance but not the other.

The accuracy score improves more with increased system level design effort when examining only the selected concept rather than all concepts. An explanation may be that by only considering the issues needed to create solutions for the selected concept, rejected ideas or ideas adopted from other conceptual consideration are neglected in the SLDI. Thus, a team that came up with one concept may be indexed no differently than a team that fully explored three concepts. The accuracy and composite scores of teams that had high SLDI scores using all concept alternatives were better than teams with high SLDI scores using only the selected concept. This indicates that focusing on the selected concept yields better design outcomes.

Why would the piece count scores for groups addressing more system level design issues across a wider range of concepts score worse than teams that focused on system level design issues for fewer concepts? The answer to this question might lie in the nature of the design requirements. The requirements of maximum accuracy and minimum piece count usage are frequently conflicting requirements. Each team prioritizes these requirements, but the problem statement doesn't explicitly state that equal weight would be given to both the accuracy score and the piece count score. In light of this ambiguity, it is possible that teams chose to prioritize these requirements differently.

From the deliverables teams based their criteria for concept selection on the expected accuracy of their solution rather than the piece count requirement. Some of the teams didn't mention the piece count requirement at all, while every team mentioned the accuracy requirement! Confusion over design requirements has a strong impact on the data obtained since not all the teams were designing a product against the same objectives.

Lessons Learned

One success of the pilot study was that it did fulfill its objective of giving experience in conducting laboratory experiments. This pilot study reinforced the lessons of how to prepare for conducting an experiment, thoroughly testing all aspects of a design problem before collecting data, practicing the script ahead of time, how to handle unexpected questions, how to ensure that the experimental protocol was followed every time, how to plan for a 'worst-case scenario', and how to plan ahead to ensure that all statistical issues will be addressed. Additionally, the need for clear and unambiguous problem statements was underscored.

While the pilot study failed to demonstrate a causal relationship between SLD and design outcome, it did provide further evidence associating SLD with quality. The SLDI was created to discern whether the results were due to the experimental process or a failure of SLD. The regression showed that groups with higher SLDI scores produced higher quality design outcomes. Thus, improving a designer's SLDI should leverage better design outcomes. Additionally, the SLDI analysis demonstrated that specific aspects of the design process, in this case SLD, could be empirically tested in a laboratory setting. While a close examination of the protocol revealed that it failed to restrain design team activities with regards to SLD, it was possible to create a measure of SLD activities.

Because students displayed confusion over how to do SLD (many groups that thought they were addressing SLD issues never did), another method to isolate specific aspects of the design process is needed. The method should also address SLD issues on a limited selection of alternatives rather than a multitude of concept alternatives because that results in higher quality outcomes.

CHAPTER 4

BASELINE EXPERIMENT

Through an adaptation of a common conceptual design tool, a protocol capable of testing a specific aspect of the design process, SLD, was developed. To address the lessons learned from the pilot study, this experimental design presents a clear and easy-to-follow SLD process focused on a limited selection of conceptual design alternatives. The tool, which helps designers think through the design of interfaces between functional subsystems, can be inserted into a general design process and creates a way to differentiate design process protocols that include SLD (i.e., team uses the tool or not). The experiment tests whether using the tool and method is beneficial for mechanical engineering student designers.

This chapter outlines the development of a SLD tool from a conceptual design decision-making tool, and an associated SLD design method. Next, the experimental design used to test the tool is presented, with special attention given to the cross-over design, followed by the results. The chapter concludes with discussion and interpretation of the experimental results.

Development of the Tool and Method

Morphological matrix tools are often used to aid in ideation using a systematic method of developing and combining potential design solutions (Holt, 1997; Marshall & Leaney, 2002). These tools prompt the designer to identify the sub-functions needed to meet the stated design requirements, then brainstorm different ways the sub-functions can be accomplished. Combining sub-function alternatives generates a large number of overall concept alternatives. While this tool provides possible working structures, it does not explicitly address system level design issues. Interface configuration, orientation, grouping, and connectivity (user and environment) all play vital roles to design success but are not normally considered explicitly in a typical morphological analysis.

Addressing system-level issues *before* making concept selection decisions may enhance the quality of such decisions and avoid difficulties later in the project caused by flawed design concepts. Interface configuration between functional components is a very important SLD issue. Interfaces become increasingly important as the complexity of the design problem grows; however, interfaces are rarely considered as part of the overall design. Preliminary evidence suggests that engineering design efforts will improve by addressing the key interface configuration issues using a morphological tool.

Tool Description

The adaptation of the general morphological tool requires that designers have identified alternative conceptual designs and narrowed to a handful of promising alternatives. Each conceptual design idea is then analyzed by identifying the key functions that the concept must execute to achieve the overall design objective. Each function of a given concept may have multiple implementation options, each having different interface requirements (see Figure 4). Once the morphological matrix has been populated with functional options, functional incompatibilities (exclusions) and necessities (dependencies) are identified. The designer then generates a list of potentially feasible alternative configurations for this particular concept. One way to generate alternative configurations is to create combinations of options that optimize each of the different functions.

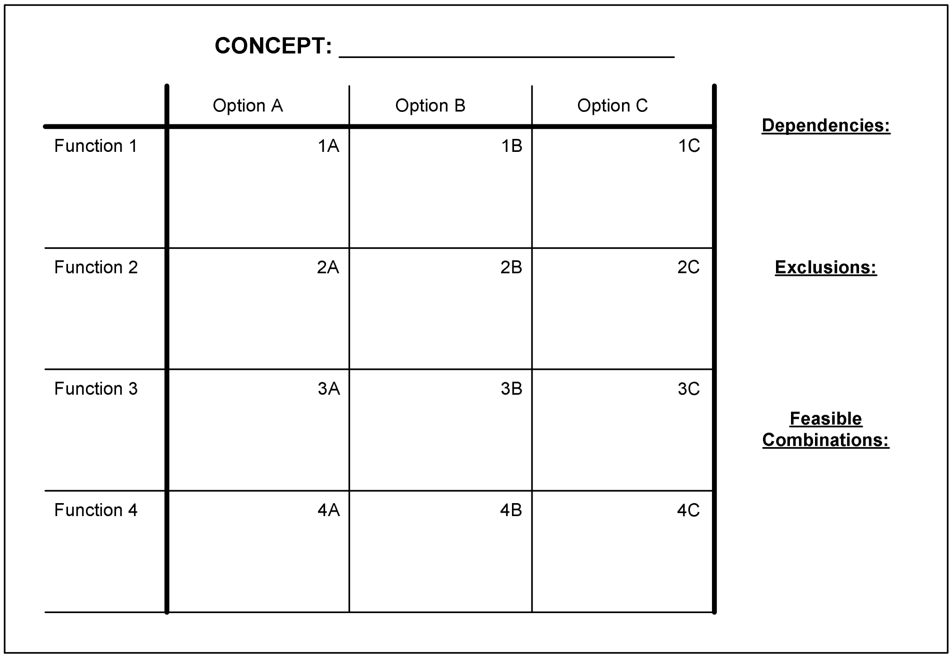


Figure 4 - Morphological System Design Tool (MSDT) Template

Interfaces Discussion

Once the list of potential combinations has been identified, a more informed discussion of the interfaces can occur. This discussion expands from the interfaces between the functional components and to additional interfaces that might include a user, the environment, or another device. Broader scope interfaces set the stage for a story-telling walk-through of the design. By focusing the walk-through on describing the functional path of the design objectives in terms of the interface requirements at each point, the designer considers how the interfaces can be handled and whether alternative methods might exist for meeting the interface requirements.

It is important to address the interface issues at a non-superficial level. For example, if an exclusion or dependency exists between two options, then the constraints that create the exclusion or dependency should be identified. The answers to these questions often lead to revisions to the functional options. This discussion relies heavily on designer expertise because it is based upon the expected behavior of the system; however, the morphological tool serves as a boundary object against which expectations can be checked.

Feasibility Check

The final step before proceeding to concept selection is a reality check: is the concept, as configured, feasible? Can it be made feasible? Or is more information needed to make the determination? This check is made against the overall design specifications, not merely against subsystem requirements. For simple problems this can often be answered by inspection but more complex problems may require some modeling. Since the answers to these questions may not be definitive, the feasibility check can be used to identify areas that require additional background research.

The above steps are then repeated for each concept alternative under consideration, resulting in a set of best configurations for each concept. This means that during concept selection, rather than comparing the preconceived versions of concepts, designers compare the best known configurations for the concept alternatives. Additionally, the concept selection decision inherently considers subsystem interface issues. An overview of the process to incorporate the morphological system-level design tool (MSDT) is displayed in Figure 5.

1. Generate conceptual design alternatives

a. Define the problem

b. Generate alternatives

c. Narrow the set of alternatives to a manageable size

2. Apply MSDT to one alternative

a. Identify the key functions of the concept needed to realize the design objectives

b. Generate 2 or more options to accomplish each function

c. Identify which function options cannot be used with other options (exclusions)

d. Identify which function options require inclusion of another option (dependencies)

e. Generate a list of alternative configurations for the concept alternative

f. Investigate interface feasibilities

g. Select the most promising configuration

3. Repeat step 2 for each alternative

4. Compare alternatives using the best configurations

5. Choose the best alternative

Figure 5 - Overview of the MSDT Process

Statement of Hypothesis

The results of the post-analysis of the pilot study point toward system-level design as a potential leverage point for improved design performance. Because the morphological system-level design tool (MSDT) and the corresponding system interfaces walk-through discussion are designed to emphasize SLD issues, the hypothesis for this experiment is:

Hypothesis: Design processes that use the morphological system-level design tool (MSDT) followed by a system interfaces walk-through discussion will produce better designs than design processes that do not include these structured SLD tasks.

Since the MSDT and interface walk-through were designed to elicit system-level design considerations, this hypothesis implies that design processes that systematically consider system-level issues will outperform processes that do not. The next section details an experiment to test the stated hypothesis among senior mechanical engineering students.

Experimental Design

The experiment was designed as a crossover design, as depicted in Figure 6. A crossover design is a special type of repeated measurement experiment where experimental units are given different treatments over time with a comparison of pre-test data to post-test data (Festing & Altman, 2002). In a crossover design each experimental unit serves as its own control. However, certain pitfalls must be avoided to ensure experimental validity. One such pitfall is the treatment of randomized experimental units. We randomized the assignment of teams to the two groups of the experimental protocol, where the comparisons of primary interest are the scores of the two problems between runs. If comparability between problems can be established, we are interested in changes in performance between runs of the two groups.

The arrows in Figure 6 show the expected comparisons and the directions of the improvement hypothesized. Note that no difference is expected between the golf ball and mouse problems in run 1 or run 2. This is important because a difference would indicate lack of comparability between design problems.

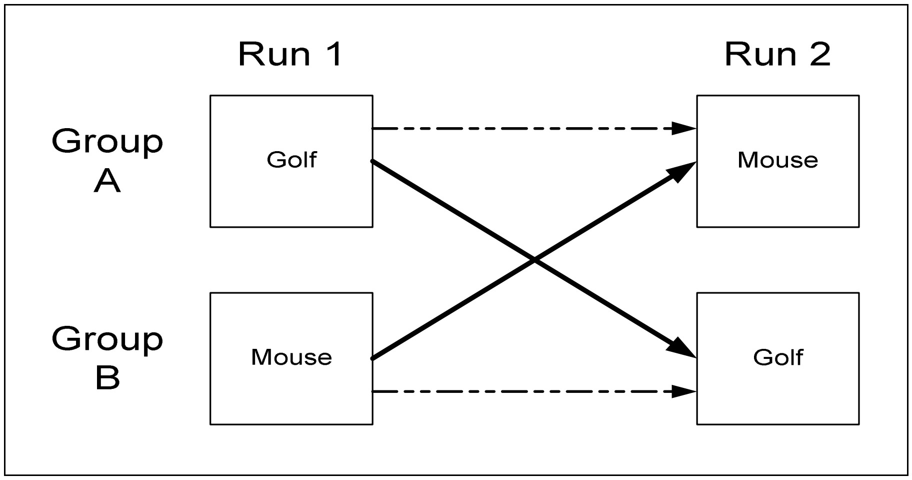


Figure 6 - Graphical Depiction of Cross-Over Design

This type of design eliminates the ethical question of exposing a group of students to a potentially beneficial treatment without giving that same treatment to the control group while maintaining good external validity. The comparisons allow for clear results that are either positive or negative, with little room for grey areas that might cloud the results. Within group testing and randomization are possible without the need for large sample sizes.

This design is not a “true” experiment since we do not randomize the second run, making internal validity less robust. In addition, bias may enter into the results due to participants learning or training between the experimental runs, or from other sequential effects. These biases can be avoided by the timing and implementation of the design. In our case, we timed the experiment to coincide with classroom activities so as to minimize the effects of sequential learning from one run to the next, and of classroom learning that might occur between runs, as will be discussed later

Participants

Again the participants were students enrolled in ME 403: Mechanical Engineering Design I. This course is structured as a design project emphasizing the use of a formal design process, presentations, and documentation. The course also includes coverage of industry machining and welding practices. The final analysis included seven two-member teams in each of groups A and B. The participant demographics are presented in Table 4.

