DESIGN OF EXPERIMENT ON ELECTRICAL

ENGINEERING DESIGN REPRESENTATIONS

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Industrial and Management Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

July 2004

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July 2004

ACKNOWLEDGEMENTS

The National Science Foundation grant entitled "CAREER: The Role of Representation in the Synthesis Process", Award No. REC – 9984484, provided funding for this thesis.

Thanks to Dr. James Peterson for allowing the experiment to be part of his Electrical Engineering Senior Design I class in Spring 2004. Thanks to the students of the class for participating.

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ABSTRACT

Over the decades humans' need and desire for artifacts has increased in quantity, variety, and complexity. Consequently, quality and first to market have become the goals of many engineering firms. This in turn has put pressure on engineering education programs to produce professionals proficient and able to design quality products fast.

Researchers have studied design from many different perspectives. One of the perspectives is the role of representations in design. Internal representations belong in our mental world while external representations are in our physical world. This thesis provides experimental evidence on the role of electrical engineering external representations on three design outcomes. The basis of this thesis is a framework developed by Goel (1995).

Goel's framework of notationality classifies external representations into three categories: notational, discursive, and non-notational systems. Non-notational systems are essential for creativity because they encourage lateral transformations and discourage vertical transformations during design. Consequently, this improves design outcome because it encourages divergence and prevents premature convergence. Lateral and vertical transformations are cognitive movements between and within ideas respectively.

This thesis attempts to test Goel's theory by performing a 2^3 factorial design experiment in the electrical engineering domain. The three factors are the three categories of external representations and the response variables are solution quality, productivity of design, and the number of ideas generated. This thesis also briefly explores transformations relation to outcome variables and representations.

Analysis of variance technique with the data reveals that the use of non-notational and discursive systems increases solution quality and productivity of design. Use of notational systems increases the number of ideas generated, which contradicts Goel's (1995) theory. Lateral transformations are better correlated to quality than are vertical transformations.

The experimental results indicate that use of a variety of external representations leads to better design outcomes, specifically representations of non-notational and discursive systems. Electrical engineering instructors may want to formally teach students to design by using non-notational and discursive systems and also re-consider their textbook selection criteria.

CHAPTER 1

INTRODUCTION

Design is an integral part of our daily lives and has been for many decades. It could be argued that mankind has advanced because of our ability to design. Humans seem to have evolved from tool creators to designers in today's world. At the same time our demand for products has increased in quantity and complexity. People today desire a much wider array of increasingly complex and specialized products such as motorized and computerized devices. This increasing demand for complex products together with humans' desire to have choices has increased global competition in the world today.

Many engineering firms design and produce products to meet the needs of human society. Increased pressure from the consumers and globalization of businesses and industries encourages engineering firms to join the race to be first to market with quality products. Consequently, engineering education programs are pressured to produce qualified designers with the necessary knowledge and skills in design problem solving.

Design is a process that consists of a series of activities that creates an object or service that fulfills a market need. Design problem solving is usually challenging because of the nature of the problem. Design problems are, by definition, ill-structured and open-ended. They are ill-structured because there is no one specific approach to solving the problem, and are open-ended because more than one satisfactory solution is possible (Dym, 1994; Romer, Leinert & Sachse, 2000; Cross, 1999). As a result, many researchers study the design process to better understand its mechanics and improve the process. One of the areas of research concentrates on representations in design.

A representation is "something that stands for something else…some sort of model of the thing (or things) it represents" (Johnson, 1998). Representations can be internal, formed and used in the mind, or external, created and used outside the designer's mind on paper, computer, or using physical objects. Engineering professionals and students frequently use external representations, such as sketches, graphs, or block diagrams, to solve design problems.

External representations are valuable to the design process because they "serve as aids for analysis, solution generation, evaluation, and communication and as external storage" (Schutze, Sachse & Romer, 2003). External representations created and used by designers act as tools during the design process. They also play a pivotal role in a designer's cognitive process during design problem solving. According to Yi-Lien Do, et. al. (2000), external representations are "an inherent part of the thinking process, thus a 'medium of thought'". Hence, researching the efficient use of external representations could lead to improvements in design outcome, and produce enhancement to design education.

This thesis, as part of a larger project funded by a NSF CAREER grant led by Dr. Durward Sobek (REC-9984484), attempts to provide experimental evidence on the role of external representations in design, specifically electrical engineering design. The basis of this thesis is a framework by Vinod Goel (1995).

Theory of Notationality

Vinod Goel (1995) developed a classification system that identifies external representations as members of notational, discursive, or non-notational symbol systems. Notational symbol systems are structured, well defined, and specific representations that correspond closely to objects of the world. Discursive symbol systems are also structured, well defined, and specific representations, but their mapping onto physical objects is not always clear. Discursive systems tend to have some ambiguity that may lead to multiple interpretations where the correct interpretation can only be determined from the representation's context. Non-notational systems are unstructured, unclear, vague, and their connection to reality is even more ambiguous than discursive systems. Non-notational systems are difficult to interpret even with the knowledge of the context.

According to Goel (1995), problem solving involves the manipulation of the three classifications of symbol systems. Goel associates non-notational systems to innovative design because of its ambiguous characteristic. Furthermore, this ambiguity enables multiple solution generation, which encourages lateral transformations and fewer vertical transformations. Lateral transformations are movements from one idea to a slightly different idea while vertical transformations are movements from one idea to a more detailed version of the same idea. Design theory research assumes that generation of numerous ideas and late convergence to a solution leads to a high quality design solution (Osborn, 1963 as cited in Yang, 2003; Sobek II, Ward & Liker, 1999). Hence, the use of non-notational systems in design can lead to high quality design solutions.

Goel’s notational and transformation theory together with a preliminary analysis of electrical engineering student design journals led to some intriguing observations and questions. Electrical engineering students depend almost exclusively on notational and discursive systems during problem solving, while rarely using non-notational systems. Hence, would the number of ideas and therefore quality of design increase if electrical engineers make greater use of non-notational systems?

Research Objectives

This thesis attempts to provide experimental evidence on the effects of the three symbol systems when used during the electrical engineering design process. The objective of this thesis is to answer the following questions:

1. Does the use of non-notational systems by electrical engineers affect solution quality, productivity of design, and the number of ideas generated?
2. Does the use of various symbol systems affect the solution quality, productivity of design, and number of ideas generated?
3. Is the number of vertical and lateral transformations associated with design quality, productivity, and amount of ideas generated?

This thesis attempts to address the research questions through a designed experiment. The designed experiment is a 23 factorial design with three factors each at two levels. The factors are the three classifications of symbol systems and the two levels are using representations of the class (high), and not using representations of the class (low). The experiment contains four replications but a total of thirty-one observations. Designing the experiment involved developing the experimental design grid, identifying the study sample, identifying where in the design process the experimental constraints would apply, determining the experimental setting, conducting the experiment, and finally determining the collection of response variables.

Thesis Overview

The following pages describe the theoretical background, experimental design and results, and conclusions and recommendations. Specifically, chapter two of this thesis briefly introduces current research on design and external representations. This is followed by a more detailed explanation of Goel's theories, and a preliminary study of electrical engineering student design journals that identified electrical engineering representations used by student designers.

Chapter three describes the design of experiment, the setup, implementation and outcome variables of the experiment. Chapter four then presents the results from the designed experiment, and discusses implications for the electrical engineering curriculum. Hence research questions one and two are addressed.

Chapter five addresses research question three regarding vertical and lateral transformations. The methodology to study transformations and the analysis approach employed is explained. The subsequent results and findings are also presented along with some implications for the electrical engineering curriculum. Finally, chapter six brings the thesis full circle to the research objectives and summarizes the results and implications. Possible future work is also presented.

CHAPTER 2

LITERATURE REVIEW

This chapter begins by describing the ubiquity of design and its importance to engineering firms and education. The main topics of research in design are mentioned before focusing the literature review on external representations in design. Benefits of external representations are discussed followed by a brief overview of some classification studies of external representations. Finally, the theoretical framework for this thesis is explained followed by a review of the research questions.

Design Process

Design seems to be part of human nature. The human species has been designing since the Stone Age (Birmingham et. al., 1997). Tools recovered from prehistoric times clearly demonstrate peoples' natural ability to design. Over the decades, products have evolved and so have humans and their capability to design. Products are no longer simple like arrowheads but are complex like vehicles, buildings, or plasma televisions. People's changing needs and requirements have encouraged the progress and importance of design in our daily lives.

So what is design? There seem to be several definitions of design in current literature. The Merriam-Webster online dictionary defines design as "to create, fashion, execute, or construct according to plan". This definition ignores an important aspect of design, which is the synthesis of information. Synthesis of information establishes and defines "solutions to and pertinent structures for problems not solved before, or new solutions to problems which have previously been solved in a different way" (Dieter, 2000). Engineering designers seem to practice design problem solving according to this definition (Dieter, 2000).

Design is an essential component of engineering firms and engineering education programs. As society continues to progress and global competition increases, there is greater pressure on engineering professionals to optimize the design process. Consequently, this creates a need to produce qualified engineers with the knowledge and skill in solving design problems (Eastman, McCracken & Newstetter, 2001).

Design is a process consisting of a series of activities that converts an initial specification into a finished artifact that meets the requirements of the specification (Johnson, 1996). This characterization of design process is applicable to situations where design specifications are clear and defined, but frequently initial specifications are vague and ambiguous, hence complicating the design process. Therefore, exploration of these vague specifications is required followed by a series of decisions before pursuing a solution for the problem.

Design activity can also be characterized as a sequence of decisions. The initial specifications of design or design problems tend to be abstract. Gradual refinement of problem concepts through a series of decisions progressively adds constraints on the possible solution until there is no more vagueness, resulting in a final solution (Birmingham et. al., 1997). For example, there is a need for a bridge linking a populated island to the mainland. Now if it is decided that the bridge will be a road bridge with enough clearance for a yacht to pass under it then certain constraints have already been applied. These constraints exclude many other solutions such as a road bridge with only water running under it or a drawbridge that allows for larger floating objects to pass through (Birmingham et. al., 1997). In general, design process is creating an object to fulfill a need created by humans.

Understanding the many facets of design is crucial to improving the design process and teaching design. For many years, researchers have studied design because of its economic and academic importance. Design research can be grouped into six areas (Finger and Dixon, 1983, as cited in Eastman, McCraken & Newstetter, 2001):

1. Identify design processes
2. Benchmark design in industry to develop prescriptive models
3. Generate computer algorithms that mimic design processes
4. Develop design aids such as language or representation
5. Develop analytical tools
6. Design for X (manufacturing, life cycles, etc)

As item number four indicates, representation in design is one of the main research areas, and is the context of this thesis.

Representation in Design

A representation is "something that stands for something else…some sort of model of the thing (or things) it represents" (Johnson, 1998). Representations can be internal or external. Internal representations are ones that are present or created in the mind while external representations are ones that are present or created in the physical world. Much of cognitive science research focuses on internal representations, while engineering design and education research on representation tends to gear towards the external.

The following sections present the support value of external representations in design, and some classifications of external representations.

Support Value of External Representations

External representations are valuable to the design process because they serve as external storage, support communication, aid analysis and evaluation, and assist idea generation (Schutze, Sachse & Romer, 2003).

The human mind contains three main resources that it relies on everyday: short-term or working memory, long-term memory, and attention (Johnson, 1998). Cognitive psychologists have extensively studied short-term memory, long-term memory, and attention to identify their limitations. Short-term memory has a maximum capacity. When this maximum capacity is exceeded, the human mind begins to forget information it is using. In contrast, long-term memory has no limit on capacity but if stored information is not used it fades away. Attention is not a storage space but it is where conscious handling of information occurs. Attention limits people to attend to one task at a time (Johnson, 1998).

Due to the limitations of cognitive resources, especially working memory and attention, mental resources are easily overloaded during problem solving. The human mind is not capable of successfully processing too much information at the same time due to bounded rationality (March and Simon, 1958 as cited in Scott, 2003). Representing information externally eases the load on the human mind (Johnson, 1998; Romer, Leinert & Sachse, 2000; Yang, 2003; Zeng et. al., 2003) hence leading to successful problem solving outcomes. Thinking through external representations also encourages creativity as a result of lesser cognitive stress on engineers during design (Zeng et. al., 2003).

The design process is strongly dependent on dialogue internal to the designer as well as external with others (McGown, Green & Rodgers, 1998). External representations function as boundary objects (Carlile, 2002) during conversations by conveying the designer's ideas clearly in the form of a sketch, model, prototype, or diagram (McKoy et. al., 2001; Schutze, Sachse & Romer, 2003). According to Zeng et. al. (2003), external representations "provide an extremely natural, flexible, and quick method for designers to express and communicate their creative ideas…". Communication with external representation helps avoid misunderstandings by making knowledge transfer explicit.