Table 4 - Baseline Experiment Participant Demographics

	Number of Participants	**Average Age**	**Average GPA**
Male	30	22	3.09
Female	2	21	3.25
Cumulative	32	22	3.10

Design Problems

The problems given to the teams were simple and straightforward (i.e., easy enough to be solved and implemented within a two-hour time window). They were designed with competing objectives and sufficiently complex requirements so that they would not have obvious solutions. The first problem was a slightly modified version of the problem used in the pilot study:

> *Move a golf ball from a stand still in the starting area so that it comes to rest on the target ring as close to center as possible using only the materials provided. The only energy that can be applied to the ball must be stored in the materials.*

> *Points will be awarded based upon a combination of the final location of the golf ball within the target and the number of parts used in the design. The objective is to score the most points possible in three runs while using a minimum number of parts.*

The measurable quantities were the location of the golf ball when it comes to rest and the number of parts used to make the device. The final resting location of the ball was determined by where the ball physically touched the target. If the design precluded the golf ball touching the target, the location of the ball was determined by a center of mass projection onto the target. The course for this problem was the same as the one used for the pilot study.

The second problem was to transport a hacky-sack to a target area that was strongly defined on one side and weakly on the other. The problem statement was:

> *Move the mouse (hacky-sack) from the starting line to a distance of no less than 3' and no more than 4'. Within that distance specification a point gradient exists from a maximum of 100 points at 3' to 25 points at 4'. Outside of this specification window no points are rewarded.*
> *Points will be awarded based upon a combination of the final location of the mouse within the specification window and the number of parts used in the design. The objective is to score the most points possible in three runs while using a minimum number of parts.*

The measurable quantities are the location of the hacky-sack when it comes to rest and the number of parts used to make the device. Since the hacky-sack was easily deformable, the location of the hacky-sack was determined by projecting the cross-section of the target area through the hacky-sack. The course for the mouse transport problem is shown in Figure 7.

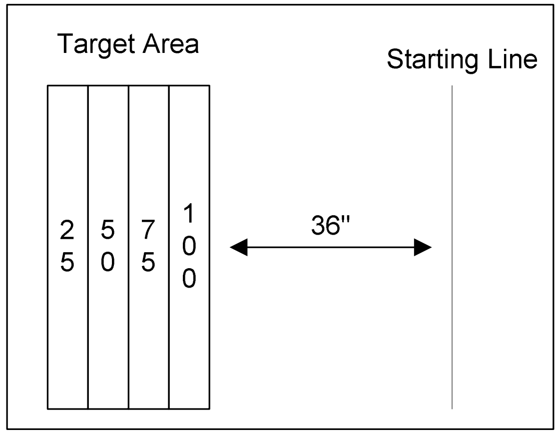


Figure 7 - Mouse Transport Course

These problems were solved using an assortment of Lego parts, some string, and a rubber band. The only difference between the problems was the amount of string (24 inches for the golf ball problem and 48 inches for the hacky-sack problem) and the number of wheels supplied (4 wheels for the golf ball problem and 6 wheels for the hacky-sack problem). Both problems featured the dual objectives of maximizing the device's accuracy and using a minimum number of parts.

Experimental Protocol

Each experimental group engaged in two runs of the protocol. During Run 1, a brief familiarization exercise preceded the actual design problem in order to introduce students to the properties and capabilities of the materials used in the exercise. After completing the familiarization, the experimenter presented a written problem statement to the group. The group read through the design problem then the experimenter walked through the course that the prototype had to navigate. During this period the groups were encouraged to ask questions about the problem statement and the course. The experimenter also reviewed the protocol to be followed.

The next step was to generate at least three concepts and select the best concept to prototype. Groups were required to turn in sketches of the three most promising concepts, indicate which concept alternative they had selected, and their criteria for selection. During this 30 minute period, the participants could pick up and handle the materials but were not allowed to assemble substructures.

Once the design documentation was complete, the participants built prototypes of their best idea using the materials provided. During the prototype phase they could test their designs on the course. After a maximum of 20 minutes, the participants demonstrated their prototype in three consecutive test runs. Calibration of the prototype was allowed between trials as long as no changes were made to the prototype. After the demonstration, scores were recorded.

Run 2 followed the same design protocol as Run 1 with the addition of the MSDT protocol and the removal of the familiarization exercise. The MSDT was conducted after participants generated conceptual design ideas, but before they narrowed to a single alternative. The idea generation and prototype building stages were unchanged. Since the student participants were only superficially familiar with the MSDT protocol (their only experience was an introduction in lecture the week prior), the experimenter walked the participants through the sequence of steps necessary to apply the tool to their problem. The experimenter was careful not to suggest design ideas or identify potential problems, but merely asked the participants to execute each step as indicated in the

MSDT protocol. The experimenter's scripts for these protocols are presented in Appendix B.

The overall amount of time allocated was not changed from the pilot study and allowed most teams to finish the design problem fairly comfortably within the timeframe; some groups finished a little early while some had to push to finish, but all groups completed a testable prototype.

Results

The two measurable quantities from the experiment were the performance score of the team's prototype over three trial runs, and the number of Lego pieces used in the prototype. The test scores were normalized against 300 and the piece count score was normalized against 1. The two normalized scores were then averaged. This created a range of scores from 0 to 1 with 1 being the best combined score.

The normality assumption was checked using a normal probability plot, and two potential outliers were identified. No assignable cause was found for the first data point; however the second data point traced to a group that completely failed to follow experimental protocol during the second run. This group resisted the use of the morphological tool, and after the interface discussion rejected not only the results based upon the tool but also the results of their initial conceptual level design work. This data point was classified as an outlier due to failure to follow protocol, and was removed from the sample.

Test of Variances

The normalized response variable was tested for equal variance using two-sample F-tests for variances. This test determines which means test must be used and helps identify the appropriateness of the experimental design. Across all categories of comparison, the variance tested as statistically indistinguishable. This test depends on the normality assumption noted above.

Tests of Means

Following the test of variance, a test of means was conducted using a two-sample Student t-test assuming equal means. Each category was tested to determine whether the run 2 scores were higher than those of run 1. A positive difference indicates support for the hypothesis. Table 5 displays the means tests results.

Table 5 - Results of Student t-test of Means Assuming Equal Variance

	Run 1	**Run 2**	**Difference**
Golf Ball Problem	0.584	0.853	0.269**
Mouse Problem	0.433	0.740	0.307**
Within-run Difference	0.152	0.113	
Group A	0.584	0.740	0.156
Group B	0.433	0.853	0.421**

* p-value ≤ 0.10, ** p-value ≤ 0.05

The golf ball problem experienced a 46% improvement between the first and second runs, with a p-value of 0.028. Similarly, the mouse transport problem displayed a

71% improvement with a p-value of 0.027. These results strongly support the stated hypothesis.

Comparing groups across runs showed a 26% improvement for group A with a p-value of 0.142. Group B showed a 97% increase in normalized score with a p-value of 0.004. While group A did not test significant, it is still suggestive of an improvement. Group B's highly significant result supports the hypothesis that use of the SLD tool improves design performance.

When testing within runs, no difference between the groups would be expected since experimental groups were randomly assigned and the problems were of a similar level of difficulty. Performing this test revealed that an average difference of 0.152 with a p-value of 0.331 for Run 1, and an average difference of 0.113 with a p-value of 0.366 for Run 2. This indicated that while the mouse problem may be slightly easier, there is not a statistical difference in difficulty between the two problems used.

Feedback Survey

A post-experiment survey of the participants was administered before the initial results were reported. The participants were asked to evaluate the experimental experience as related to their educational expectations. From this survey, 89% of the participants felt that the design experience was worthwhile, 59% felt that the SLD tool was moderately to very helpful, 41% of the students could envision themselves using this tool on a future design project, and 59% felt that they would be willing to use the tool on a future project. While not conclusive, the survey results triangulate with the experimental results indicating that the observed performance improvement was due to use of the SLD tool.

Discussion

The variance and means tests conducted on the normalized scores of the experimental groups support the hypothesis of the experiment. The non-significant result of the means test between runs for group A does not contradict the hypothesis. The other three comparisons are highly significant and support the stated hypothesis of the paper. Figure 8 displays these results graphically.

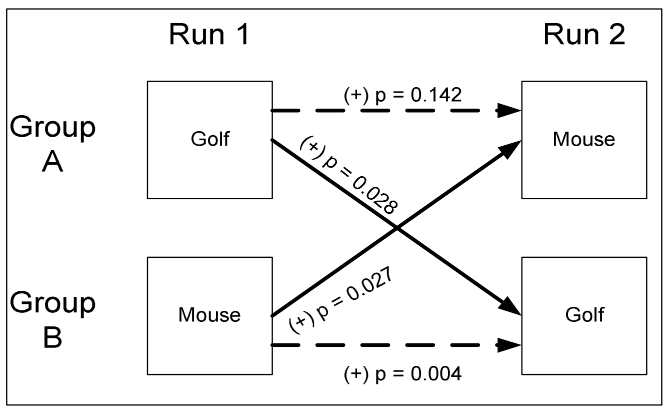


Figure 8 - Graphical Summary of the Comparison Results

The experiment is not without potential biases, the most serious of which may be that participants learned something in the first run that helped them improve performance in the second run. We took two actions to counter this potential bias. The first was to include a materials familiarization exercise at the beginning of the first run to minimize effects from material familiarity. The second precaution was to separate the runs by approximately five weeks (including Spring Break) to make it difficult to reconstruct the details of the previous run.

The hazard associated with this delay is that the students might learn something that would improve their performance on the second run. While we cannot completely eliminate this possibility, we took several steps to minimize it. First, ME 403 classroom topics addressed items (such as catalog selection and machine shop tours) that would not likely apply to the experiment's design problems, save for training in the morphological tool used in the experiment and the theory behind it. Second, the experimenter recorded careful observations and retained the participants' work products, and observed no indication that such learning occurred. For example, the students' level of ideation was comparable between runs, no comments referring to things learned in class or textbook were witnessed, and the only comments referring to the first experiment were statements such as, "we can't do this the same way we did last time."

A final source of possible bias is the interaction of the experimenter with the participants. In order to guide the students in use of the novel design tool, the experimenter necessarily interacted with the participants more in run 2 than in run 1. It is possible that simply interacting with an "expert" lead to superior results irrespective of the content of that interaction. However, the post-experiment survey results seem to indicate otherwise.

Conclusions

The experimental results strongly suggest that using the proposed SLD tool and method helps student create higher performing designs. However, many questions remain. For example, it's not clear from this experiment that the tool and method are scalable to more complex problems. One observation was that the transition from the easier problem to the harder problem (mouse transport to golf ball) was highly significant while the reverse transition, from the harder to the easier problem was not significant.

Reviewing the documentation, it appears the MSDT helped design teams successfully identify superior designs for the problems provided, but it is not possible to separate the effects of the MSDT from the interface walk-through. Being able to separate the effects is important because it would allow case specific SLD tools to substitute for the MSDT in the protocol, and increase the applicability of the SLD method to other design domains. However, before other SLD tools can be developed, we need a greater understanding of why the MSDT and the walk-through method were beneficial. Fundamentally, this question is whether a systematic exploration of subsystem alternatives or a discussion of interfaces contributes more to higher quality outcomes. It is also possible that both the systematic exploration and the interface discussion are needed since either one has little value on its own. Many of these questions are the subject of the follow-on study presented in the next chapter.

CHAPTER 5

FOLLOW-ON EXPERIMENT

The baseline study established that SLD, specifically the MSDT and associated method, is beneficial to the design process. But it also raised a number of questions regarding how SLD can most effectively be used. The follow-on experiment addresses three of those questions:

1. Is the method created to leverage system level design sensitive to changes in the complexity of the problem being solved?
2. Should SLD activities be implemented before or after concept selection in the design process in order to produce the highest quality design?
3. Does the MSDT, the interface walk-through, or the combination have the strongest effect on the outcome of the design?

The motivation for the first question is that problems found outside of a laboratory are more complex. Can the method address SLD issues effectively on harder problems? The second question seeks to understand the costs and benefits associated with performing concept selection before or after SLD. This question is important because it enables designers to position their SLD activities more effectively in the design process rather than addressing SLD haphazardly or not at all. The final question addresses which combination of tools produces the strongest effect on design outcome. Not only does this question further our knowledge of how SLD impacts design outcomes, it also precipitates the development of other SLD tools that can leverage design outcome in a similar manner. For example, SLD modules could be substituted for the MSDT allowing the method to address a broader class of design problems, or the interface walk-through could be tailored to address other aspects of SLD.

This chapter describes the experimental protocol used to answer the three questions selected for further testing, the techniques used to analyze the data, the results of the analysis and their implications.

Experimental Design

The experiment was a 2^4 factorial design. The factors used were problem complexity, location of SLD in the design process, the use of the MSDT, and the use of the interface walk-through method (see Table 6). This type of design was chosen in order to address all three research questions with one experimental protocol.

Table 6 - Experimental Factors and Treatment Conditions

Factor	**Treatment Condition**	
	High	***Low***
Problem Complexity	basic problem + an additional navigation requirement	basic problem
SLD Location	before concept selection	after concept selection
Tool	MSDT	no MSDT
Method	interface walk-through	no interface walk-through

The problems given to the participants were based on the golf ball problem used in the baseline experiment; however, they were implemented at two levels of complexity to meet the treatment condition requirements. Both levels of complexity were designed with competing objectives and complex requirements so that they would not have obvious solutions. The problem read:

> *Move a golf ball from a stand still in the starting area so that it comes to rest on the target ring as close to center as possible using only the materials provided. The only energy that can be applied to the ball must be stored in the materials.*
> *Points will be awarded based upon the final resting location of the golf ball in relation to the target area. The objective is to score the most points possible while using a minimum number of parts.*

For the more complex problem, a 6-inch x 1-inch x 2-inch barrier was added to the course centered in front of the target area. The barrier represented an additional constraint, making the problem more complex.

The response variable was constructed from the location of the golf ball when it came to rest and the number of parts used to make the device. As in the previous experiments, these measurables were combined by normalizing each measure individually then averaging to create an outcome response between 0 and 1. The final resting location of the golf ball was determined by where the ball physically touched the scoring target. If the design precluded the golf ball from touching the target then the location of the ball was visually projected down onto the target to determine its location. The number of pieces used in the design was counted after the demonstration period. Pictures of design solutions from this study are included in Appendix D.

The subjects for the experiment were freshman from ENGR 100 and ME 101 with little or no previous design experience. Engineering 100 is a one-credit introduction to general engineering whose topics include: the fields of engineering, engineering technology, and computer science; engineering design, career opportunities, professionalism, and ethics. ME 101 is a one-credit introduction to mechanical engineering course whose topics include: the mechanical engineering profession, logical process of problem solving and design, professionalism, and ethics. This sample population was selected because the enrollment of these classes allowed for a much larger sample population than had been used in either of the previous studies.

Student participation was facilitated by the classroom instructor making the exercise a class assignment. Students signed up in teams of two or three. In total, 154 students, in 58 teams of 2-3 students each, participated in the experiments. Four teams were excluded from analysis because the teams had fewer than two or more than three students and could not be rescheduled.

Experimental Protocol

Based upon our previous experiences with the type of problem used in this exercise and the number of participants anticipated for this study, we modified the protocol from the baseline study. The design time was left unchanged from the baseline experiment but introductory, familiarization, and clean-up/set-up time was reduced so that the entire exercise could be completed in 90 minutes. The shorter protocol allowed for each class of participants to be processed in the space of one week. Design teams were randomly assigned to the appropriate protocol, blocked by the day of the week. The protocol is outlined in Table 7.

Table 7 - Follow-on Experimental Protocol Timeline

Phase	Activities	Time
Welcome/Introduction	Welcome the students and outline the activities	5 min.
Familiarization	Handle the parts Guided assembly work	10 min.
Problem Statement	Read about and look at set-up Answer Questions	5 min.
Design (Idea Generation)	*No handling of parts!* 1. Generate ideas 2. Sketch at least 3 promising ideas	15 min.
Design (Concept Selection)	Option A: SLD After 3. Select best idea to prototype (5 min) 4. SLD exercise protocol (10 min) -or- Option B: SLD Before 3. SLD exercise protocol (10 min) 4. Select best idea to prototype (5 min) *Deliverable*: 3+ sketches, winner, & criteria	15 min.
Prototype & Test	Build and test selected idea	20 min.
Demo	Three trials	10 min.
	Total Time	**90 min**

The familiarization exercise preceded the introduction to the design problem in order to introduce students to the properties and capabilities of the materials used during the exercise. After completing the familiarization, the experimenter presented a written problem statement to the group. The group read through the design problem and the experimenter walked through the course. During this period, the groups were encouraged to ask questions about the problem statement and the course, then the protocol was reviewed.

Next, at least three ideas were generated. Then, based on the protocol for the randomly selected treatment, the group selected the best idea to prototype or conducted a SLD exercise. All groups did SLD; the differences were whether SLD preceded or followed concept selection, and whether they used the MSDT, used the walk-through method, neither, or both. The subjects were guided through using the MSDT and the interface walk-through as appropriate to their protocol. Prior to the exercise, the classes had been given a lecture on the general design process. Each group was provided scratch paper for sketches and the required deliverables and the experimental materials to build the design. Fifteen minutes were allocated to generate ideas, ten minutes to complete the SLD exercise and five minutes to select the best idea. During this period, the design participants were allowed to pick up and handle the materials, but were not allowed to assemble substructures.

At the end of the design period, three sketches, the “best” idea, the criteria used to decide which idea was the best, and any documents produced during the SLD exercise were due. The participants then built their prototypes and tested their designs on the course. After a maximum of 20 minutes prototyping, the participants demonstrated their prototype during three consecutive runs. Calibration of the prototype was allowed between trials as long as no changes were made to the prototype.

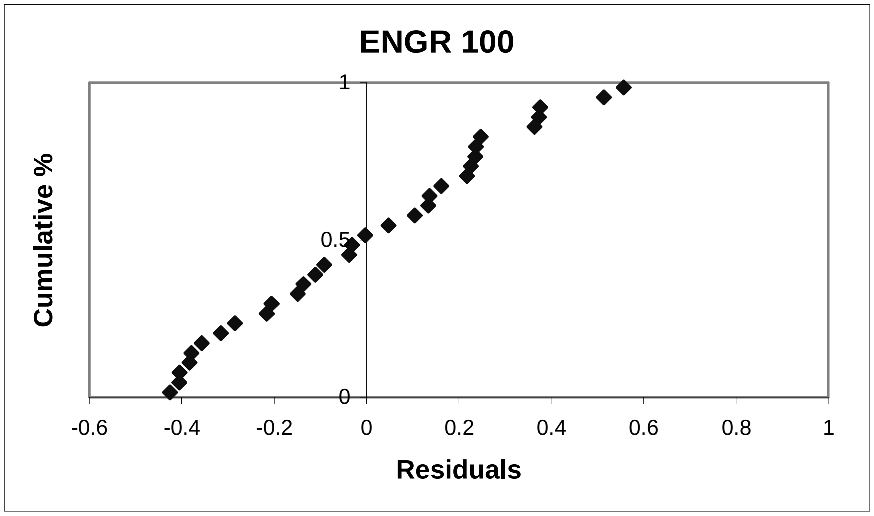
Analysis Methods

The response variable was first tested for the normality assumption using a normal probability plot (NPP) and checked using a histogram. Because the data were found to be normally distributed, they were then tested for equal variances using the two-sample F-test. The means of the response variables were tested with a two-sample Student t-test assuming equal or unequal variances depending on the outcome of the test for equal variances. A regression analysis of composite score, accuracy score, and piece count score using the four treatment conditions as the independent variables was then computed with Mini-Tab Statistical Software. Another regression analysis using the four treatment conditions and a dummy variable to account for noise in the data was also conducted.

Finally, a detailed analysis of variance (ANOVA) was also conducted for both the ME 101 and ENGR 100 data. This analysis included tests of normalization, variance, and means. Additional graphical comparisons of the main and secondary effects within the treatment conditions were done.

Results

The normality checks on the composite score response variables for each class indicated that the normality assumption was reasonable (Figure 9). Testing the comparability of variances showed that the data from the two courses were not statistically similar. However, the means of the composite score were not found to differ significantly (see Table 8 for the comparison of the means and the variances). In all cases the level of significance used is 10%.



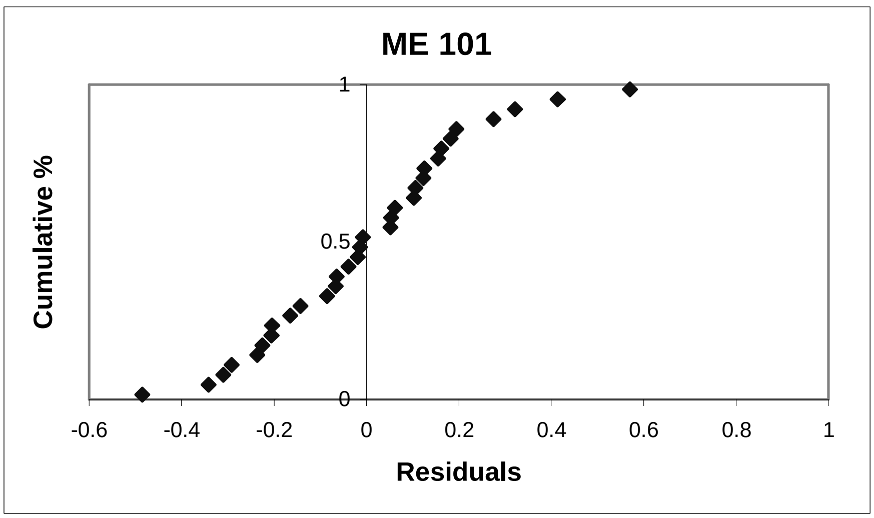


Figure 9 - Normal Probability Plots for ME 101 and ENGR 100

Table 8 - Variance and Means Test for ME 101 and ENGR 100 Composite Scores

F-Test Two-Sample for Variances

	ME 101	*ENGR 100*
Mean	0.6114	0.5994
Variance	0.0683	0.0372
Observations	31	22
Degrees of freedom	30	21
F	1.8377	
P(F<=f) one-tail	0.0753	
F Critical one-tail	2.0102	

t-Test: Two-Sample Assuming Unequal Variances

	ME 101	*ENGR 100*
Mean	0.6114	0.5994
Variance	0.0683	0.0372
Observations	31	22
Hypothesized Mean Difference	0	
Degrees of freedom	51	
t Statistic	0.1925	
P(T<=t) one-tail	0.4241	
t Critical one-tail	1.6753	
P(T<=t) two-tail	0.8481	
t Critical two-tail	2.0076	

The regression model of the combined score for both courses poorly explained the data (R-squared of 7.5%), and none of the regression coefficients had significant p-values. The piece count and trial scores were also analyzed using this technique with similar results. The piece count model resulted in a R-squared of 5.6% and the trial score model had a R- squared of 8.6%. The strongest p-value in the regressions was approximately 23%, well outside the stated level of significance. The regression analysis results can be seen in Appendix E.

The results of the standard ANOVA analysis of the individual courses showed no significant terms in the first or second order but did indicate significant interactions in the third and fourth order terms of the ME 101 data (see Tables 9 and 10 for the ANOVA results). Some secondary effects appeared to be nearly significant so a rigorous graphical comparison of main and secondary effects was pursued. This graphical analysis can be seen in the Appendix F. This graphical analysis revealed no patterns to the data and offered no potential analytical direction to pursue. These results, or more accurately, non-results give us interesting answers to the questions we were seeking to answer with this study.