Analysis and evaluation of the problem, specifications, and possible solutions is an important activity during problem solving. According to Bilda and Demirkan (2003), external representations are “essential for recognizing conflicts and possibilities as well as for revising and refining ideas,…”. External representations also present “opportunities for improved evaluation and the re-stating of problems.” (Rodgers, Green & McGown, 2000). Using external representation as visual interpretation tools “gives designers a direct access to the intuitive assessment of the design concepts against design specifications.” (Zeng et. al., 2003). External representations enable structured thinking processes, which leads to improved problem and solution analysis and evaluation.

Designer’s ability to create and use external representations is an important skill for generating innovative solutions (McKim, 1980 as cited in Yang, 2003). External representations allow designers “to ‘try out’ a new idea on paper, quickly and cheaply” (McGown, Green & Rodgers, 2000). Use of external representations can lead to creative solutions because it enables the designer to create a “ ‘virtual world’ where the drawing reveals qualities and relations unimagined beforehand.” (McGown, Green & Rodgers, 1998). Realization of ideas through external representations results in success of product design in industry (Yang, 2003).

External representations are clearly valuable to the design process and its outcomes. It enables the designer to avoid mental over load, and to have more productive conversation with oneself and with others. It also enhances analysis and evaluation abilities, and helps in generating quality solutions. All these benefits of external representations in design result in successful and quality outcomes. Table 1 summarizes these studies supporting the different benefits of external representations.

Table 1: Summary of Benefits of External Representations

Benefits of External Representations	**References**
External Storage	Johnson, 1998 Romer, Leinert & Sachse, 2000 March and Simon, 1958 as cited in Scott, 2003 Yang, 2003 Zeng et. al., 2003
Communication	Carlile, 2002 McGown, Green & Rodgers, 1998 McKoy et. al., 2001 Schutze, Sachse & Romer, 2003 Zeng et. al., 2003
Analysis and Evaluation	Rodgers, Green & McGown, 2000 Bilda and Demirkan, 2003 Zeng et. al., 2003
Idea Generation	McGown, Green & Rodgers, 2000 McKim, 1980 as cited in Yang, 2003 Yang, 2003

Classification of External Representations

Given the apparent importance of external representations to the design process, some authors have attempted to classify external representations. Classification of external representations occurs in one of two forms. Either a single type of representation is classified in terms of its function or the full spectrum of external representations is categorized in terms of the representation's characteristics.

Zeng et. al. (2003) attempts to model the hierarchical structure of mechanical design sketches in mathematical form. The author uses logical steps based on mathematical concepts and axioms to represent the hierarchical structure of drawn objects based on mereology theory. The result of the application of these theories is a syntactic and semantic structure of information involved in design process. The syntactic and semantic structure is a mathematical representation that naturally and logically models the evolution of sketches generated during a mechanical design process.

Ferguson (1992), as cited in McGown, Green & Rodgers (1998), identifies three categories of sketches. First type of sketch is the thinking sketch, which is used to center and direct a designer's thought process. The second sketch is the prescriptive sketch, which is created by a designer to pass onto the draftsman to complete the drawing. Finally, the last type of sketch is the talking sketch. The talking sketch is created to communicate with other designers and technical support people to evaluate and improve the drawing. The talking sketch is used to encourage discussion among designers.

One of the most detailed studies conducted to classify representations is by Nelson Goodman (1968). Nelson Goodman (1968) categorizes all representations of the physical world in three categories. His work is extensive and complex to understand. Goel (1995) adopts Nelson Goodman's (1968) study and manages to interpret the exhaustive work into a more comprehensible representation framework. Goel's representation framework and application to design process is the basis for this thesis.

Goel's Theory of Notationality

Goel's (1995) "theory of notationality" (based on Nelson Goodman's (1976) work) categorizes external representations into three classifications of symbol systems: notational systems, discursive systems, and non-notational systems.

Notational symbol systems are structured, well defined, and specific representations that correspond closely to artifacts in the physical world without ambiguity. For example, ZIP codes, telephone numbers, and musical scores are notational systems. Discursive symbol systems are also structured, well defined, and specific representations, but their associativity with physical artifacts is not always clear. Examples of discursive systems include natural and artificial languages such as, English, French, Latin, and predicate calculus. While the ambiguity in the discursive systems can lead to multiple interpretations, the correct interpretation can be determined from the representation's context. In contrast, non-notational systems are not structured, well defined, or specific and therefore their connection to reality is even more ambiguous. Examples of non-notational systems are paintings, sculptures, and sketches. Non-notational systems are difficult to interpret even with the knowledge of the context. The classification of symbol systems is summarized in Table 2.

Table 2: Goel's Classification of Symbol Systems

Classification	**Notational System**	**Discursive System**	**Non-Notational System**
Definition	• Structured • Well defined • Specific • Unambiguous	• Structured • Well defined • Specific • Ambiguous	• Unstructured • Unclear • Vague • Ambiguous
Examples	ZIP code, Telephone Number, Musical score	Languages (English, French, etc), predicate calculus	Painting, sculpture, sketches, seismograph readout

Goel describes the design process as a manipulation of representations of the world that transforms an input into an output, as shown in Figure 1.

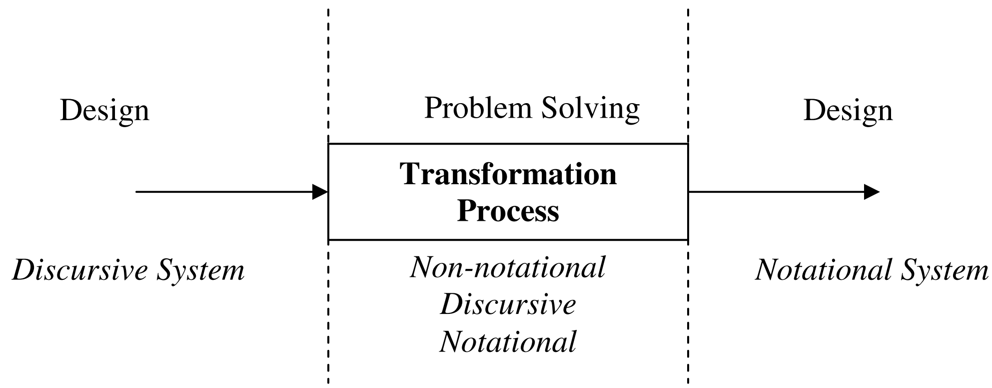


Figure 1: Design as a Process of Transforming Representations

Inputs are often presented using discursive symbol system, such as a design brief, while outputs are usually in the form of a notational representation, such as an engineering drawing. The process that transforms the inputs into outputs also involves representations, but these representations can be notational, discursive or non-notational.

The cognitive processes that parallel management of representations during problem solving are termed lateral transformations and vertical transformations. Lateral transformations are movements from one idea to a slightly different idea while vertical transformations are movements from one idea to a more detailed version of the same idea. Lateral transformation is associated with the preliminary design phase where alternative solutions are generated and explored. The nature of information being considered in this stage of problem solving is coarse, vague, and abstract. According to Goel, "lateral transformations are necessary for widening the problem space and exploring and developing…ideas." (Goel,1995). Vertical transformations narrow the problem space and are associated with the refinement or detailing phases of design. This final stage of problem solving works with information that is more refined, clear, and concrete.

According to Goel, non-notational symbol systems are central to innovative design because their ambiguous characteristic encourages creativity. This ambiguity enables lateral transformations by allowing for multiple interpretations of representations. Transformations among multiple ideas, prevents the designer from committing to a solution too early in problem solving. It facilitates divergence and prevents early convergence. Design theory research assumes that exploration of multiple ideas and late convergence leads to a high quality design solution (Osborn, 1963 as quoted in Yang, 2003; Sobek II, Ward & Liker, 1999). Hence, the use of non-notational systems in design can lead to high quality design solutions.

Goel develops his theories based on interior and graphic designers. Interior and graphic designers rarely perform complicated mathematical analyses during design. In contrast, engineering design seems to concentrate heavily on mathematical analyses. So do Goel's theories hold true for engineering design? This question motivated the application of Goel's work to electrical engineers.

Application of Theory of Notationality to Electrical Engineering

In order to identify the different representations present and better understand the electrical engineering design process, a preliminary analysis of electrical engineering student journals in Fall 2003 was conducted. Once the representations from the journals were identified, they were categorized according to Goel's theory of notationality. This categorization was discussed and verified by Vinod Goel through email and telephone communication. Table 3 lists the classification of electrical engineering representations (refer to appendix A for the detailed table).

Table 3: Electrical Engineering Examples

Notational Systems	**Discursive Systems**	**Non-notational Systems**
• Circuit diagrams • Equations (symbolic & numerical) • Technical Jargon • Component pinout • Computer/pseudo code	• Languages • Software Flow Chart	• Block Diagrams • Response Curves (graphs)

Further analysis of the electrical engineering student journals found that electrical engineering students tend to use notational and discursive systems for problem solving almost exclusively, while rarely using non-notational systems. This observation motivates some interesting thoughts. Perhaps the diversity of symbol systems employed by electrical engineering students during design compensate for the lack of non-notational symbol systems in the electrical engineering domain. But what if electrical engineering students use non-notational systems during design? Perhaps the current number of ideas generated would increase, which in turn could lead to better quality design solutions. These thoughts lead the author to experiment and discover the effect of using the three symbol systems during the design process.

In the next two chapters the experiment design and analysis method is described and the consequent results are reported. The design of experiment answers research questions one and two listed in the introduction: whether the use of non-notational systems or a variety of symbol systems affect the solution quality, design productivity, and the number of ideas generated. Following these chapters is a short chapter investigating the relation of vertical and lateral transformations to solution quality, design productivity, and the number of ideas generated.

CHAPTER 3

EXPERIMENT DESIGN

There are two aspects to any experimental problem: the design of the experiment and the statistical analysis of the data. This chapter concentrates on describing the design of experiment, the setup, implementation and outcomes measurement for the experiment.

Design of Experiment

Design Grid

The experiment was a simple 2^3 factorial design; three factors at two levels, and eight runs in the basic design. See Table 4 for the basic design, where the two levels are indicated by a plus (+) and a minus (-).

Table 4: Basic Design of a 2^3 Factorial Experiment

Runs	Factors			Treatment Combination
	A	B	C	
1	-	-	-	(I)
2	+	-	-	a
3	-	+	-	b
4	+	+	-	ab
5	-	-	+	c
6	+	-	+	ac
7	-	+	+	bc
8	+	+	+	abc

Treatment combination is a coding system to indicate the levels of the factors. For example, treatment combination "ab" means both factors A and B are at the high level, while factor C is at the low level.

The factors were electrical engineering representations grouped according to Goel's three classifications of symbol systems: notational, discursive, and non-notational. Table 5 lists the factors and their corresponding electrical engineering representations used for this experiment.

Table 5: Electrical Engineering Representations matched onto Design Factors

Factors		
A: Non-notational System	**B: Discursive System**	**C: Notational System**
Block Diagrams Response curves – graphs	Language – Text	Circuit Diagrams Equations – symbolic and numerical

The factors are coded A, B and C as shown in Table 5. The non-notational system, factor A, consisted of block diagrams and response curves or graphs. The discursive system, factor B, consisted of language in the form of text. Text included written sentences or paragraphs but not labels for diagrams and graphs. Finally, the notational system, factor C, consisted of circuit diagrams and equations including both symbolic and numerical equations.

Factor levels were discrete, binary, and qualitative. Each factor had two levels, high and low. Factor level high corresponded to creating electrical engineering representations listed for the factor or symbol system while low corresponded to not creating those representations.

This experiment was designed to have four replications (i.e., repetition of the basic experiment) resulting in thirty-two total observations (4replicates * 8runs). Replication is necessary to obtain an estimate of the experimental error. The error determines if observed differences in the data are statistically different. For this experiment, each replicate occurred in a different day because all thirty-two runs per day were infeasible. This meant that blocking was necessary.

Days were blocked in this experiment. One day (replicate) was one block so there were a total of four blocks. Days, a nuisance factor, is statistically proven to influence the experimental outcome. Because the effect of days on outcome variables was not of interest to the experimenter, blocking was used to reduce or eliminate the variability transmitted from days and to improve precision of comparisons among factors of interest. When blocking is used in experimental design, randomization of runs occurs differently than when there are no blocks.

Randomization is randomly determining the allocation of experimental material and order of runs. For this experiment, randomization was designed to occur within blocks and not between blocks. Random order of the eight runs in every block was achieved by having the subjects arbitrarily pick a folded piece of paper that had one of the eight runs written inside. The paper they picked determined their experimental constraints. Randomization is important because it enables independent distribution of observations and assists in averaging out the effects of extraneous factors such as intelligence, experience, or time of day.