Table 9 - ME 101 ANOVA Results

Source of Variance	Effects	Contrast	Sum Squared Error	Degrees of freedom	Mean Squared Error	F - statistic	p-value	
A	-0.1449	-2	0.1681	1	0.1681	2.4152	0.1410	
B	-0.0084	0	0.0006	1	0.0006	0.0082	0.9291	
AB	0.0423	1	0.0143	1	0.0143	0.2058	0.6565	
C	-0.0622	-1	0.0309	1	0.0309	0.4446	0.5150	
AC	-0.0242	0	0.0047	1	0.0047	0.0673	0.7989	
BC	0.0368	1	0.0108	1	0.0108	0.1558	0.6986	
ABC	-0.2054	-3	0.3376	1	0.3376	4.8523	0.0437	*
D	0.1441	2	0.1660	1	0.1660	2.3861	0.1433	
AD	0.0371	1	0.0110	1	0.0110	0.1579	0.6967	
BD	-0.0674	-1	0.0364	1	0.0364	0.5229	0.4807	
ABD	-0.0052	0	0.0002	1	0.0002	0.0031	0.9564	
CD	-0.0612	-1	0.0300	1	0.0300	0.4304	0.5217	
ACD	-0.2107	-3	0.3551	1	0.3551	5.1035	0.0392	*
BCD	0.0093	0	0.0007	1	0.0007	0.0100	0.9218	
ABCD	-0.1584	-3	0.2008	1	0.2008	2.8861	0.1100	
Error			1.0437	15	0.0696			
Total			2.4110	31				

* significant at $p \leq 0.1$

Table 10 - ENGR 100 ANOVA Results

Source of Variance	Effects	Contrast	Sum Squared Error	Degrees of freedom	Mean Squared Error	F - statistic	p-value
A	-0.0442	-1	0.0156	1	0.0156	0.1066	0.7486
B	0.0233	0	0.0043	1	0.0043	0.0297	0.8656
AB	-0.0154	0	0.0019	1	0.0019	0.0130	0.9107
C	-0.0623	-1	0.0311	1	0.0311	0.2119	0.6519
AC	-0.1151	-2	0.1059	1	0.1059	0.7225	0.4087
BC	-0.0581	-1	0.0270	1	0.0270	0.1840	0.6741
ABC	-0.1701	-3	0.2314	1	0.2314	1.5783	0.2282
D	0.0242	0	0.0047	1	0.0047	0.0319	0.8606
AD	-0.2118	-3	0.3589	1	0.3589	2.4484	0.1385
BD	-0.0298	0	0.0071	1	0.0071	0.0485	0.8287
ABD	0.0214	0	0.0037	1	0.0037	0.0251	0.8763
CD	-0.0017	0	0.0000	1	0.0000	0.0002	0.9902
ACD	0.1456	2	0.1695	1	0.1695	1.1563	0.2992
BCD	0.0981	2	0.0769	1	0.0769	0.5248	0.4800
ABCD	-0.0434	-1	0.0151	1	0.0151	0.1030	0.7527
Error			2.1989	15	0.1466		
Total			3.2520	31			

* significant at $p \leq 0.1$

Discussion

The MSDT and interface walk-through appear to perform equally well for more and less complex problems. There was no measurable effect from problem complexity in the experiment. Thus this study did not find that the methodology was sensitive to problem complexity. A potential bias for this result might be that the treatment conditions for problem complexity may not have been distinguishable. Possible evidence for this is that well-scoring deflection and trap designs for both the high and low complexity case often used similar design solutions. This could imply that for some solutions types there was little or no practical difference in problem complexity. The similarity of designs was not anticipated for two reasons: first, preliminary testing of the complex treatment condition seemed to indicate that going over the obstacle would be preferred to going around it; and second, in the previous studies teams did not have much success with indirect paths to the target.

No statistical difference from doing SLD before concept selection rather than after was found during this experiment. This would imply that it doesn't matter where in the design process SLD occurs. A reason for this may be that the costs and benefits from locating SLD in a certain location are balanced and 'wash' each other out. Unfortunately this matter is complicated because of the limited training of these novice designers in SLD. The baseline study featured junior and senior level engineering students, who presumably had more experience with engineering design and had some (albeit limited) training in the MSDT prior to the design exercise. The freshmen in this study were only briefly introduced to the design process in class the week before the exercise and had no prior training in the MSDT (all training was provided during the experiment). While many of the groups quickly grasped the use of the tool, some groups struggled with it. This effect could be confounding the results. Because the protocol required the experimenter to teach the MSDT and interface walk-through method to the students during the experiment, there was more room for the experimenter to bias the results. During these interactions, the experimenter was conscious of this possibility and tried not to have any undue effect on the design process.

Testing the use the MSDT and the SLD walk-through method produced no statistically significance trends. Because all teams engaged in some form of SLD, this implies that the form SLD takes doesn't matter as long as SLD occurs. A slightly negative trend was discovered in the third-order interactions during the ANOVA testing of the individual course data. The third-order interaction between high level design complexity, SLD before selection and tool use tested moderately significant (p-value of 7.1%).

This result is difficult to interpret but it is possible that the difficulty of a more complex problem being added to the difficulty of learning a complex tool (MSDT) and making the decision with less knowledge about conceptual alternatives proved significant. This negative impact is potentially the result of combining a complex idea with limited training to novice designers. The added task of learning a design tool on top of producing a solution to the design problem may have been too much for novice designers. The same combination featuring the simpler SLD walk-through method rather than the MSDT did not have a significant result. It is possible that the results are due to the novice designers themselves. Differences based on the refinements on SLD may not be detectable in this population due to lack of design experience.

CHAPTER 6

CONCLUSION

This chapter summarizes what has been learned about SLD and experiments on the design process over the course the three experiments described in Chapters 3, 4 and 5. The first section focuses on what has been learned about SLD, specifically its significance, use, and educational value. Then the usefulness of the SLD methodology is evaluated for instructional use and as a design tool in practice. The lessons learned while testing design process in an experimental setting are presented next. Such testing is relatively new to the field of design research, and the insights into the testing process are expected to shape future design experimentation. Additional experiments will be needed to test the new questions that have arisen during this research. Some of the possible research paths and plans for future work in SLD are covered next. The final section discusses recommendations for implementing SLD in practice and education.

What has been Learned about SLD?

When the pilot study was conducted, our research group considered SLD to be an important step in the design process. The engineering design literature recognizes that SLD is important to the design process, and previous analysis of design journals had identified SLD as a contributing factor to design outcome success. However, the literature claiming that SLD is important to the design process is based on experience rather than empirical evidence. The analysis of the design journals did not test SLD's effect on design outcome. The pilot study was conducted to test whether design process, specifically SLD, could be researched in a laboratory setting.

The pilot study did provide evidence of a correlation between SLD activities and positive design outcomes. Addressing SLD issues on a limited selection of alternatives seemed to result in higher quality design outcomes than not addressing SLD. Also evident was the student’s confusion over how to do SLD. Many groups that thought they were addressing SLD issues never did.

In order to guide the students in SLD for the baseline study, a tool was adapted to aid in SLD decision making. This tool, the MSDT, coupled with a detailed walk-through of interfacing issues, proved to have a strong effect on design quality. This was particularly remarkable because it showed that, with even limited training in SLD, using a SLD tool benefited the design process. This tool aided the design process on two fronts: decision-making and interface problem identification. This evidence supports the claim that decision-making at different abstraction levels, in this case the system-level, was not only possible but beneficial.

One of the lessons of the follow-on study was that SLD is not second nature for most people. Even with the presence of a tool, many of the students in the follow-on study (mostly freshman and sophomores) seemed to struggle to consider SLD issues. Students from the baseline study (juniors and seniors), who had more training in design process, were able to explore SLD issues in greater depth with seemingly less effort. This was especially apparent on the protocols that made use of the MSDT where a lot of effort was made in learning to use the tool in addition to considering SLD issues.

During the baseline study, the participants were introduced to the MSDT before the laboratory exercise. Although this introduction was cursory, the participants of the baseline study were quicker to make use of, and had fewer questions about, the MSDT. One hypothesis for this was that it seemed that while using SLD tools with complex problems resulted in better outcomes, SLD tools also had the potential to add complexity to the problem. Without the capacity to handle the added complexity, SLD tools had little or no benefit. Increased training in the SLD tools might lower the complexity that SLD tools add to problem and decrease the capacity demanded from the designer.

How Effective is the Methodology?

Since the SLD methodology only covers a subset of SLD issues that can affect a design, other tools and emphases may have more general application than the one proposed. The design methodology presented here does provide a structured set of SLD activities appropriate for general mechanical design work and can be empirically tested. The limitations of the highly structured MSDT is somewhat alleviated by the flexibility of the interface walk-through exercise, but it takes practice to implement both aspects effectively.

One of the primary weaknesses of this methodology is the complexity that it adds to a design problem. Complexity mounts when large numbers of permutations are required to fully explore the design combinations with the MSDT. Designer experience can reduce the affects of complexity. The interface walk-through also can be limited by the designer's ability to 'see' potential interface problems. The interface walk-through protocol places the designer in a position to see areas for improvement but the designer must make use of that opportunity. If the designer fails to see a potentially better interface, this methodology has no way of catching that failure and correcting it.

Not forcing a designer to address an interface is part of what makes this methodology effective. The flexibility of the walk-through is that it helps identify areas where improvement are possible and prompts communication between teammates to discuss the assumptions and ideas that are required to make that interface work. If during this communication potential problems are found, the MSDT is a structured method for constructing other interface alternatives. Ultimately, these other alternatives are made based upon the designer's judgment but using the MSDT provides a repeatable and organized method of addressing specific problem areas in a design.

What has been Learned about Conducting Design Experiments?

When the pilot study was proposed, the research group had little experience in conducting laboratory research experiments. One of the pilot study's objectives was to learn how to conduct experiments on design process. Not only did the pilot study succeed in introducing many considerations that greatly benefited both the baseline and follow-on studies, but the baseline and follow-on studies provided lessons about conducting experiments as well.

Experimental preparation proved very important to the experimental process. It was vital to thoroughly test all aspects of a design problem before collecting data. Practicing the script ahead of time helped, but reading from the script during the experiment ensured that the same script was followed every time. Unfortunately, the unexpected happens. How unexpected questions are handled can invalidate the collected data. In the case of a deviation from the expected script, it is important to record as many details as possible and establish a plan based on that twist. Changes in the experimental protocol happen and having a ‘worst-case scenario’ planned ahead of time can help salvage a bad situation.

Statistically, experimental studies must be planned rigorously. It is necessary to plan out response variables, measurable, required sample sizes and anticipated analysis methods. All experimental studies require randomization, but randomization can be very tricky to implement due to issues with scheduling. If a participant does not show up, it can ruin a pre-planned design grid. It was more effective to randomize at the start of a laboratory session by drawing a number out of a hat than being constrained to a rigid design grid.

Another important issue statistically was designing an experiment with a sufficient sample size. Some of the proposed experimental designs were not possible because of changes in classroom enrollment, participation in the exercise, or lack of students. This problem is not avoidable in a classroom setting and is aggravated by the ethical consideration of introducing each student to the possible benefits of our treatment conditions. In many cases, the best experimental design for maximizing statistical benefit in an academic setting would unfairly give an advantage to a subset of students. The cross-over design used in the baseline experiment is one method that can alleviate that concern.

Choosing the appropriate sample for a study is very important. In some regards, the sample for the pilot study was chosen for convenience. It wasn’t until the baseline study when the effects of testing a complex SLD method on novice designers became apparent. The choice to conduct the follow-on study on a sample that was made of primarily freshman was a conscious choice to test the effect of the tool on truly novice designers.

An early experimental decision that had a large impact on the experimental design was the choice of design problem. A design-build protocol was chosen because it allowed for easy data collection, experimenter observation of the design process, and the flexibility to structure the design protocol as necessary. In hindsight, the first two points were the most important. It quickly became apparent that it was important to carefully prepare what information needed to be gathered during the experiment. Whenever possible, forms were created for the routine information so that more time could be spent gathering observational data. Regardless of the amount of data collected, it is more important to anticipate what factors might require more attention later. That way an observational protocol can be created to capture useful data rather than voluminous data. Observational protocols are more helpful when they are established before experimentation but can be adapted during the process based on information gathered during the runs.

Future Work

The follow-on study was not as conclusive as desired. The question of whether this method provides more benefit to problems of greater complexity remains ambiguous. Attempting to create problems that are simple and straightforward but have distinguishable levels of complexity proved difficult. It is not clear whether repeating the experiment as it is currently designed but including greater differentiation in problem complexity would provide more answers. Implementing concept selection before or after SLD activities doesn't seem to make a difference to design outcome. Using the MSDT and interface walk-through as means of systematic exploration of subsystem alternatives was successful, but our attempts at separating the effects of these SLD activities did not provide additional insight into how and why SLD is improving the design process. Another question that needs to be addressed is the effect that novice and more experienced designers have on the experimental protocol. Including truly novice designers in the follow-on study provided insight into the benefits novice designers get from SLD, but more satisfactory answers to the research questions may have been obtained if the participants of the follow-on study had been upper-classmen.

The potential causes of how SLD benefits the design process need more study before applying this or another SLD method to other design domains. A good start would be providing satisfactory answers to the questions above. With a greater understanding of how SLD works other tools and methods could be created to aid in the exploration and improvement of designs at a systems level. Another area to consider is the effect of gender differences on the MSDT and interface walk-through; most of the participants were male.

Recommendations

Based on the results of these studies, there are lessons that can be put to use in practice. One lesson is that SLD should not be pursued at the expense of fundamental concept and detailed design practices. A SLD methodology should give designers a way to systematically address core issues relating to a design's architecture, configuration, layout, and interfacing. By themselves these issues will not produce a better design, but adding development on SLD issues early enough in the design process to inform decision-making can have a great effect on outcome.

When dealing with decisions at a system's level, it was important to approach that problem in its own right without preconceived notions potentially biasing the process. By problem-solving at the systems level of abstraction, more solutions acceptable to the systems level problem should develop. Those possible solutions themselves can provide information to designers that otherwise would not be available. The designer can then use the extra system-level information to improve conceptual decisions and detailed drawings.

Educationally, SLD problem solving is usually not explicitly taught though it is valuable to students. The same benefits that designers can get in practice, namely, better informed conceptual and detailed decision-making and more effective solutions to system-level issues, are available to novice designers like students. Students also benefit in that a SLD methodology can provide an introductory guide for students learning design. Thus while the student is practicing design, he is able to achieve a higher quality outcome without sacrificing good design practices.

Exposure to SLD practices can be introduced to the curriculum through the use of mini-design projects or even experimental studies such as those presented here. These mini-projects give students hands-on experience with a design process, and with short enough project turn about times, they can learn from their own experiences and apply them to more difficult challenges. During this hands-on experience students can contextualize their theoretical knowledge of the design process and gain experience solving problems through the use of a specific tool or method. Quality SLD, like any other level of design, requires practice and experience. Exercises like the ones used in these studies benefit the students by exposing them to good design practices and benefit educators by expanding the reservoir of knowledge about the design process.

The three studies presented in this thesis address not only the fundamental understandings of SLD and the exploration of the design process but also propose a path to merge design education and research to the benefit of both. Hopefully, the lessons learned from these experiments guide and teach future researchers and educators as the field of design research, specifically in the area of SLD, continues to develop.

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APPENDICES

APPENDIX A:

CONTROL AND EXPERIMENTAL PROTOCOL FOR PILOT STUDY

Phase	Control: Activities	Control: Time	Experimental: Activities	Experimental: Time
Familiarization	Handle the parts Guided assembly work	15 min.	Handle the parts Guided assembly work	15 min.
Problem Statement	Read about and look at set-up	5 min.	Read about and look at set-up	5 min.
Design	*No handling of parts!* 1. Generate ideas 2. Sketch at least 3 promising ideas 3. Select best idea for prototype *Deliverable*: 3+ sketches, winner, & criteria	20 min.	*No handling of parts!* 1. Generate ideas 2. Sketch at least 3 promising ideas 3. System-level work on alt's 4. Select best idea for prototype *Deliverable*: 3+ sketches, winner, & criteria	30 min.
Prototype & Test	Build and test selected idea	40 min.	Build and test selected idea	30 min.
Demo	Three trials	10 min.	Three trials	10 min.

APPENDIX B:

EXPERIMENTER'S SCRIPTS FOR THE PILOT, BASELINE, AND FOLLOW-ON STUDIES

<u>Pilot Study Experimenter's Script</u>

Purpose Speech – given at the beginning as an introduction to what this is

Good morning/afternoon/evening, my name is Joshua Ruder and I've been working with Dr. Sobek's research group in an attempt to get a better understanding of Student Design Processes. We have some interesting initial results and have been looking at ways of applying these finding into the class room. This lab exercise is a key step to doing this.

We hope you come away with some more hands-on experience with the design process, while at the same time seeing how emphasizing different aspects of the process can lead to different outcomes. Today we'll be looking at just one process but when we report the results in class you'll be able to see the results of different process after everyone has had a chance to run through the exercise.

Do you have any questions before we get started?

Guided Assembly Instructions (verbal) – given at the start of the familiarization stage

To give you an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. Materials will be provided to you now for a brief familiarization and again when you build your prototype. However while you are designing your solution you won't have access to the materials.

To familiarize your group with the materials, take 15 minutes and play with the parts. During that time I'll ask you to build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. After you have completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – handed out

> "Move a golf ball from a stand still in the starting area so that it comes to rest on the target ring as close to center as possible using only the materials provided. The only energy that can be applied to the ball must be stored in the materials.
>
> Points will be awarded based upon the final resting location of the golf ball in relation to the target area. The objective is to score the most points possible in 3 runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. As you can see the starting area is a raised landing overlooking the target area. You'll have to start the ball from rest, navigate the drop, and bring the ball to rest in the target area. There is no time limit on this process. However, remember that only energy that can be stored in the materials can be applied to the ball.

Are there any questions?

Design Introduction (A control) – given at the beginning of the design stage

This first step will be the design stage. Here you will be designing your device but won't have access to handle the materials. During the next 20 minutes you should generate as many ideas as you can. Then sketch at least 3 of the best ideas you come up with. From these 3 or more sketches you should select the best choice for prototyping which will be the next step.

At the end of 20 minutes you need to be able to provide the sketches, your winning choice, and the criteria you based your selection on. Any questions?

Design Introduction (B experimental) – given at the beginning of the design stage

This first step will be the design stage. Here you will be designing your device but won't have access to handle the materials. During the next 30 minutes you should generate as many ideas as you can. Then sketch at least 3 of the best ideas you come up with.

Once you have gotten your sketches of the promising solutions done, think about the configuration of each alternative: 1) could you implement the concept with a different configuration? 2) Which interfaces are crucial to the design? What is an alternative way to make these pieces interact? You should ask yourself either 1 or 2 for each conceptual sketch. So for each of these sketches you should develop at least 2 different approaches to accomplish the same concept. For example if you were to design a parachute areas of interfacing might be the straps to hold the person to the pack, the cord to activate the chute, and the lines to attach the chute to the pack. Then maybe an alternative to using a cord to activate the chute is to use a button. Questions?

Once you have studied the configuration issues and possibilities for each solution, let me look them over briefly. Then I'll ask you to select the best option for prototyping, including which alternative would work best.

At the end of 30 minutes you need to be able to provide sketches of the 3 best ideas, documentation of your configuration study, your winning choice, and the criteria you based your selection on. Any questions?

Prototyping Introduction – Given at the beginning of the Prototype and test stage

Now that you have selected your design it is time to build and test a prototype. During the next 40 minutes (30 for experimental) you have free access to the materials and the testing area. At the end of the time you need to have a working prototype for use in the final stage as well as a piece count for the number of pieces you used (be sure to include the rubber band and string if used).

Demonstration Introduction – given at the beginning of final testing

For this next stage you will demonstrate the capability of your prototype. Let me quickly review the scoring rules:

> "Points will be awarded based upon the final resting location of the golf ball in relation to the target area. The objective is to score the most points possible in 3 runs while using a minimum number of parts."

Be aware that while you may reset or rebuild your design after a trial no additions or changes to your design are permitted at this stage. Let me know when you are ready to begin.

Baseline Study <u>Experimenter's Script</u>

Purpose Speech – given at the beginning as an introduction to what this is
(week 1)
Good morning/afternoon/evening, my name is Joshua Ruder and I've been working with Dr. Sobek's research group in an attempt to get a better understanding of Student Design Processes. We have some interesting initial results and have been looking at ways of applying these finding into the class room. This lab exercise is the second step to doing this.

We hope you come away with some more hands-on experience with design processes, while at the same time seeing how emphasizing different aspects of the process can lead to different outcomes. Today we'll look at one process but when we are in the class next week we'll talk about other processes and how to use them.

Do you have any questions before we get started?
(week 2)
Welcome back, I hope you had a productive week. Today we are going to apply the tool you learned about in class to a different design problem than the one you did last week.

I will assisting you to apply the tool to the problem so if you have questions at anytime please let me know.

Guided Assembly Instructions (verbal) – given at the start of the familiarization stage –
(week 1)
To give you an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. Materials will be provided to you now for a brief familiarization and again when you build your prototype. However while you are designing your solution you won't have access to the materials.

To familiarize your group with the materials, take 15 minutes and play with the parts. During that time I'll ask you to build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. After you have completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – handed out
Problem A

> "Move a golf ball from a stand still in the starting area so that it comes to rest on the target ring as close to center as possible using only the materials provided. The only energy that can be applied to the ball must be stored in the materials.
>
> Points will be awarded based upon a combination of the final location of the golf ball within the target and the number of parts

> used in the design. The objective is to score the most points possible in three runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. As you can see the starting area is a raised landing overlooking the target area. You'll have to start the ball from rest, navigate the drop, and bring the ball to rest in the target area. There is no time limit on this process. However, remember that only energy that can be stored in the materials can be applied to the ball.
Are there any questions?

Problem B

> "Move the mouse (hacky-sack) from the starting line to a distance of no less than 3' and no more than 4'. Within that distance specification a point gradient exists from a maximum of 100 points at 3' to 20 points at 4'. Outside of this specification window no points are rewarded.
>
> Points will be awarded based upon a combination of the final location of the mouse within the specification window and the number of parts used in the design. The objective is to score the most points possible in three runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. As you can see the starting line is over here and the finish line is there. Notice that these lines demark point totals for scoring. There is no time limit on this process. However, remember that only energy that can be stored in the materials can be applied to the device.
Are there any questions?

Design Introduction (week 1) – given at the beginning of the design stage

This first step will be the design stage. Here you will be designing your device but won't have access to handle the materials. During the next 30 minutes you should generate as many ideas as you can. Then sketch at least 3 of the best ideas you come up with. From these 3 or more sketches you should select the best choice for prototyping which will be the next step.

At the end of 20 minutes you need to be able to provide the sketches, your winning choice, and the criteria you based your selection on. Any questions?

Design Introduction (week 2) – given at the beginning of the design stage

This first step will be the design stage. Just like last time you will be designing your device but won't have access to handle the materials. During the next 15 minutes you should generate as many ideas as you can, sketching 2 of the best ideas you come up with.

Once you have gotten your sketches of the promising solutions done, I will step you through the application of the morphological chart to each of your design concepts. After the morphological chart has been completed you will select the best alternative, which you will then prototype in the next stage.

At the end of 30 minutes you need to be able to provide you morphological chart, your winning choice, and any sketches you created during the process. Any questions?

Prototyping Introduction – Given at the beginning of the Prototype and test stage

Now that you have selected your design it is time to build and test a prototype. During the next 30 minutes you have free access to the materials and the testing area. At the end of the time you need to have a working prototype for use in the final stage as well as a piece count for the number of pieces you used (be sure to include the rubber band and string if used).

Demonstration Introduction – given at the beginning of final testing

For this next stage you will demonstrate the capability of your prototype. Let me quickly review the scoring rules:

> "Points will be awarded based upon the final resting location of the golf ball in relation to the target area. The objective is to score the most points possible in 3 runs while using a minimum number of parts."

Be aware that while you may reset or rebuild your design after a trial no additions or changes to your design are permitted at this stage. Let me know when you are ready to begin.

Follow-on Study Option 1 (1) Script –

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Consider what the critical interfaces in your design alternatives are, what is the flow of the materials through the alternatives, how can those interfaces be improved. It might help look at the key functions of the design and how they interact. You will have about 10 minutes to consider these issues.
3. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 2 (a) Script – Block in Front of the Target

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course. The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Consider what the critical interfaces in your design alternatives are, what is the flow of the materials through the alternatives, how can those interfaces be improved. It might help look at the key functions of the design and how they interact. You will have about 10 minutes to consider these issues.
3. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 3 (b) Script – After Selection

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course. The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.
3. Consider what the critical interfaces in your best design has has, what is the flow of the materials through the design, how can those interfaces be improved. It might help look at the key functions of the design and how they interact. You will have about 10 minutes to consider these issues.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 4 (ab) Script – Block + After selection

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course. The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.
3. Consider what the critical interfaces in your best design has has, what is the flow of the materials through the design, how can those interfaces be improved. It might help look at the key functions of the design and how they interact. You will have about 10 minutes to consider these issues.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 5 (c) Script – Use Tool

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Use the tool that is provided to consider what the critical functions in your design alternatives are and how they are inter-dependent or exclusive. Also consider the flow of the materials through the alternatives, how can those interfaces be improved. You will have about 10 minutes to consider these issues.
3. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 6 (ac) Script – Block + Use Tool

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Use the tool that is provided to consider what the critical functions in your design alternatives are and how they are inter-dependent or exclusive. Also consider the flow of the materials through the alternatives, how can those interfaces be improved. You will have about 10 minutes to consider these issues.
3. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 7 (bc) Script – After selection + Use Tool

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.
3. Use the tool that is provided to consider what the critical functions in your design and how they are inter-dependent or exclusive. Also consider the flow of the materials through the alternatives, how can those interfaces be improved. You will have about 10 minutes to consider these issues.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 8 (abc) Script – Block + After selection + Use Tool

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.
3. Use the tool that is provided to consider what the critical functions in your design and how they are inter-dependent or exclusive. Also consider the flow of the materials through the alternatives, how can those interfaces be improved. You will have about 10 minutes to consider these issues.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 9 (d) Script –Use Method

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area,* so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Use the method provided to consider what the flow of the materials through the design alternatives are, what interfaces the design has and how can they be improved. It might help to identify critical functions in your design and how they are inter-dependent or exclusive. You will have about 10 minutes to consider these issues.
3. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Option 10 (ad) Script –Block + Use Method

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Use the method provided to consider what the flow of the materials through the design alternatives are, what interfaces the design has and how can they be improved. It might help to identify critical functions in your design and how they are inter-dependent or exclusive. You will have about 10 minutes to consider these issues.
3. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 11 (b) Script – After Selection + Method

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder. I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course. The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.
3. Use the method provided to consider what the flow of the materials through the design alternatives are, what interfaces the design has and how can they be improved. It might help to identify critical functions in your design and how they are inter-dependent or exclusive. You will have about 10 minutes to consider these issues.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 12 (abd) Script – Block + After selection + Method

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course. The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.
3. Use the method provided to consider what the flow of the materials through the design alternatives are, what interfaces the design has and how can they be improved. It might help to identify critical functions in your design and how they are inter-dependent or exclusive. You will have about 10 minutes to consider these issues.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 13 (cd) Script – Use Tool + Method

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Use the tool and the method that is provided to consider what the critical functions and the flow of material through the critical interfaces in your design and how they are inter-dependent or exclusive. You will have about 10 minutes to consider these issues.
3. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 14 (acd) Script – Block + Use Tool + Method

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
2. Use the tool and the method that is provided to consider what the critical functions and the flow of material through the critical interfaces in your design and how they are inter-dependent or exclusive. You will have about 10 minutes to consider these issues.
3. Select your best option. Record what criteria you used to make your selection on the paper provided. You'll have about 5 minutes to do this.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 15 (bcd) Script – After selection + Use Tool + Method

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
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3. Use the tool and the method that is provided to consider what the critical functions and the flow of material through the critical interfaces in your design and how they are inter-dependent or exclusive. You will have about 10 minutes to consider these issues.

Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

Follow-on Study Option 16 (abcd) Script – Block + After selection + Tool + Method

Introduction –Good morning/afternoon/evening, my name is Joshua Ruder.
I hope this exercise gives you a hands-on experience with the design process, while at the same time emphasizing how different aspects of the process can affect design outcome. Today we'll be looking at just one process alternative but when we report the results in class you'll be able to see the results of different process.

As an overview of what you'll be doing today let me say that we'll start by giving you a design problem. You'll design a solution, prototype, and test it. In order to familiarize you with the materials that will be used for the exercise we'll run through a brief exercise.

Do you have any questions before we get started?

Familiarization –Take 10 minutes and build two modules. The first module will be a wheeled frame capable of rolling a short distance (think car frame). The second module will be an adjustable armature that can be "locked" into place. If you completed that, please use the remaining time to experiment on your own. Any questions?

Problem Statement – "Move a golf ball, from *rest on the starting area*, so that it comes to rest on the target ring as close to center as possible using only the materials provided. You will have to navigate the obstacles on the course The only energy that can be applied to the ball must be stored in the materials.

During the testing points will be awarded based upon the final resting location of the golf ball in relation to the target area and the number of parts used in the design. These will be weighted equally when determining the final score. The objective is to score the most points possible in three consecutive runs while using a minimum number of parts."

Now that you've read the statement lets take a closer look at the course. Any questions?

Design –This first step will be the design stage. Here you will be designing your device but won't be able to handle the materials. You will have 30 minutes to complete the design process:

1. Sketch as many ideas as you can in about 15 minutes.
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Prototyping –Now that you have selected your design, you get to build and test it. Take 20 minutes to build it. During this time you can use the course and all of the materials. At the end of the time you need to have a working prototype for use in the final test.

Testing –You will have 10 minutes to make your three consecutive runs. You can rebuild your device between runs if necessary. Let me know when you are ready to start.

APPENDIX C:

SLDI SCORING SHEET

Lego System Level Design Index Checklist v3

Group #: ___________________

Check which of these system level issues were addressed during the design phase, include system level issues addressed for conceptual alternatives not selected.

Drag

□	□	□	Activating the device in such a way that starting the ball in motion will interface smoothly with other aspects of the concept.
□	□	□	Causing the ball to come to rest in the target area after the transitions through prior interfaces.
□	□	□	Considering the interface between the ball and the device.
□	□	□	How will the available energy be used to drive the device?

Roll

□	□	□	Activating the device in such a way that starting the ball in motion will interface smoothly with other aspects of the concept.
□	□	□	Causing the ball to come to rest in the target area after the transitions through prior interfaces.
□	□	□	How will the ball make the transition from the top ledge to the bottom ledge?
□	□	□	For the transition were control of the ball's speed and/or angle of impact addressed?
□	□	□	*If the transition is accomplished with a ramp, then was the interface with the starting device considered?

Carry

□	□	□	Activating the device in such a way that starting the ball in motion will interface smoothly with other aspects of the concept.
□	□	□	Causing the ball to come to rest in the target area after the transitions through prior interfaces.
□	□	□	How will the ball make the transition from the top ledge to the bottom ledge?
□	□	□	Was the interface between the ball and the device considered?
□	□	□	*If the transition is accomplished with a ramp, then was the interface with the starting device considered?
□	□	□	*If the transporting device is to be dropped, was the structural impact resistance of the device considered?

Slide

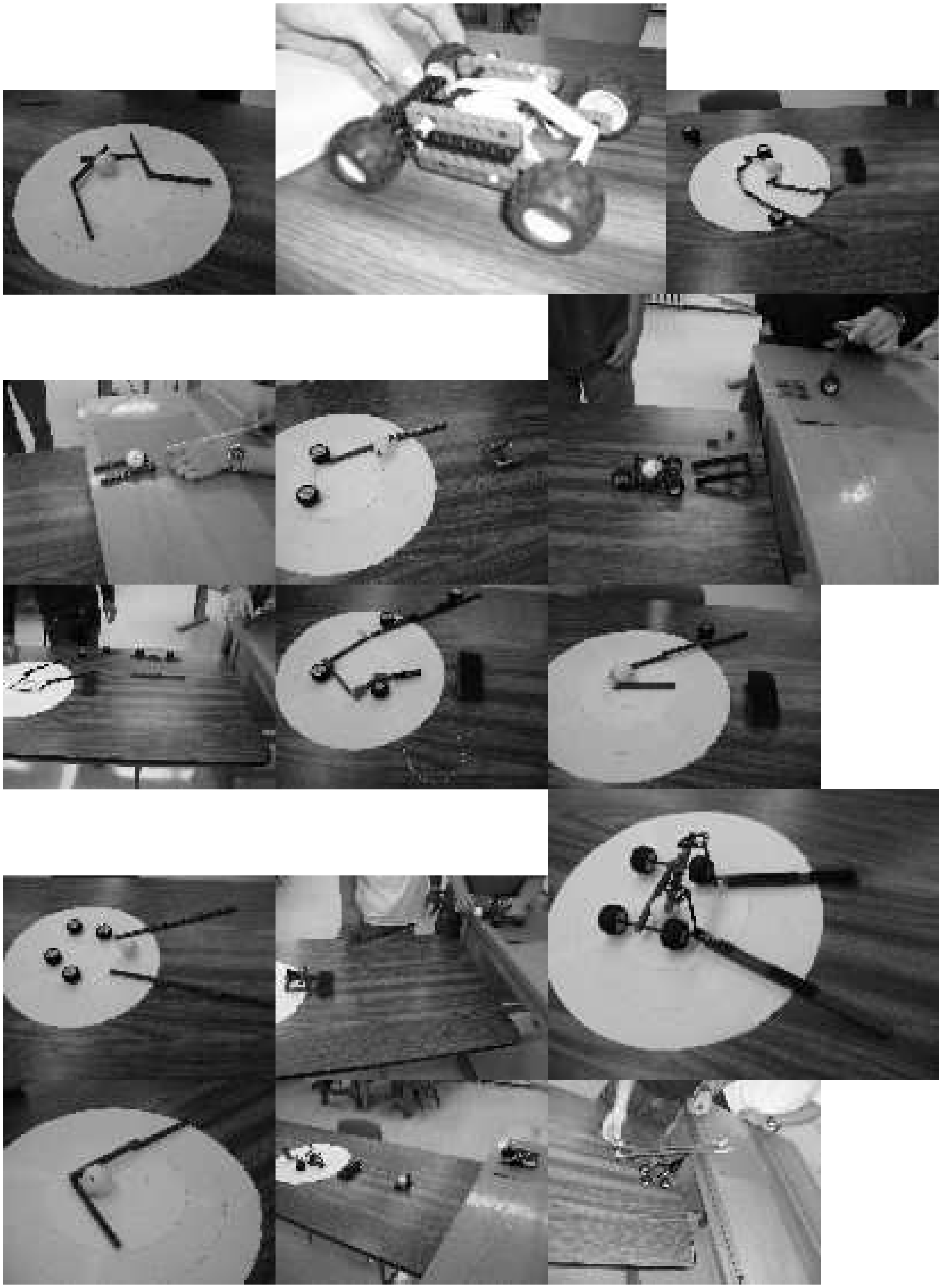
□	□	□	Activating the device in such a way that starting the ball in motion will interface smoothly with other aspects of the concept.
□	□	□	Causing the ball to come to rest in the target area after the transitions through prior interfaces.
□	□	□	Was the interface between the ball and the device considered?
□	□	□	Were the weight of the ball and balance/counter-balance of the device considered?
□	□	□	Was the clearance requirement of the ball/device interface considered?