Study Sample

The subjects for the experiment were initially thirty-two students from the Electrical Engineering Senior Design I (EE391) class of spring 2004. In reality, only thirty-one students showed up at the right time for the experiment, therefore there was one missing observation.

A personal information form (see appendix B) was developed to collect descriptive data on the study sample, which the subjects completed before participating in the experiment. The majority of the subjects (84%) were male. Most of the subjects (72%) were between the ages of twenty and twenty-two. Half had a cumulative grade point average (GPA) above 3.0 of which a third were above a 3.5 GPA. Only a few participants (19%) had internship experience in the past. The internships were technical support, product designer, or product testing positions. Conversely, 69% of the subjects had technical employment experience that was not an internship. The technical employment experiences were mostly in information or computer technology fields. Finally, almost all the subjects had completed and received a grade of "C" or better in the same courses: circuits, electronics, digital logic, signal systems, and microprocessors.

The EE391 instructor allocated three percent of the class grade to experiment participation to motivate the students to take part in the experiment. The purpose of the study and possible personal benefits from the results were explained to them as an additional incentive.

Design Process

The design process has an input and an output. The process that converts the input into an output is the transformation process, or problem solving (Goel, 1995). The experimental constraints were applied during the problem solving stage of the design process. Refer to Figure 2 for an illustration.

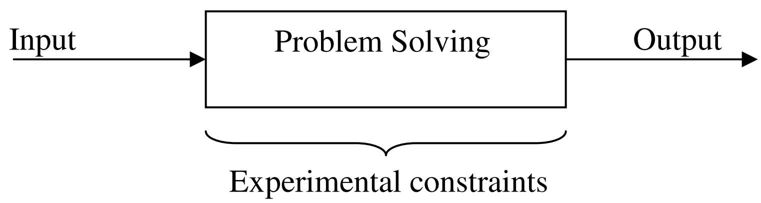


Figure 2: Design Process and Experimental Constraints

Input of the design process was a design question. The EE391 instructor developed the requirements for the problem in Fall 2003 for an EE391 mini-project assignment. For this experiment, the same problem was presented. The objective, specifications, and deliverables of the design problem were explicitly presented to the subjects (see appendix B). The design problem also presented the solution evaluation criteria that were applied.

Problem solving required all the subjects to follow a design protocol while solving the problem so that each subject would go through the same process steps. A systematic problem solving protocol would discard the effect of different problem solving methods on the outcome variables, thus isolating the effect of representation. Appendix B illustrates the main design activities of the design protocol.

The five main activities of the design protocol in sequence are:

- Problem definition
- Preliminary Idea Generation
- Research
- Idea Development
- Analysis

These activities and their order of execution was determined from a preliminary analysis of six electrical engineering student journals from Fall 2003 who solved the same design problem as part a of class assignment.

Each activity of the design protocol was converted into a specific instruction that directed the subjects to execute the activity using a particular set of representations. This was achieved by first identifying the representations commonly used for every activity, then using the common activity representations to develop instructions for the "abc" treatment combination, and finally developing instructions for the other treatment combinations by eliminating or changing "abc" instructions.

Instructions were first constructed for the "abc" treatment combination because it allowed the use of all factors, all representations. For the other seven treatment combinations, instructions were eliminated according to the experimental constraints. For example, for treatment combination "bc" all instructions that prompted the subject to draw graphs or block diagrams were eliminated. In some cases, instructions had to be changed because experimental conditions prohibited the use of the customary representation. For example, for treatment combination "ac" where text is prohibited, the preliminary brainstorming activity could not be externalized on paper. To avoid subjects skipping this activity, they were prompted to think about possible ideas and not write them.

A set of instructions for every treatment combination was compiled. There was an instruction on top of every page and blank space below for subjects to write or draw on. Refer to appendix B for the instructions for each treatment combination. For ease of evaluation, the outputs of the transformation process were all in one representation type. The subjects were required to present the solution in the form of a circuit diagram regardless of their design constraints. The last page of the instructions provided a specific location for the final solution.

Experiment Setup

The experiment took place in the electrical engineering controls lab that was made available exclusively for this study. Two isolated and private workstations were each setup and equipped with:

- A computer containing PSpice, a software program used to simulate analog and digital circuits
- Two textbooks (Dorf & Svoboda, 2001; Sedra & Smith, 1998)
- Paper, pencil, and calculator.

A video camera was setup to capture the work of all participants who volunteered to be filmed. A working space was marked on the table for the subjects to adhere to so that only their written work and hands would be filmed. The video did not record details of computer work but it was clear from the film if a computer was being used. All computer work was saved on a disk.

Implementation of Experiment

Implementation of the experiment involved scheduling the participants, randomizing the runs, getting the subjects to fill out the personal data survey, explaining the rules of the experiment, running the experiment, enforcing the protocol, and video taping.

The experiment was scheduled on Tuesday, Wednesday, Thursday, and Friday of the last week in January 2004. The estimated time to complete the experiment was two hours. To provide the subjects with ample sign up options, fourteen two-hour slots were created per day with an hour overlap. Subjects were sent an email a week before the experiment with the sign up sheet asking them to reply with their top three preferences for time slots. In class on Monday of the week of the experiment, the subjects were explained the purpose and benefits of the experiment, the location, and an overview of what to expect at the experiment. The students who had replied to the email sign-up were given their times while others signed up in class. At the end of class, there were eight subjects per day signed up.

To randomize within a day, a box with eight folded pieces of paper was set up. One of the eight treatment combinations was written on each piece of paper. Every subject picked a piece of paper at the beginning of the experiment. Every time a piece of paper was selected it was kept aside and not returned to the box. The treatment combination selected determined their experimental conditions.

After the experimental condition was selected the subjects signed a non-disclosure agreement to not share any information regarding the experiment to anyone until after all individuals completed the experiment and were asked to complete the personal information form. They were also asked if they were willing to be filmed at this stage.

The subjects received an explanation of the basic rules of the experiment in a different room adjacent to the controls lab. The extra room was available to avoid distracting the other subject already an hour into solving the problem. Refer to appendix B for the explanations given to all subjects.

Spot-checking the subjects while they were solving the problem further enforced the protocol. Some subjects had to be told to stop using a representation because the instructions did not prompt them to do so. Fortunately these interventions were not frequent. After the experiment was completed, the subjects' work was compiled together with the videotapes and labeled using a cover sheet.

Outcome Variables

There were three outcome variables: solution quality, productivity, and number of ideas generated. An evaluation form was developed to measure the quality of the solution (refer to appendix B). The quality measure was a combination of two scores: functionality and component score.

The functionality score measured the solutions' conformance to three design specifications. The higher the functionality score, the better the quality of solution. To achieve objective evaluations, functionality score was designed using a binary system. The solution either met a specification and received ten points or did not meet the specification and received a zero. Subjects were penalized ten points for not assigning component values for their solution.

The component score measured the inverse of reliability, manufacturability, and simplicity of the design. Hence, the lower the component score the better the solution quality. The EE391 instructor developed the component point assignment for his mini-project assignment in Fall 2003, which was used for the evaluations. The different types of components used in a solution were counted and assigned points according to their pin and point system. The point system depended on the complexity of the component. For example, a resistor was assigned one point for two pins while a complicated part such as a transistor was assigned two points for one pin. Pins for integrated circuits (IC's) were based on available parts in the electrical engineering stock room.

Two electrical engineering professors each evaluated the solutions. Photocopies of only the solution page were provided to them together with the evaluation forms. The binary nature of the functionality score was explained to them and additional information regarding pin count for different IC's was also provided.

Once the evaluations were complete, functionality and component scores were combined to make up the quality score. The maximum possible score for functionality was thirty, but the maximum possible score for component was indefinite. Hence, the highest assigned component score by the evaluators was roundup to the nearest ten. For example, the highest number assigned for component score was 117, so the maximum possible score for component was 120.

Correlation analysis was performed on the two evaluator's functionality and component scores. The correlation coefficient was 0.66 and 0.99 for functionality and component respectively. The correlation between the evaluators' functionality scores was considered to be satisfactory and combination of the two quality sub-measures proceeded. The method to combine functionality and component scores is shown in Table 6.

Table 6: Quality Score Calculations

Symbols	
F_1 = Evaluator 1 Functionality Score	C_1 = Evaluator 1 Component Score
F_2 = Evaluator 2 Functionality Score	C_2 = Evaluator 2 Component Score
F_{avg} = Average Functionality Score	C_{avg} = Average Component Score
F_{norm} = Normalized F_{avg}	C_{norm} = Normalized C_{avg}
w_f = Weight assigned to Functionality	w_c = Weight assigned to Component
Q w_f/w_c = Quality score at different weights for functionality and component scores	

Combining Functionality and Component Scores	
$F_{avg} = (F_1 + F_2)/2$	$C_{avg} = (C_1 + C_2)/2$
$F_{norm} = F_{avg}/30$	$C_{norm} = (1-C_{avg})/120$
$Q\ w_f/w_c = ((w_f * F_{norm}) + (w_c * C_{norm}))*100$	

Notice that the average component score is converted to "higher is better quality" before adding the normalized average functionality score. The experimenter chose the weights at twenty-five percent intervals. For example, weights for functionality and component score respectively were: 100% and 0%, 75% and 25%, 50% and 50%, and finally 25% and 75%.

Productivity of the design was measured by dividing the quality score by the total time spent on the design process. The total time spent was recorded during the experiment by the observer and confirmed from video recordings. There were a total of four productivity measures because of the four quality scores at different weights for functionality and components scores.

To count the number of different ideas generated by every subject an operational definition of lateral transformations was developed, which was used to identify the different ideas from photocopies of subject's actual work and their videos. Two ideas were considered to be different when a subject's action altered the structure of the idea or initiated a different approach to the problem. Hence, a low pass filter, high pass filter, and another idea that was a combination of a low pass and a high pass filter were all considered different ideas and counted as three ideas. See appendix B for an example. A summary of outcome variables is shown in Table 7.

Table 7: Outcome Variables

Outcome Variable	**Data Collection**	**Measure**
Solution Quality	2 Professor Evaluations	Quality Score at different weights for functionality and component scores
Number of Ideas	Work on paper	Count of ideas using operational definition of lateral transformation and representation process flow
Productivity of design	2 Professor Evaluations Time recorded during observation	Quality score divided by time spent on design

The following chapter explains the statistical analysis approach employed and results of the experiment.

CHAPTER 4

DESIGN OF EXPERIMENT ANALYSIS AND RESULTS

This chapter describes the statistical analysis approach employed to analyze data from the designed experiment, and presents and discusses the results. The analysis was performed on three different response variables: quality, productivity, and number of ideas generated.

Analysis Approach

The statistical approach applied on the experimental data was analysis of variance (ANOVA). ANOVA models are statistical tools for studying the relation between a response variable and one or more factors or independent variables. For this study, the three qualitative factors were electrical engineering representations categorized in non-notational, discursive, and notational symbol systems, while the response variables were quality, productivity, and the number of ideas generated by subjects

Quality, and hence productivity, were calculated using four different weight combinations for functionality and component score as explained in the preceding chapter. ANOVA was performed on all four quality and productivity calculations. Hence, a total of nine ANOVA procedures were performed: four for quality, four for productivity, and one for number of ideas. See Table 8 for a summary of all the response variables analyzed.

Table 8: Summary of ANOVA Analysis

ANOVA Performed on	**Functionality Score Weight (%)**	**Component Score Weight (%)**
Quality 100/0	100	0
Quality 75/25	75	25
Quality 50/50	50	50
Quality 25/75	25	75
Productivity 100/0	100	0
Productivity 75/25	75	25
Productivity 50/50	50	50
Productivity 25/75	25	75
Number of Ideas	-	-

The ANOVA procedure entailed completing the design grid for the experiment and creating an ANOVA table. The ANOVA table and a predetermined level of significance were used to identify factors and interactions significant to the response variable. The results were then expressed in terms of a regression model because this approach is much more natural and intuitive (Montgomery, 2001). The regression model was used to obtain the predicted or fitted values for the response variable and then the residuals. To verify model adequacy, residual analysis was performed. Residual analysis involved plotting normal probability plots of residuals to test the assumption of normality and residuals against fitted values to test the assumption of constant variance. ANOVA, constructing a regression model, and residual analysis, are explained further in the following sections.

ANOVA

The observed data or response variable data was inputted in the design grid. The grid contained one empty space in the C positive cell; treatment combination "c" had missing a value for the second replicate. This missing observation was a result of thirty-one subjects participating in the experiment instead of thirty-two. Hence, the design grid was incomplete and therefore unbalanced. ANOVA is complicated to apply on unbalanced data, so the missing observation was estimated by using an averaging technique considered reasonable by Montgomery (2001). The estimation procedure used the average of the available three data points of treatment combination "c" for the missing value. Once the design grid was complete, the level of significance was set.