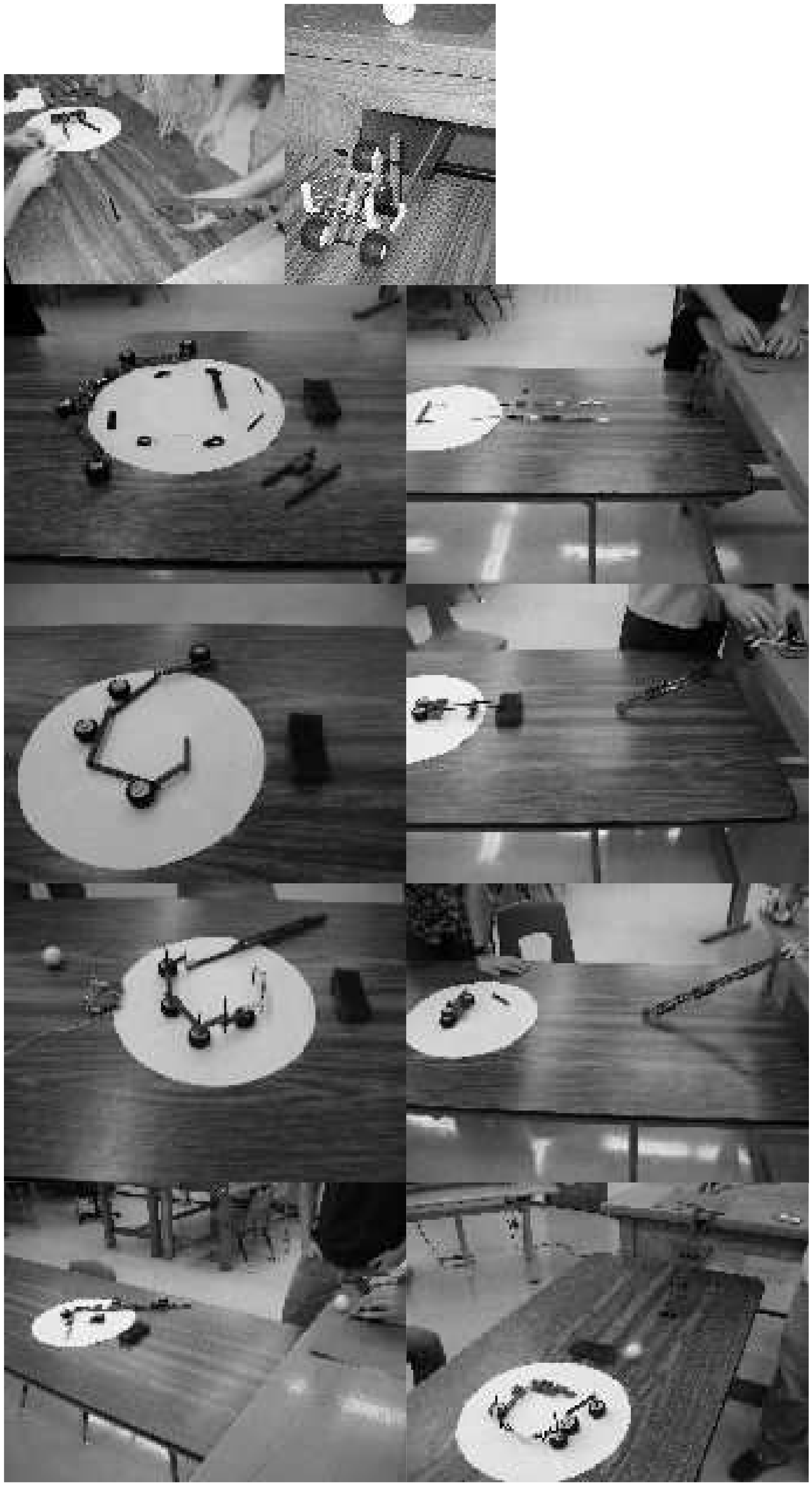
□ Early Convergence □ Late Convergence

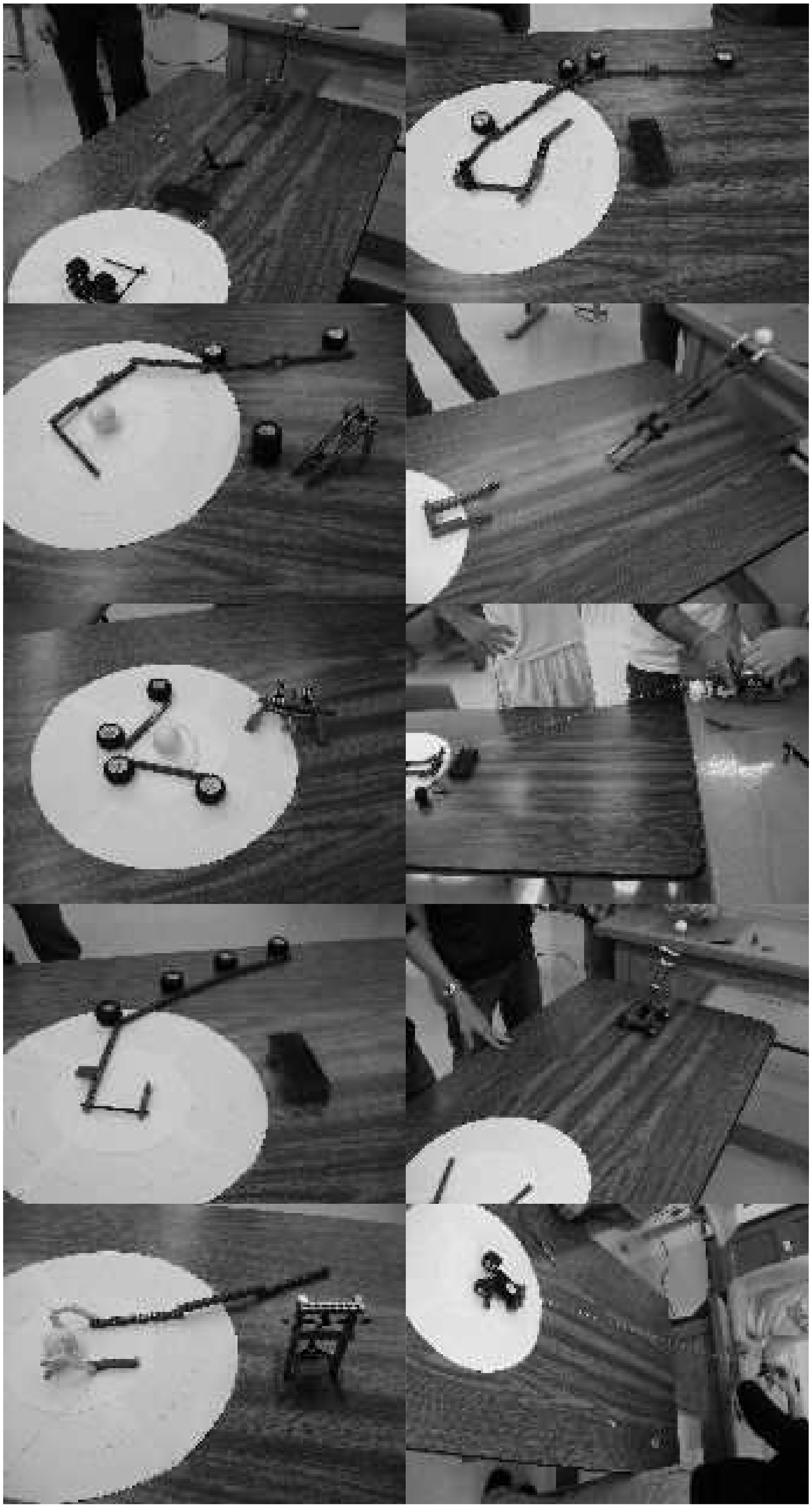
Total SL Issues: ___________________

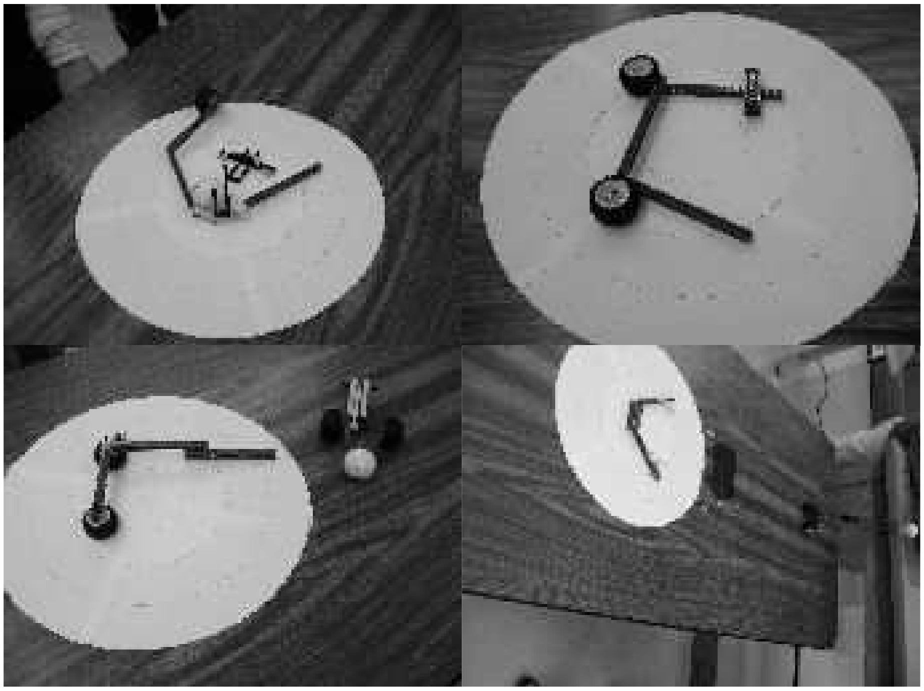
APPENDIX D:

PICTURES OF ME101 AND ENGR 100 DESIGN TEAM SOLUTIONS









APPENDIX E:

ME 101 AND ENGR 100 REGRESSION RESULTS

ME 101 & ENGR 100 Combined Scores Regression Results

Predictor	**Coefficient**	**Squared Error Coefficient**	**T Statistic**	**p-value**
Constant	0.6036	0.03291	18.34	0
Class (ME = 0, ENGR =1)	0.0064	0.03296	0.19	0.847
Complexity	-0.04197	0.03258	-1.29	0.204
SLD location	-0.00895	0.03244	-0.28	0.784
Tool Use	-0.02527	0.0325	-0.78	0.441
Method Use	0.03502	0.03258	1.07	0.288

Source	**Degrees of Freedom**	**Sum of Squared Error**	**Mean Squared Error**	**F Statistic**	**p-value**
Regression	5	0.21486	0.04297	0.77	0.575
Residual Error	47	2.61695	0.05568		
Lack of Fit	26	1.55444	0.05979	1.18	0.351
Pure Error	21	1.06251	0.0506		
Total	52	2.83181			

Source	**Degrees of Freedom**	**Sequential Sum Squared**
Class (ME = 0, ENGR =1)	1	0.00182
Complexity	1	0.11007
SLD location	1	0.00329
Tool Use	1	0.03534
Method Use	1	0.06433

ME 101 & ENGR 100 Piece Count Scores Regression Results

Predictor	**Coefficient**	**Squared Error Coefficient**	**T Statistic**	**p-value**
Constant	0.76634	0.0198	38.7	0
Class (ME = 0, ENGR =1)	-0.00158	0.01983	-0.08	0.937
Complexity	-0.02388	0.0196	-1.22	0.229
SLD location	-0.01533	0.01952	-0.79	0.436
Tool Use	0.0121	0.01955	0.62	0.539
Method Use	0.0098	0.0196	0.5	0.619

Source	**Degrees of Freedom**	**Sum of Squared Error**	**Mean Squared Error**	**F Statistic**	**p-value**
Regression	5	0.05635	0.01127	0.56	0.731
Residual Error	47	0.94729	0.02016		
Lack of Fit	26	0.51517	0.01981	0.96	0.542
Pure Error	21	0.43212	0.02058		
Total	52	1.00364			

Source	**Degrees of Freedom**	**Sequential Sum Squared**
Class (ME = 0, ENGR =1)	1	0.00001
Complexity	1	0.03124
SLD location	1	0.01255
Tool Use	1	0.00751
Method Use	1	0.00504

ME 101 & ENGR 100 Trial Scores Regression Results

Predictor	**Coefficient**	**Squared Error Coefficient**	**T Statistic**	**p-value**
Constant	0.44068	0.05332	8.26	0
Class (ME = 0, ENGR =1)	0.01451	0.0534	0.27	0.787
Complexity	-0.0601	0.05277	-1.14	0.261
SLD location	-0.00258	0.05255	-0.05	0.961
Tool Use	-0.06261	0.05264	-1.19	0.24
Method Use	0.0601	0.05277	1.14	0.261

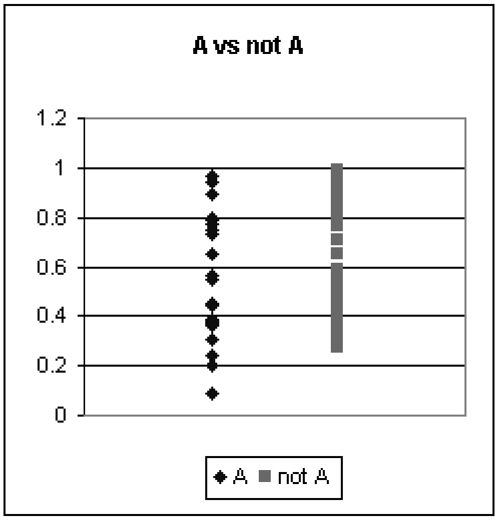
Source	**Degrees of Freedom**	**Sum of Squared Error**	**Mean Squared Error**	**F Statistic**	**p-value**
Regression	5	0.6485	0.1297	0.89	0.497
Residual Error	47	6.8682	0.1461		
Lack of Fit	26	4.4166	0.1699	1.46	0.192
Pure Error	21	2.4516	0.1167		
Total	52	7.5167			

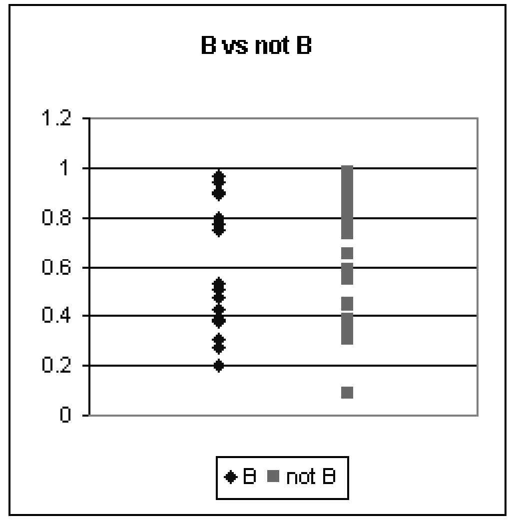
Source	**Degrees of Freedom**	**Sequential Sum Squared**
Class (ME = 0, ENGR =1)	1	0.0081
Complexity	1	0.2371
SLD location	1	0
Tool Use	1	0.2137
Method Use	1	0.1895

APPENDIX F:

GRAPHICAL ANALYSIS OF MAIN AND SECONDARY EFFECTS FOR ME 101 AND ENGR 100

A is Complexity, B is SLD location





F-Test Two-Sample for Variances

	A	*not A*
Mean	0.5477778	0.6512593
Variance	0.0587689	0.0523447
Observations	27	27
df	26	26
F	1.1227274	
P(F<=f) one-tail	0.3850557	
F Critical one-tail	1.6656614	

F-Test Two-Sample for Variances

	B	*not B*
Mean	0.5996296	0.5994074
Variance	0.0624529	0.0542208
Observations	27	27
df	26	26
F	1.1518264	
P(F<=f) one-tail	0.3606299	
F Critical one-tail	1.6656614	

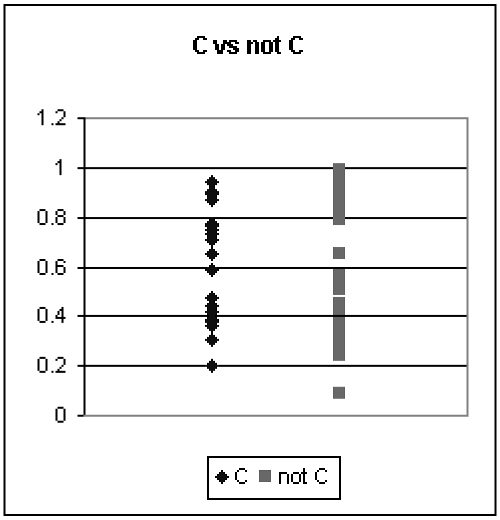
t-Test: Two-Sample Assuming Unequal Variances

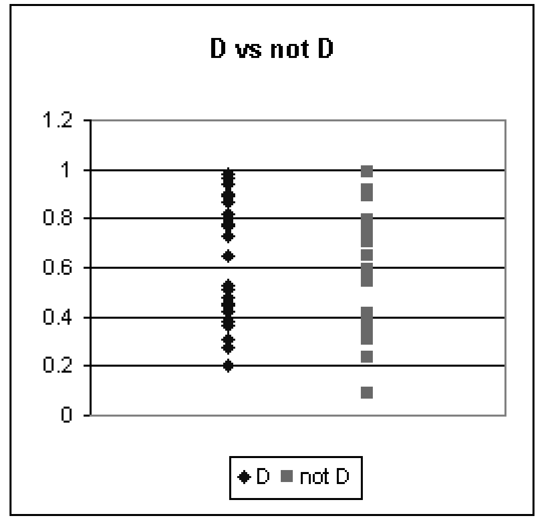
	A	*not A*
Mean	0.5477778	0.6512593
Variance	0.0587689	0.0523447
Observations	27	27
Hypothesized Mean Difference	0	
df	52	
t Stat	-1.6130985	
P(T<=t) one-tail	0.0563881	
t Critical one-tail	1.2980445	
P(T<=t) two-tail	0.1127762	
t Critical two-tail	1.674689	

t-Test: Two-Sample Assuming Unequal Variances

	B	*not B*
Mean	0.5996296	0.5994074
Variance	0.0624529	0.0542208
Observations	27	27
Hypothesized Mean Difference	0	
df	52	
t Stat	0.0033805	
P(T<=t) one-tail	0.4986578	
t Critical one-tail	1.2980445	
P(T<=t) two-tail	0.9973157	
t Critical two-tail	1.674689	

C is use of MSDT, D is use of interface walk-through.





F-Test Two-Sample for Variances

	C	*not C*
Mean	0.5947692	0.6039286
Variance	0.0476706	0.0681712
Observations	26	28
df	25	27
F	0.6992777	
P(F<=f) one-tail	0.185896	
F Critical one-tail	0.5979093	

F-Test Two-Sample for Variances

	D	*not D*
Mean	0.6450741	0.553963
Variance	0.0607154	0.0516481
Observations	27	27
df	26	26
F	1.1755585	
P(F<=f) one-tail	0.341563	
F Critical one-tail	1.6656614	

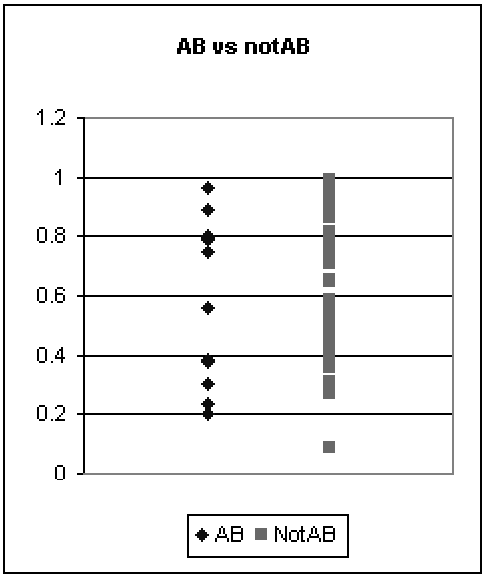
t-Test: Two-Sample Assuming Unequal Variances

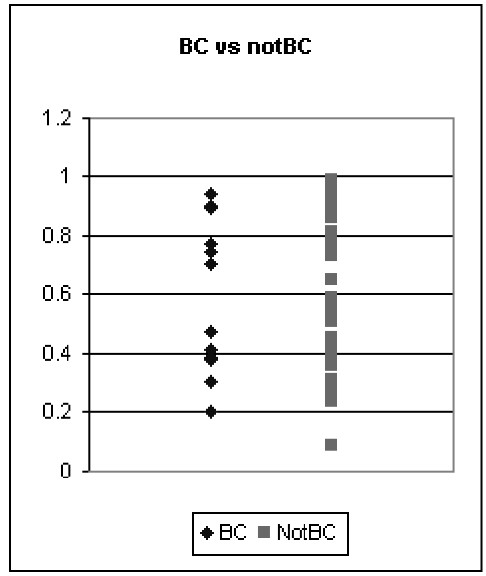
	C	*not C*
Mean	0.5947692	0.6039286
Variance	0.0476706	0.0681712
Observations	26	28
Hypothesized Mean Difference	0	
df	51	
t Stat	-0.1401985	
P(T<=t) one-tail	0.4445277	
t Critical one-tail	1.2983719	
P(T<=t) two-tail	0.8890554	
t Critical two-tail	1.6752847	

t-Test: Two-Sample Assuming Unequal Variances

	D	*not D*
Mean	0.6450741	0.553963
Variance	0.0607154	0.0516481
Observations	27	27
Hypothesized Mean Difference	0	
df	52	
t Stat	1.4123444	
P(T<=t) one-tail	0.0819028	
t Critical one-tail	1.2980445	
P(T<=t) two-tail	0.1638056	
t Critical two-tail	1.674689	

AB is Complexity and SLD location, BC is SLD location and use of MSDT





F-Test Two-Sample for Variances

	AB	*not AB*
Mean	0.572769	0.608
Variance	0.072108	0.053899
Observations	13	41
df	12	40
F	1.33783	
P(F<=f) one-tail	0.236373	
F Critical one-tail	1.714563	

F-Test Two-Sample for Variances

	BC	*not BC*
Mean	0.577846	0.60639
Variance	0.06562	0.055951
Observations	13	41
df	12	40
F	1.172814	
P(F<=f) one-tail	0.334515	
F Critical one-tail	1.714563	

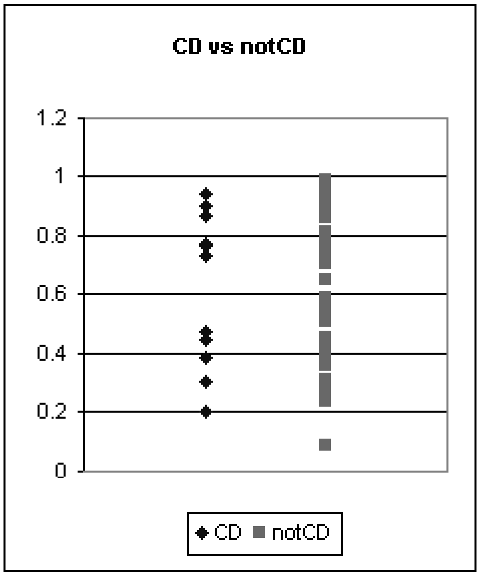
t-Test: Two-Sample Assuming Unequal Variances

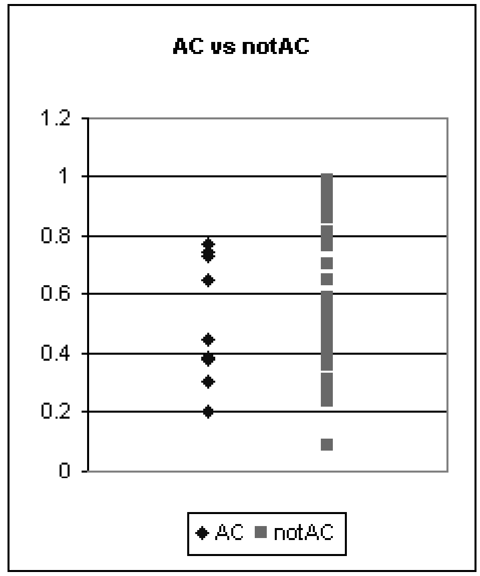
	AB	*not AB*
Mean	0.572769	0.608
Variance	0.072108	0.053899
Observations	13	41
Hypothesized Mean Difference	0	
df	18	
t Stat	-0.42532	
P(T<=t) one-tail	0.337822	
t Critical one-tail	1.330391	
P(T<=t) two-tail	0.675645	
t Critical two-tail	1.734063	

t-Test: Two-Sample Assuming Unequal Variances

	BC	*not BC*
Mean	0.577846	0.60639
Variance	0.06562	0.055951
Observations	13	41
Hypothesized Mean Difference	0	
df	19	
t Stat	-0.35646	
P(T<=t) one-tail	0.362713	
t Critical one-tail	1.327728	
P(T<=t) two-tail	0.725426	
t Critical two-tail	1.729131	

A is Complexity, C is use of MSDT, and D is use of interface walk-through,





F-Test Two-Sample for Variances

	CD	*not CD*
Mean	0.612231	0.595488
Variance	0.063507	0.056717
Observations	13	41
df	12	40
F	1.119717	
P(F<=f) one-tail	0.371944	
F Critical one-tail	1.714563	

F-Test Two-Sample for Variances

	AC	*not AC*
Mean	0.508692	0.628317
Variance	0.038856	0.06065
Observations	13	41
df	12	40
F	0.640664	
P(F<=f) one-tail	0.205198	
F Critical one-tail	0.503499	

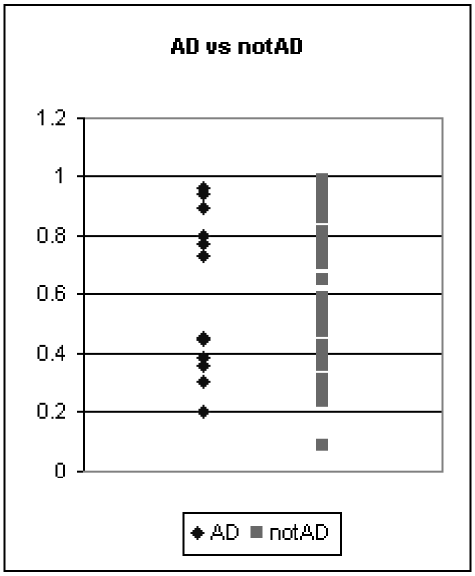
t-Test: Two-Sample Assuming Unequal Variances

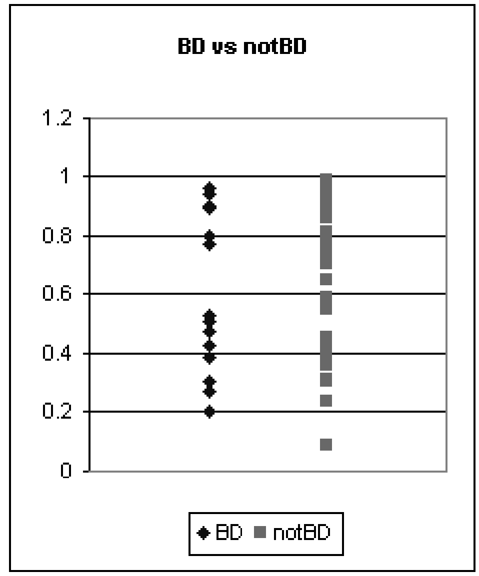
	CD	*not CD*
Mean	0.612231	0.595488
Variance	0.063507	0.056717
Observations	13	41
Hypothesized Mean Difference	0	
df	19	
t Stat	0.211471	
P(T<=t) one-tail	0.417386	
t Critical one-tail	1.327728	
P(T<=t) two-tail	0.834771	
t Critical two-tail	1.729131	

t-Test: Two-Sample Assuming Unequal Variances

	AC	*not AC*
Mean	0.508692	0.628317
Variance	0.038856	0.06065
Observations	13	41
Hypothesized Mean Difference	0	
df	25	
t Stat	-1.78959	
P(T<=t) one-tail	0.042821	
t Critical one-tail	1.316346	
P(T<=t) two-tail	0.085642	
t Critical two-tail	1.70814	

A is Complexity, B is SLD location, and D is use of interface walk-through





F-Test Two-Sample for Variances

	AD	*not AD*
Mean	0.604417	0.598119
Variance	0.074171	0.05408
Observations	12	42
df	11	41
F	1.371504	
P(F<=f) one-tail	0.222882	
F Critical one-tail	1.732722	

F-Test Two-Sample for Variances

	BD	*not BD*
Mean	0.5985	0.599875
Variance	0.073617	0.053243
Observations	14	40
df	13	39
F	1.382658	
P(F<=f) one-tail	0.211327	
F Critical one-tail	1.699515	

t-Test: Two-Sample Assuming Unequal Variances

	AD	*not AD*
Mean	0.604417	0.598119
Variance	0.074171	0.05408
Observations	12	42
Hypothesized Mean Difference	0	
df	16	
t Stat	0.072872	
P(T<=t) one-tail	0.471406	
t Critical one-tail	1.336757	
P(T<=t) two-tail	0.942811	
t Critical two-tail	1.745884	

t-Test: Two-Sample Assuming Unequal Variances

	BD	*not BD*
Mean	0.5985	0.599875
Variance	0.073617	0.053243
Observations	14	40
Hypothesized Mean Difference	0	
df	20	
t Stat	-0.01694	
P(T<=t) one-tail	0.493327	
t Critical one-tail	1.325341	
P(T<=t) two-tail	0.986653	
t Critical two-tail	1.724718	