Significance level is the probability of type I error, which is the probability of rejecting the truth. Level of significance set at 0.05 or 5% means that the experimenter is willing to reach the wrong conclusion 5% of the times. For example, a conclusion stating that factor A is significant will be incorrect 5 out of 100 times. In other words, a researcher that concludes a factor is significant has 95% confidence that he is correct. For this analysis, the level of significance was first set at 10% for all outcome variables. If there were no significant factors at 10% significance level then a greater risk was assumed by interpreting the results using a 15% significance level so as to gain some insight on the effect of representations on the outcome variables. Fairly high significance levels were chosen because of the possible bias from the experiment's and response variables' dependence on humans. Humans generally tend to add more variability than machines or mechanized processes.

Creating the ANOVA table required calculating the degrees of freedom, contrasts, effects, sums of squares, mean squares, F-distribution values, and p-values for all the treatment combinations, blocks, error, and total source of variance. Two important values on the ANOVA table are p-values and factor effects. P-values were compared with the level of significance to identify the significant factors and interactions. P-value is the smallest level of significance that leads to rejecting the truth. Hence, if the P-value for a factor or interaction was smaller than the level of significance, then that factor or interaction was concluded to be significant to the response variable. The sign on the significant factor's effect determined the direction of affect of the factor on the response variable. For example, a positive significant factor effect meant that as the significant factor increased, so did the response variable. Factor effects are also useful in obtaining regression model coefficients.

Regression Model

The regression model for a 2^k factorial design is based upon the factors that are significant according to ANOVA. For example, if only the main factors were significant in a 2^3 factorial design, then the regression model would be:

$$y = \beta_o + \beta_A x_A + \beta_B x_B + \beta_C x_C + \varepsilon$$

where, x_A, x_B, and x_C are coded variables that represent factors A, B and C respectively and the β's are regression coefficients. The intercept, β_o, is the average of all the thirty-two observations, and the regression coefficients β_A, β_B, and β_C are half of the corresponding factor effect estimates. Factor effect estimates were obtained from the ANOVA table.

Once the regression model was determined, different levels of the factors were inputted in the model to obtain the fitted values. For this study, the factors were present at only two levels. Hence, +1 and -1 values were assigned to the coded variables at all possible combinations to obtain the predicted or fitted values. Assigning all possible combinations of +1 and –1 to the coded variables would also tell the researcher which combination affects the response variable the most.

Finally, the R^2 statistic for the model was calculated. The ordinary R^2 statistic for the model measures the proportion of total variability explained by the model. A problem with this statistic is that it always increases as factors are added to the model thus it is not reliable statistic to compare two models for a response variable. Therefore, the adjusted R^2 statistic was calculated when two models were compared for the same response variable. This statistic is adjusted for the number of factors in the model.

Residual Analysis.

Residual analysis consisted of two plots: a normal probability plot of residuals, and a residual versus fitted values plot. Residuals were obtained by subtracting the fitted values from the observed values of the response variable. These residuals were then used to construct the two plots.

For the normal probability plot, the residuals were first ranked in ascending order. Their cumulative frequencies were calculated and then converted to z-values using the standard normal distribution. Finally, the normal probability plot was constructed by plotting residuals (x-axis) against their z-values (y-axis). If the underlying error distribution is normal, meaning that the normality assumption is valid, then this plot will resemble a straight line. More emphasis was placed on the central values of the plot than on the extremes to determine whether the normality assumption was valid for the model.

The plot of residuals versus fitted values checks the assumption of constant variance. Fitted values were plotted on the x-axis and their corresponding residuals were plotted on the y-axis. If this plot demonstrated no obvious pattern, meaning the residuals were structure-less, then the model was adequate and the constant variance assumption was valid.

Results and Discussion

The results of ANOVA and regression model for each response variable are presented and discussed in the following subsections. The details of the analysis, such as calculations and plots are presented in appendix C for quality, productivity, and number of ideas respectively.

Quality

The results of ANOVA on the four different quality weightings are presented in Table 9. The two numbers after “Quality” in the table signify the weights assigned to the functionality and component scores respectively (e.g., Quality 75/25 means 75% functionality score and 25% component score).

Table 9: ANOVA Results for Quality, p< 0.10 and p< 0.15

	Significant Factors at 10%	Significant Factors at 15%
Quality 100/0	None	None
Quality 75/25	None	None
Quality 50/50	None	None
Quality 25/75	None	B and AB

As Table 10 indicates, no factors were significant at p<0.10 for all quality variables and p<0.15 when functionality has equal or greater weight. However when the component score receives proportionally more weight, factor B and interaction AB become significant (p<0.15). The ANOVA table for response variable Quality 25/75 is reported in Table 10. A regression model for "Quality 25/75" was then created using the two most significant variables from the ANOVA.

Table 10: Analysis of Variance: Quality 25/75 as Response Variable

Source of Variance	**Degrees of Freedom**	**Contrasts**	**Effects**	**SS**	**MS**	**F_o**	**P-value**
Blocks	3			130.297	43.432	0.138	0.936
A	1	-97.882	-6.118	299.402	299.402	0.952	0.340
B	**1**	**152.743**	**9.546**	**729.076**	**729.076**	**2.319**	**0.143**
C	1	122.882	7.680	471.874	471.874	1.501	0.234
AB	**1**	**166.424**	**10.401**	**865.526**	**865.526**	**2.753**	**0.112**
AC	1	128.785	8.049	518.297	518.297	1.648	0.213
BC	1	-16.424	-1.026	8.429	8.429	0.027	0.872
ABC	1	-129.826	-8.114	526.715	526.715	1.675	0.210
Error	21			6602.786	314.418		
Total	31			10152.403			

The regression model for predicting Quality 25/75 is:

$$y = 66.56 + 4.77x_B + 5.20x_Ax_B$$

where y is the response variable, and x_B represents factor B. The x_Ax_B term is the AB interaction. The R^2 for this model is 0.16, which means that this model explains 16% of the total variance of quality at 25% weight for functionality and 75% weight for the total variance of quality at 25% weight for functionality and 75% weight for component score.

Model adequacy results for this response variable are shown in the form of a normal probability plot of residuals, Figure 3, and a residuals versus fitted values plot, figure 4.

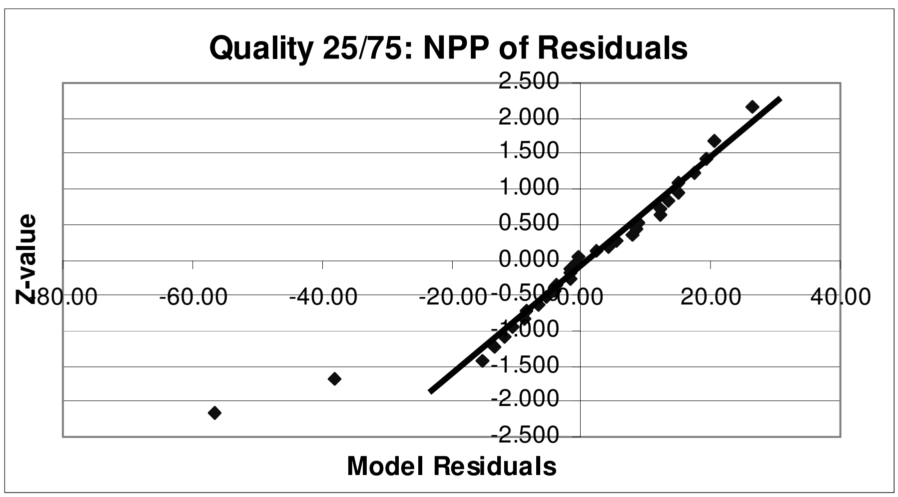


Figure 3: Normal Probability Plot of Residuals for Quality 25/75

The normal probability plot forms a very straight line with all points except two on the left tail. These two points are less than three sigma away and are therefore not outliers. All the points in the center of the plot are on the straight line so the normality assumption is valid. The validity of constant variance assumption is debatable because the points fall into a cone like pattern as shown in Figure 4. Hence, the results of ANOVA need to be interpreted with caution.

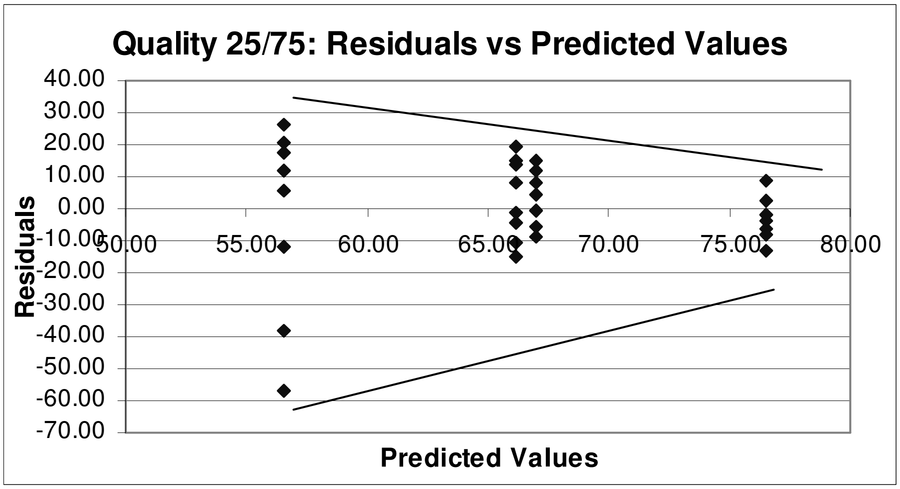


Figure 4: Residuals versus Fitted Values for Quality 25/75

Productivity

The results of ANOVA on the four different productivity scores are presented in Table 11. As before, the two numbers after "Productivity" signify the weights assigned to the functionality and component scores respectively (e.g., Productivity 75/25 means 75% functionality score and 25% component score).

Table 11: ANOVA Results for Productivity, $p < 0.10$

	Significant Factor	Sign on Factor
Productivity 100/0	None	None
Productivity 75/25	None	None
Productivity 50/50	AB	+
Productivity 25/75	AB	+

As Table 11 shows, when the component score receives equal or more importance than functionality, interaction AB is positively significant at 10% significance level. No factors were significant for the other weightings. The ANOVA table for response variable Productivity 50/50 and Productivity 25/75 are in Table 12 and Table 13 respectively.

Table 12: Analysis of Variance for Productivity 50/50, p< 0.10

Source of Variance	Degrees of Freedom	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	3			2527.068	842.356	1.041	0.395
A	1	-241.957	-15.122	1829.472	1829.472	2.261	0.148
B	1	-82.504	-5.156	212.715	212.715	0.263	0.613
C	1	82.212	5.138	211.211	211.211	0.261	0.615
AB	**1**	**304.425**	**19.027**	**2896.084**	**2896.084**	**3.580**	**0.072**
AC	1	-29.448	-1.840	27.099	27.099	0.033	0.857
BC	1	162.737	10.171	827.601	827.601	1.023	0.323
ABC	1	-5.558	-0.347	0.965	0.965	0.001	0.973
Error	21			16989.959	809.046		
Total	31			25522.175			

Table 13: Analysis of Variance for Productivity 25/75, p<0.10

Source of Variance	Degrees of Freedom	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	3			2742.643	914.214	0.726	0.548
A	1	-328.221	-20.514	3366.533	3366.533	2.672	0.117
B	1	10.189	0.637	3.244	3.244	0.003	0.960
C	1	46.662	2.916	68.041	68.041	0.054	0.818
AB	**1**	**412.288**	**25.768**	**5311.915**	**5311.915**	**4.216**	**0.053**
AC	1	-60.340	-3.771	113.780	113.780	0.090	0.767
BC	1	155.743	9.734	757.993	757.993	0.602	0.447
ABC	1	-78.130	-4.883	190.757	190.757	0.151	0.701
Error	21			26458.993	1259.952		
Total	31			39013.900			

Based on the ANOVA table results, a regression model at $p< 0.10$ was identified for "Productivity 50/50" and "Productivity 25/75". This model contained the significant interaction AB. The R^2 value for "Productivity 50/50" was 0.11 and for "Productivity 25/75" was 0.14. These R^2 values seemed low, therefore greater risk in interpreting the results was assumed by identifying another regression model at $p< 0.15$ for "Productivity 50/50" and "Productivity 25/75". At 15% level of significance, factor A and interaction AB were significant. Factor A was negatively significant and interaction AB was positively significant to the response variable. After adding Factor A to the first model ($p<0.10$), the adjusted R^2 for "Productivity 50/50" increased from 8% to 13% while the adjusted R^2 for "Productivity 25/75" increased from 11% to 17%. Hence the regression model for predicting productivity when equal weight is assigned to functionality and component score is:

$$y = 63.80 - 7.56x_A + 9.51x_Ax_B \text{ (Productivity 50/50)}$$

and the regression model for productivity when component score is weighted more than functionality is:

$$y = 75.71 - 10.26x_A + 12.88x_Ax_B \text{ (Productivity 25/75)}$$

where y is the response variable, and x_A, and x_B represent factors A, and B respectively. The x_Ax_B term is the AB interaction. The R^2 for "Productivity 50/50" model is 0.19 and for "Productivity 25/75" model is 0.22.

Model adequacy results for these response variables are shown in the form of a normal probability plot of residuals and residuals versus fitted values plot. Figure 5 and 6 show plots for "Productivity 50/50".

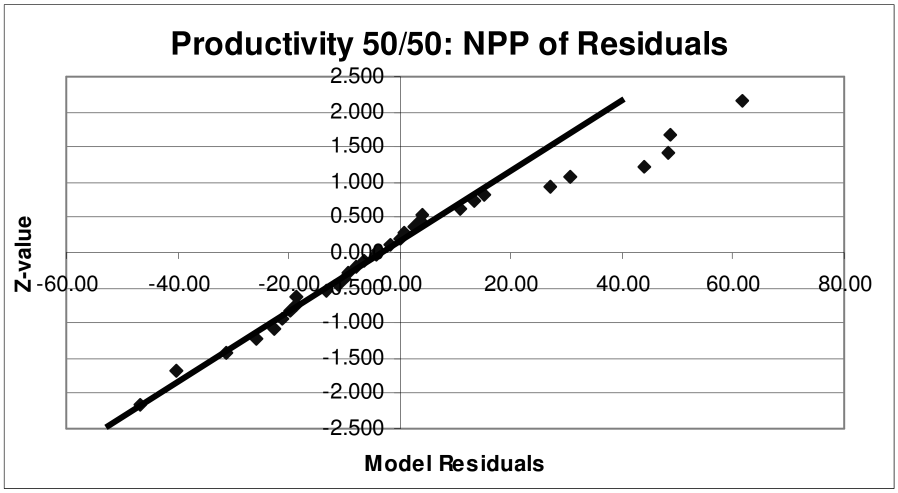


Figure 5: Normal Probability Plot for Productivity 50/50

The normal probability plot shows a fairly straight line. The points at the center of the plot lie on the straight line but there seems to be a slight skew in the data towards the right. Overall, the plot seems fairly normal and therefore the normality assumption is valid. The points at the top right that are not on the line are within three standard deviations and should not be considered outliers.

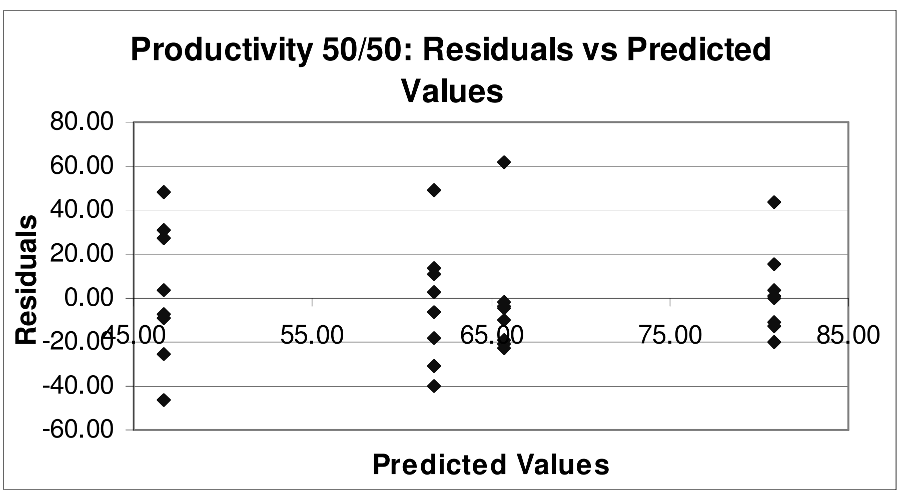


Figure 6: Residuals versus Fitted Values for Productivity 50/50

The residual plot (Figure 6) does not show evidence of a pattern. Hence, the constant variance assumption is also valid for response variable “Productivity 50/50”.

The normal probability plot and residual versus residual plot for “Productivity 25/75” (Figure 7and 8) show similar results. Thus the normality and constant variance assumptions are reasonable.

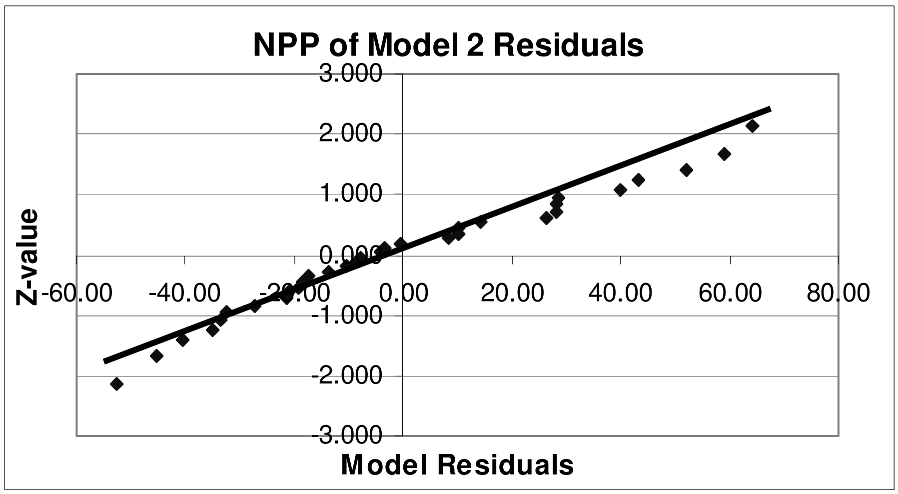


Figure 7: Normal Probability plot for Productivity 25/75

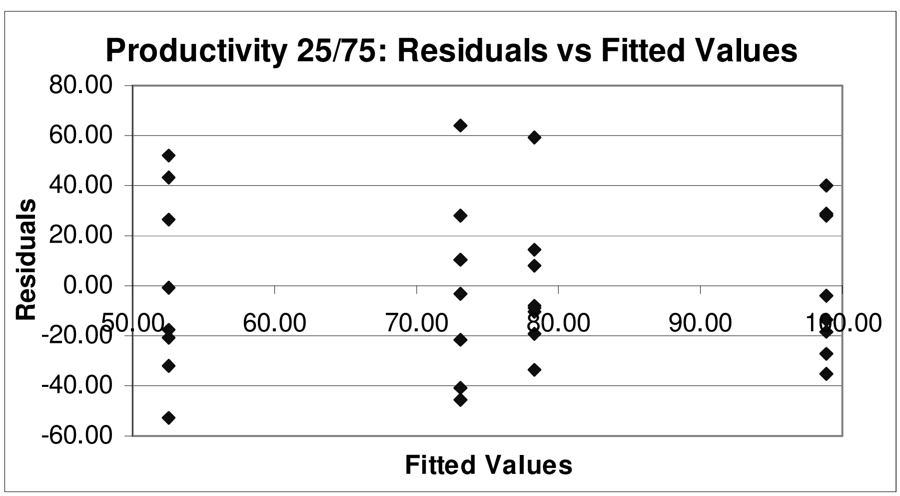


Figure 8: Residual versus Fitted Values for Productivity 25/75

Number of Ideas Generated

Table 14 shows the ANOVA table for the response variable number of ideas generated.

Table 14: Analysis of Variance: Number of Ideas Generated, p< 0.10

Source of Variance	Degrees of Freedom	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	**3**			**41.094**	**13.698**	**3.566**	**0.031**
A	1	9.000	0.563	2.531	2.531	0.659	0.426
B	1	15.000	0.938	7.031	7.031	1.831	0.190
C	**1**	**37.000**	**2.313**	**42.781**	**42.781**	**11.139**	**0.003**
AB	1	3.000	0.188	0.281	0.281	0.073	0.789
AC	**1**	**-19.000**	**-1.188**	**11.281**	**11.281**	**2.937**	**0.101**
BC	1	-5.000	-0.313	0.781	0.781	0.203	0.657
ABC	1	3.000	0.188	0.281	0.281	0.073	0.789
Error	21			80.656	3.841		
Total	31			186.719			

From the table it can be seen that factor C, interaction AC, and days (blocks) are significant to the number of ideas generated. Summing the total number of ideas per day revealed that Friday was the most creative day and Wednesday was the least creative day. Figure 9 shows the total number of ideas for every block.

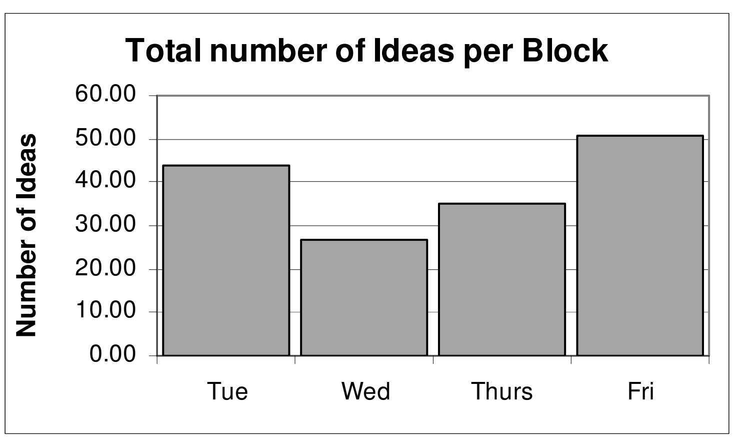


Figure 9: Total Number of Ideas Generated for every Day

For this analysis there was no regression model because there is currently no measure for days (blocks). The assumptions of normality and constant variance were validated using the means model. The plots are in Figure 10 and 11.

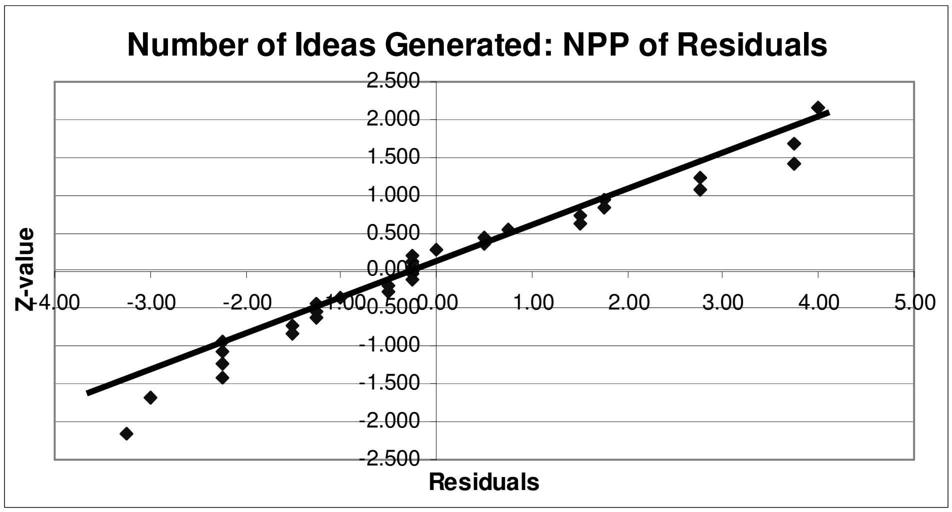


Figure 10: Normal Probability Plot for Number of Ideas Generated

Given the discrete nature of the response variable, a count of ideas, the normal probability plot shows a fairly straight line. Hence, it can be considered that the normality assumption is valid.

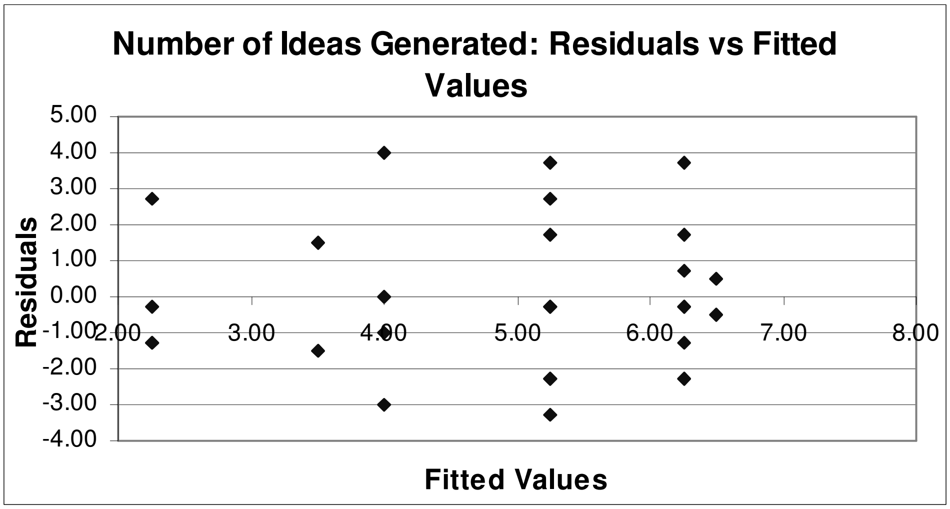


Figure 11: Residuals versus Fitted Values for Number of Ideas Generated

The residual versus fitted values plot demonstrates no pattern or structure. So the assumption of constant variance is valid.

Discussion

The analysis considers three factors that will help control the representations electrical engineers use in a designed experiment. Factor A is a code for non-notational system representations, specifically block diagrams and response curves and factor B is a code for discursive systems, in particular text. Interaction AB represents a combination of the representations in non-notational and discursive systems. The results from ANOVA show that factor B and interaction AB are positively significant to response variable Quality 25/75 at 15% confidence level. Refer to Figure 12 for a pictorial representation of the results.

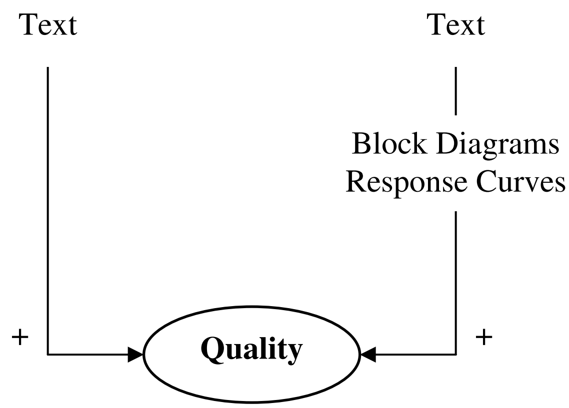


Figure 12: Results for Quality 25/75

When more advanced design criteria receive increasing importance, such as cost and reliability, it appears that creating and using text alone and text together with block diagrams and response curves increases the solution quality. Manufacturability and simplicity approximate cost in this study. A component score, which is a point system assigned to pin count, measure manufacturability and simplicity. A small number of components in a device means fewer electrical connections, which simplifies the design and manufacturing process. The component score was also used to measure reliability. Electrical components can fail, so the more components in a device the lower its reliability. Analysis results indicate that electrical engineering designers should use text alone and a combination of block diagrams, response curves, and text when the customer values cost and reliability more than functionality.

For productivity, results show that interaction AB is positively significant at 50/50 and 25/75, at 10% significance level. But regression models and adjusted R^2 statistic show that factor A and interaction AB explain productivity better at 15% significance level, with factor A negatively and interaction AB positively significant. Refer to Figure 13 for a graphical representation of the results.

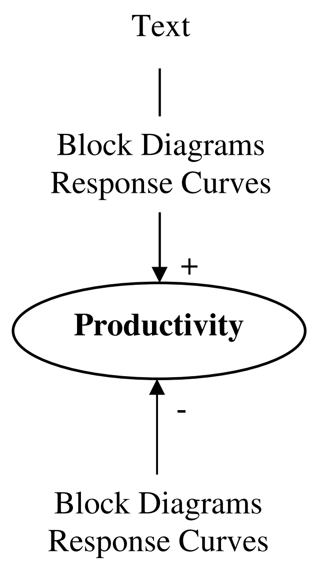


Figure 13: Results for Productivity 50/50 and 25/75

The results then suggest that using block diagrams and response curves decreases productivity, but when combined with text it increases productivity. Electrical engineers should use block diagrams and response curves only in combination with text for higher productivity when the customer prefers cost and reliability in addition to functionality.

So why is it that text combined with block diagrams and response curves is important for increasing quality and productivity? It could be because response curves and block diagrams are easier to understand with words. Non-notational symbol systems (block diagrams and response curves) may be too ambiguous to comprehend. The addition of text might reduce the ambiguity to a comprehensible level while still allowing for creativity. Using text with response curves and block diagrams may explain the underlying concepts, context or scale better (McGown, Green & Rodgers, 1998). Note that using response curves and block diagrams alone has a negative effect on productivity.

Another interpretation is that students may not receive enough training in the use of block diagrams and response curves during design. If so, this interpretation has interesting implications for the electrical engineering curriculum at Montana State University. Maybe instructors are not formally teaching students to use block diagrams and response curves together with text in design. Even without proper training, these representations appear as significantly affecting quality and productivity. A second designed experiment can help test if the currently significant factors (AB) enhance the students' performance on design quality, and productivity. One group of students would be trained to work with block diagrams and response curves and another one would serve as a control group. Individuals from both groups would then solve a design problem. The group that is previously trained would develop solutions of higher quality faster if training affects the outcome variables. Another implication is that the selection criteria for textbooks may need to be reconsidered. A textbook that uses several external representations and not just circuit diagrams may lead to better representation use by students. The low R^2 of regression models and the lack of constant variance suggest that there are other unknown factors affecting the response variables. So the aforementioned changes may not increase design quality or productivity by large amounts.

The previous discussion focused on design quality and productivity, which are two of the three outcome variables for this experiment. The third outcome variable is the number of ideas generated. ANOVA results show that factor C, interaction AC, and the day of the week are significant to number of ideas generated, with factor C positively and interaction AC negatively significant. Factor C is a code for notational symbol systems, in particular circuit diagrams and equations and interaction AC is a combination of non-notational and notational representations. Hence using circuit diagrams and equations increases generation of ideas while these same representations combined with block diagrams and response curves decrease the number of ideas. Refer to the graphical representation of results in Figure 14.

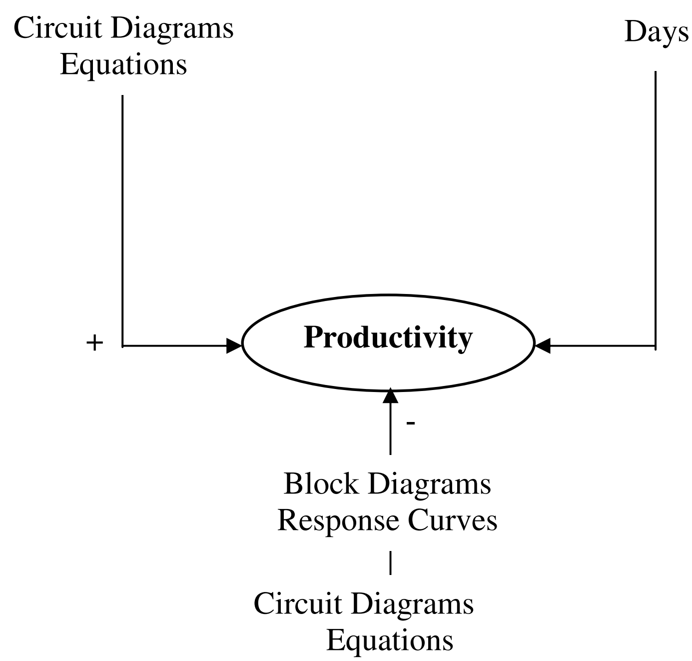


Figure 14: Results for Number of Ideas Generated

Goel's framework classifies symbol systems in an attempt to improve the design process using the number of ideas generated as a measure of outcome. Goel (1995) assumes that non-notational systems help generate multiple ideas. In contrast, this experiment reveals that notational systems, rather than non-notational, increase the number of ideas. This may be because electrical engineering students are trained to generate ideas using circuit diagrams and not other external representations. Or maybe Goel's framework, which is based on interior and graphic design, does not apply to technical fields.

The results also show that using notational and non-notational systems together have a negative effect on the number of ideas generated. Maybe a large cognitive gap between specific representations (notational system) and very ambiguous representations (non-notational system) is causing this negative effect. For example, students may find it difficult to convert a response curve into a circuit diagram and vice versa. Maybe an intermediate representation, such as text, might provide enough clarity to a response curve to make the conversion easier.

Another interesting aspect of the analysis is the effect days has on the number of ideas generated. Friday has the highest number of ideas generated while Wednesday has the least. This could simply be because students are looking forward to the weekend on Friday and so are more relaxed compared to the rest of the week. It could also be that the class load on Wednesday is heavier than the other days. Maybe the emotions or stress levels on a certain day of the week affect creativity. Or maybe similar types of personalities clustered during the four days as a consequence of allowing students to choose the day to complete the experiment. An interesting next step from this particular analysis would be to design another experiment that would consider days as a factor, and not block its effect.

The results from this experiment are preliminary but they reveal interesting opportunities for future work such as another designed experiment to better understand external representations in design.

CHAPTER 5

REPRESENTATION TRANSFORMATIONS

This chapter describes the methodology adopted to determine the relation of vertical and lateral transformations to outcome variables and reports the findings. Videos of subjects' design processes were observed to study transformations. A protocol was developed to code vertical and lateral transformations from the videos. This information was then analyzed to determine the number of vertical and lateral transformations and their relation to outcome variables and representations. The following sections expand on data collection, analysis approach, and the results of the transformation study.

Data Collection

Collection of vertical and lateral transformations involved observing videos of the subjects' design processes and developing a systematic method to extract transformations from these videos. The first step in the systematic method to code vertical and lateral transformations entailed developing operational definitions of Goel's descriptions. The second step was to watch the videos and create a representation flow diagram that illustrated the subject's use of different representations for every idea during their design process. Step three required the data collector to watch the video again and record the start times for every representation on the flow diagram. The final step involved transferring the representation flow and start times to a transformation time sheet and presenting the data in a graphical form. In the following sections each of the four steps are further explained.

Operational Definitions of Vertical and Lateral Transformations

According to Goel, vertical transformations are movements from one idea to a more detailed version of the same idea while lateral transformations are movements from one idea to a slightly different idea. In order to test Goel's assertions in electrical engineering context, operational definitions of vertical and lateral transformations were developed to determine when the two transformations occur in the subject's design process.

For the purposes of this study, vertical transformation was defined as *adding new information or changing existing information to the same idea proximal in time*. Some examples of adding new information to the same idea adjacent in time were adding:

- Component values
- A resistor to a circuit without changing the basic structure of the idea
- A light emitting diode (LED)

Some examples of changing existing information included altering:

- Component values
- Direction of LED's
- Location of a resistor without completely changing the structure of the circuit

Similarly, lateral transformation was defined as transition from one idea to another where one of the ideas resulted from *an action that will alter the structure of the idea or initiate a different approach to the problem.* Some specific examples of change in structure were:

- Adding an analog-to-digital converter to an idea
- Adding a filter
- Changing the number of electronic connections that did not involve an addition of a resistor

Examples of a different approach to the problem were:

- Adding a capacitor or an inductor because frequency discrimination behavior of these components is different
- Changing a capacitor for an inductor and vice versa
- Changing a low pass filter for a high pass filter or vice versa
- Brainstorming ideas in the form of a list

Table 15 summarizes the of operational definitions for vertical and lateral transformations.

Table 15: Operational Definitions for Vertical and Lateral Transformations

	Goel's Definition	**Operational Definition**
Vertical	Movement from one idea to a more detailed version of the same idea	Adding new information or changing existing information to the same idea proximal in time
Lateral	Movement from one idea to a slightly different idea	An action that will alter the structure of the idea or initiate a different approach to the problem

<u>Representation Flow Diagram</u>

The representation flow diagram was developed to highlight the evolution of different representations used for every idea generated during problem solving. The different representations were the electrical engineering representations used in the designed experiment: response curves or graphs, block diagrams, text, circuit diagrams, and finally symbolic and numerical equations. This flow diagram served an intermediate step between observing videos and recording the sequence of transformations. An example of a representation flow diagram is in appendix D.

Representation flow diagrams were created on 11” x 14” paper by carefully studying photocopies of the written record of the subject’s work and the video recording. Before watching the videos, the number of different ideas generated by every subject was identified using photocopies of their actual work and the operational definition for lateral transformations. The different ideas were listed and labeled using letters of the alphabet and numbers on paper. The subject’s identification information such as name, code, run performed, and date of experiment were also recorded.

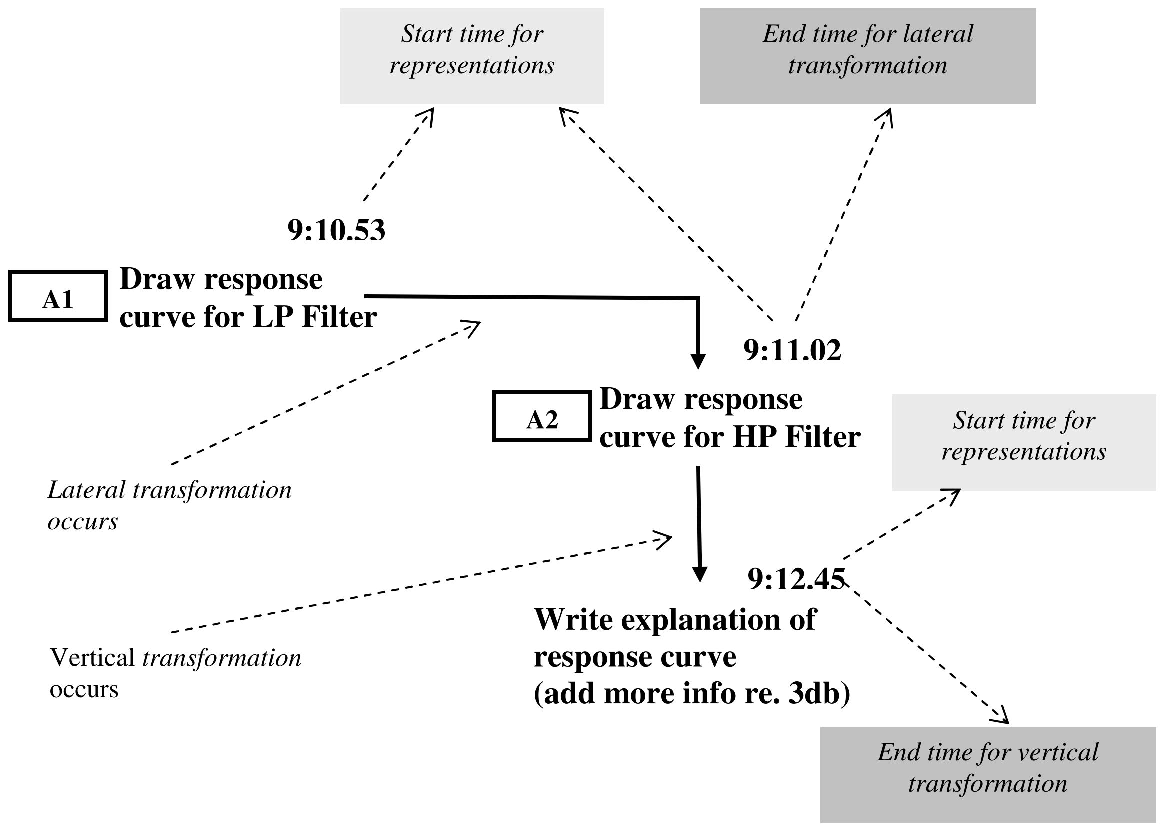
While watching the videos, the subject’s problem solving process was followed by numerically marking the flow of representations on the actual paper copy of their work. Refer to appendix D for an example page. A square was drawn around a representation and assigned a number that indicated the location of that particular representation in the course of the problem solving process. Once this was completed, subject’s video was watched again to draw the sequence of the different representations for every idea and transitions between ideas to create the representation flow diagram.

The final step in completing the representation flow diagram entailed watching the video a third time and recording the start times for every representation on the flow diagram using the clock on the camera or VCR.

Two observers completed twenty-seven representation flow diagrams. Only twenty-seven videos were observed because out of the thirty-one subjects who participated in the study, four declined to be filmed. The first observer was an undergraduate student who had completed and passed the mandatory electrical engineering class: Introduction to Circuits. Observer one was trained to produce the representation process flow diagrams and was knowledgeable enough to understand the technical content of subject's design process. The first observer identified the different ideas generated by subjects and watched the video to draw the representation process flow diagram while observer two, the author, verified observer one's work by watching the video again to record start times for every representation on the flow diagram. Observer two also completed the transformation time sheet.

Transformation Time Sheet

A transformation time sheet, refer to appendix D, was developed to record the start times for the different representations in a table form. This task was simple and straightforward as the start times were documented on the representation diagram. The transformation time sheet also included the end times for vertical and lateral transformations. Refer to Figure 15 for an illustration of end times for vertical and lateral transformations and how they were recorded on the transformation time sheet.



Record the time after a transition occurs		Record the start times for every representation				
Vertical	**Lateral**	**Graphs**	**Block Diagrams**	**Text**	**Circuit Diagrams**	**Equations**
		9:10.53				
	9:11.02	9:11.02				
9:12.45				9:12.45		

Figure 15: End Times for Vertical and Lateral Transformations

In Figure 15, the text and arrows in bold stand for a section of a representation flow diagram. A1 and A2 are labels for two different ideas and the times indicate when externalization of a representation started. This is labeled using the lighter gray description boxes. Vertical and lateral transformations occur instantaneously and therefore measuring their time of occurrence is difficult. Transformations are easier to identify after they have occurred, hence end times for the transformations are easier to identify after they have occurred, hence end times for the transformations are easier to measure. The representation flow diagram and the content of subject's actual work on paper helped to identify the occurrence of vertical and lateral transformations. The representation start time right after a transformation took place became the end time for that transformation.

Finally, the transformation time sheet information was transferred to a spreadsheet, which was used to convert the data into a graph that showed the transitions between representations and between transformations over time. This made counting the number of vertical and lateral transformations simpler.

Analysis Approach

Two analysis methods were applied to the transformations data. The first was simple correlation and the second was analysis of variance (ANOVA). Correlation between number of vertical and lateral transformations and design outcomes sufficed to address objective three listed in the introduction, but further investigation using ANOVA was also pursued to understand the relationship between representations and transformations.

Number of vertical and lateral transformations was each correlated to design quality, productivity, and amount of ideas generated by the subjects. The sample size for correlation was twenty-seven. There were four measures for both quality and productivity because of the weight assignments to functionality and component scores.

Two ANOVA's were performed, one with number of vertical transformations as a response variable, and the other with lateral transformations as a response variable. The design factors were the same as the 2^3 factorial design explained in chapter three: non-notational, discursive, and notational systems. There were five missing values because out of the thirty-one subjects who participated in the experiment, four declined to be filmed. Therefore, five missing values were estimated using averages to complete the design grid. The level of significance was set at 10%, the results were expressed using a regression model, and residual analysis was performed to check for normality and constant variance. Details of ANOVA, regression model, and residual analysis are explained in the preceding chapter.

Results and Discussion

This section presents the results of correlation analysis and ANOVA. Correlation results between transformations and design outcomes are presented first, followed by ANOVA for vertical transformations, and finally ANOVA for lateral transformations.

Correlation Analysis

The correlation results are summarized in Table 16. Correlation coefficients for only quality and number of ideas are presented because productivity coefficients were all less than 0.1, meaning there was practically no association between transformations and productivity.

Table 16: Correlation Results

		Vertical Transformations	**Lateral Transformations**
Quality	**100/0**	0.247	0.154
	75/25	**0.264**	0.233
	50/50	0.247	0.309
	25/75	0.179	**0.326**
Number of Ideas		0.309	0.637

There is some, but very little, correlation between quality and transformations. The maximum common variance between quality and vertical transformation is 7% (correlation coefficient squared) while the maximum common variance between quality and lateral transformation is 10%. Number of vertical transformations and amount of ideas share a common variance of 9.5% while number of lateral transformations and amount of ideas generated share a common variance of 40.5%.

Vertical Transformations

Table 17 shows the ANOVA table for response variable vertical transformations.

Table 17: Analysis of Variance: Vertical Transformations

Source of Variance	Degrees of Freedom	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	3			34.250	11.417	1.869	0.166
A	1	20.000	1.250	12.500	12.500	2.047	0.167
B	1	24.000	1.500	18.000	18.000	2.947	0.101
C	**1**	**42.000**	**2.625**	**55.125**	**55.125**	**9.026**	**0.007**
AB	1	-24.000	-1.500	18.000	18.000	2.947	0.101
AC	1	-2.000	-0.125	0.125	0.125	0.020	0.888
BC	1	6.000	0.375	1.125	1.125	0.184	0.672
ABC	1	-14.000	-0.875	6.125	6.125	1.003	0.328
Error	21			128.250	6.107		
Total	31			273.500			

From the analysis of variance, it can be seen that p-value for factor C is lower than the predetermined significance level (0.1). Therefore, factor C is significant with a positive effect. This means that use of circuit diagrams and equations (symbolic and numerical) lead to higher number of vertical transformations. From the ANOVA table it can also bee seen that factor B and interaction AB are very close to the level of significance and may be included in the regression model to reach a better description of the response variable.

The regression model for predicting number of vertical transformations is:

$$y = 4.38 + 0.75x_B + 1.31x_C - 0.75x_Ax_B$$

where y is the response variable and x_A, x_B, and x_C represent factors A, B, and C respectively. The x_Ax_B term is the AB interaction. Factor B and interaction AB were included in the regression model because their p-values are close to the level of significance. Notice, that interaction AB has a negative effect on the number of vertical transformations. This means that using response curves, block diagrams, and text decrease the number of vertical transformations. The R^2 for this model is 0.33, which means that the model explains 33% of the total variance of the number of vertical transformations. This means that there are other factors (or factor) that affect (67%) the number of vertical transformations together with this model.

Model adequacy results are presented as normal probability plot of residuals, Figure 16 and residual versus fitted values plot, Figure 17.

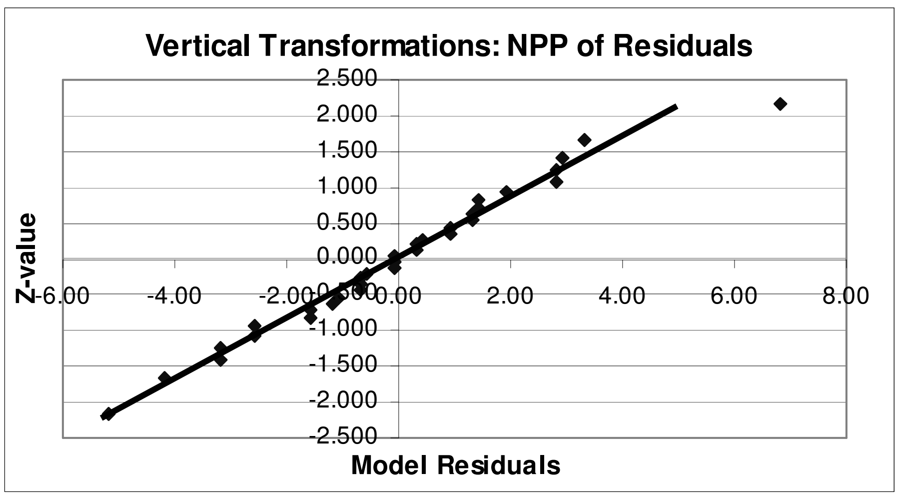


Figure 16: Normal Probability Plot for Vertical Transformations

The normal probability plot shows a fairly straight line. The point at the top right corner of the plot is less than three sigma away and therefore is not an outlier. All of the points in the center of the plot are on the straight line; hence the assumption of normality is valid.

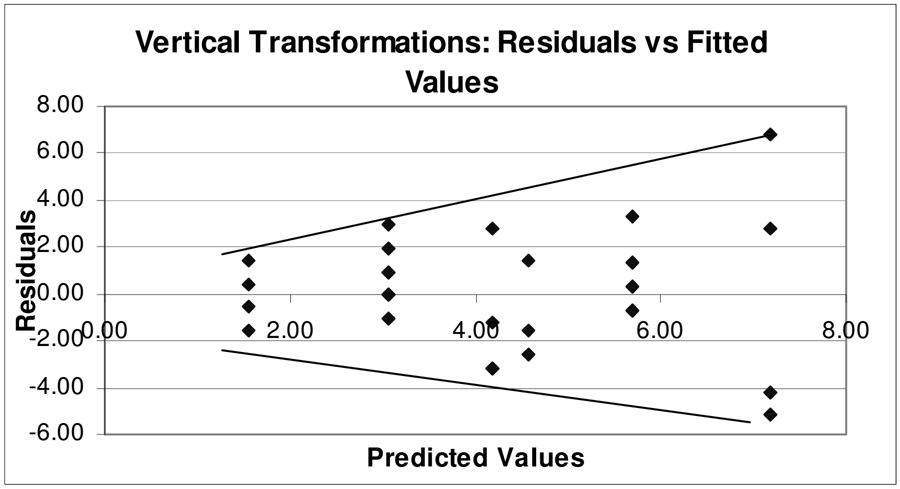


Figure 17: Residuals versus Fitted Values for Vertical Transformations

The validity of constant variance assumption is debatable because the points fall in a cone like pattern, therefore the results of ANOVA need to be interpreted with caution. This could be a result of lurking variables, or unknown factors, that are affecting the response variable or because of five estimated missing values.

Lateral Transformations

Table 18 shows the ANOVA table for response variable lateral transformations.

Table 18: Analysis of Variance: Lateral Transformations

Source of Variance	Degrees of Freedom	Contrasts	Effects	SS	MS	Fo	P-value
Blocks	3			154.094	51.365	1.797	0.179
A	1	5.000	0.313	0.781	0.781	0.027	0.870
B	**1**	**87.000**	**5.438**	**236.531**	**236.531**	**8.276**	**0.009**
C	**1**	**117.000**	**7.313**	**427.781**	**427.781**	**14.968**	**0.001**
AB	1	-39.000	-2.438	47.531	47.531	1.663	0.211
AC	1	-17.000	-1.063	9.031	9.031	0.316	0.580
BC	1	49.000	3.063	75.031	75.031	2.625	0.120
ABC	1	15.000	0.938	7.031	7.031	0.246	0.625
Error	21			600.156	28.579		
Total	31			1557.969			

From the ANOVA table, it can be seen that p-value for factors B and C is lower than the predetermined significance level (0.1). Therefore, factors B and C are significant with a positive effect. This means that use of text (sentential) together with circuit diagrams and equations (symbolic and numerical) lead to higher number of lateral transformations. Interaction BC, with a p-value of 0.12 is very close to the level of significance and may be included in the regression model to reach a better description of the response variable.

The regression model for predicting number of lateral transformations is:

$$y = 8.47 + 2.72x_B + 3.66x_C + 1.53x_Bx_C$$

where y is the response variable and x_B, and x_C represent factors B, and C respectively. The x_Bx_C term is the BC interaction. Interaction BC was included in the regression model because its p-value is close to the level of significance. The R^2 for this model is 0.47, which means that the model explains 42% of the total variance of the number of lateral transformations. This means that the other 53% of variance of the number of lateral transformations is explained by other factors or factor.

Normal probability plot of residuals, Figure 18, and residual versus fitted values plot, Figure 19, are presented below.

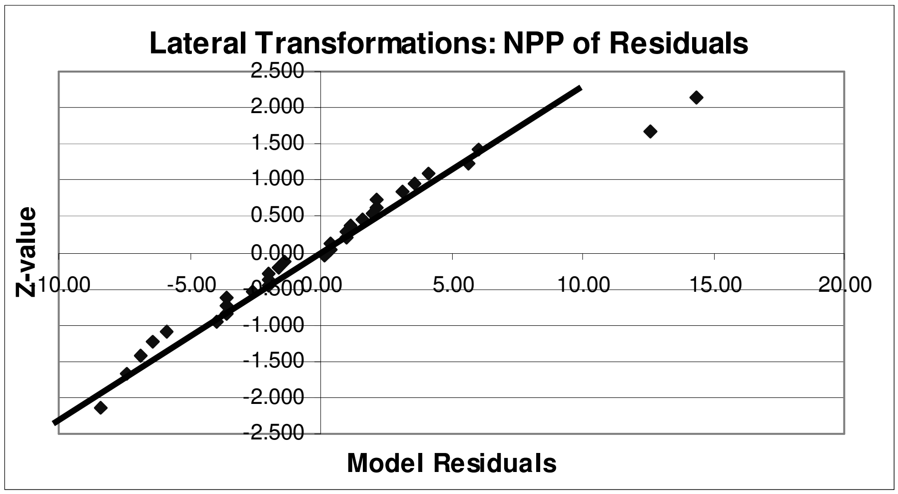


Figure 18: Normal Probability Plot for Lateral Transformations

The normal probability plot shows a fairly straight line. Two points at the top right corner of the plot are less than three sigma away and therefore are not outliers. All of the points in the center of the plot are on the straight line; hence the assumption of normality is valid.

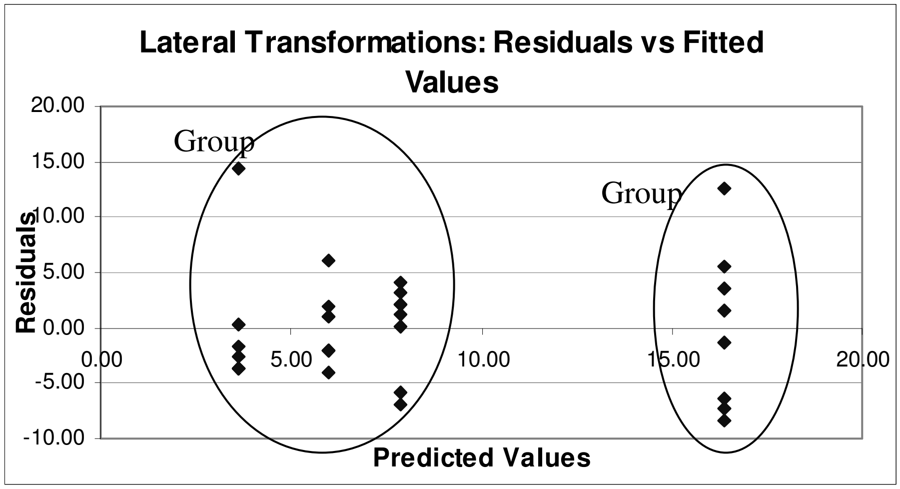


Figure 19: Residual versus Fitted Values for lateral Transformations

The validity of constant variance assumption is debatable because the points cluster into two groups, therefore the results of ANOVA need to be interpreted with caution. This could be a result of lurking variables, or unknown factors, that are affecting the response variable or because of five estimated missing values.

Discussion

Forming conclusions based on the low correlation coefficients is risky. The low correlation coefficients could be a result of one or more unknown factors affecting the variables, the manner in which the transformations were defined and identified, the fact that the experiment from which the raw data was extracted was not designed to study the association between transformations and design outcomes, or simply because of noise in the data. Correlations results for vertical and lateral transformations separately do not provide meaningful results but when they are compared they lead to interesting results.

Comparison is not affected by the bias in the data because it can be assumed that the bias is the same for both vertical and lateral transformations data.

Lateral transformations associate more highly with number of ideas generated by subjects than do vertical transformations. This shows that there is a greater link between lateral transformations and number of ideas generated than vertical transformations and number of ideas. According to Goel's claims, this result makes sense because lateral transformations are generally present in the first stage of problem solving where several ideas are generated and evaluated, while vertical transformations tend to occur at the later end of problem solving where design refinement on a single solution usually occurs. These results (table 16) confirm that investigation of multiple ideas and late convergence, frequent lateral transformations early in the design process, leads to a high quality design solution because lateral transformations associate better with quality (10%) than vertical transformations (7%).

This result implies that electrical engineering students should increase the number of lateral transformations relative to vertical transformations during problem solving to increase the quality of their solution. Now, this does not mean that no vertical transformations should occur because they are associated with quality but just at a lesser degree than lateral transformations. So, how can educators teach electrical engineering students to perform more lateral transformations than vertical?

According to the ANOVA results for vertical and lateral transformations, creating and using circuit diagrams and equations positively affects the number of both vertical and lateral transformations. This significant factor is the same for both, hence encouraging students to create and use more circuit diagrams and equations will not increase the number of lateral transformations compared to vertical transformations. But there is another factor that is significant for lateral transformations and not for vertical transformations. Creating and using text or sentential representation during problem solving positively affects the number of lateral transformations. Hence according to the model for lateral transformations, instructors in the electrical engineering curriculum should encourage students to use text, and circuit diagrams and equations separately and jointly (model explains 47% of variance). In operational terms this could mean teaching students to write the problem statement in their own words, write explanations for their circuit diagrams, perform analysis through writing (i.e. pros and cons), and explaining their numerical analysis.

Interestingly, the ANOVA results for lateral transformations do not confirm Goel's claim that using non-notational systems, in this case response curves and block diagrams, increase the number of lateral transformations. This could be because the subjects are not formally trained to use response curves and block diagrams for problem solving or that Goel's theory does not apply to the electrical engineering domain because it is a very technical and math oriented field. On the other hand, there is slight evidence that vague and ambiguous representations, such as the use of response curves, block diagrams, and text together, negatively affect the number of vertical transformations (the negative effect of interaction AB in the model). So, Goel's association of notational systems to the late stages of design and therefore vertical transformations is confirmed by the vertical transformation model.

These analyses on transformations agreed with some of Goel's theories and disagreed with others. There are many possible reasons for the disagreements. One, Goel's theory regarding vertical and lateral transformations is not applicable to technical field such as electrical engineering. Second, the subjects for this experiment are not trained to work with non-notational electrical engineering representations and therefore are biasing the experiment. Third, there are unknown factors affecting transformations (response) that is biasing the result. Lastly, the manner in which the response variables were collected or the experiment was conducted is introducing bias in the data.

Future work for the study of transformations may involve:

- Re-evaluating quality and productivity measures for the correlations analysis
- Re-evaluating the coding and determining of the amount vertical and lateral transformations for the ANOVA analysis
- Setting up a designed experiment with two sample groups. One group would solve a problem with no previous training while the other group would solve the same problem but with formal training in using non-notational electrical engineering representations. Then the number of vertical and lateral transformations would be determined and a regression analysis would be applied.

CHAPTER 6

CONCLUSION

This thesis provides insight to the effect of electrical engineering non-notational representations on solution quality, productivity of design, and number of ideas. It also shows the effect of various symbol systems on design outcomes in an electrical engineering context, as well as how vertical and lateral transformations relate to design quality, productivity, and the use of representations.

Non-notational electrical engineering representations (response curves and block diagrams) used independently do not have any effect on solution quality, productivity, or number of ideas generated during design, which does not confirm Goel's (1995) assertions of non-notational system being central to the design problem solving. Electrical engineering, as well as other technical fields, may be an outlier for Goel's framework.

On the other hand, non-notational representations used together with discursive representations (text) have a positive effect on quality when more importance is given to component score (simplicity, reliability, and manufacturability) over functionality. When equal or more importance is given to component score over functionality, the use of discursive systems alone and the combination of discursive and non-notational systems increases designer productivity. Hence, use of various symbol systems affects design quality and designer productivity depending on the level of importance given to functionality and component scores.

Using notational systems in electrical engineering, circuit diagrams and equations, increases the number of ideas generated, which contradicts Goel's (1995) theory on lateral transformations. Maybe notational systems positively affect the number of ideas generated by designer in electrical engineering because the subjects of this experiment are trained to use notational systems in idea generation, or because the technical nature of electrical engineering makes it difficult to generate ideas using non-notational systems. Either way, this thesis shows that neither non-notational systems nor a variety of symbol systems affects idea generation.

Finally, this thesis finds that lateral transformations correlate better to quality and number of ideas generated than vertical transformations, which agrees with Goel's (1995) theory that generation of multiple ideas leads to increased number of lateral transformations. However, analyzing representations and the number of ideas generated we find that notational systems rather than non-notational systems lead to increased idea generation. One might ask where does the ambiguity necessary to produce multiple ideas, and hence lateral transformations, come from for electrical engineers. The missing link might be seen when studying the effect of representations on number of lateral transformations. Both notational and discursive systems positively affect the number of lateral transformations. It seems then that electrical engineering notational systems enhance idea generation while discursive systems, which are partially ambiguous, enable designers to jump from one idea to another more easily.

The amount of vertical transformations increases with the use of notational systems, which agrees with Goel's (1995) theory on how vertical transformations map onto the later stage of the design process where more specific and clear representations are used on a single idea. Most of the vertical representations for this study were seen during analysis of a solution or on design refinement.

Implications

The implications of this thesis are important for electrical engineering instructors at Montana State University. Instructors should not only concentrate on teaching students to work with circuit diagrams and equations during design but also expose students to use text and response curves, block diagrams, and text altogether. Instructors may want to emphasize writing explanations regarding how a circuit functions, drawing response curves for circuits combined with explaining what the graph shows in writing, or evaluating ideas using text by writing pros and cons. Maybe requiring a formal lab notebook for a percentage of the grade and more formal written reports might help students to explain their work using various types of representations.

This may also affect the criteria instructors use to choose a text for a course in the curriculum. A textbook that contains only circuit diagrams as the only figures may not be the best choice, while a textbook that contains a variety of representations might be beneficial for students in the long run. These possible changes may not improve the students' design ability to 100% as there are other factors that affect design outcomes, but it may take student problem solving abilities closer to the final goal: an optimized design process. It may also help graduating electrical engineers to fulfill the market need for knowledgeable and skillful engineers who can produce quality designs quickly.

Selection criteria of computer tools by the department might need to be reconsidered too. For example, PSpice, an analog and digital simulation tool, does not require any input of text or block diagrams. PSpice allows students to draw circuit diagrams and then simulates it and produces response curves. The electrical engineering department may want to research other computer tools that allow for input of text so that response curves and circuit diagrams may be linked with explanations in the form of text.

The courses required by the electrical engineering curriculum may need to be evaluated. Introducing a technical writing class in the curriculum may benefit the students more than a creative writing class. Or an introductory electrical engineering course that provides an overview of the field and exposes students to various representations might also be beneficial.

Limitations and Future Work

The main limitation of this experiment is the involvement of people in the experiment. People are difficult to control and therefore introduce a lot of variability in the experiment. Control measures were implemented during the experiment to minimize the variability from people but cannot be expected to eliminate it. This thesis is also limited to electrical engineering students of Senior Design I (EE391) class in Spring 2004 at Montana State University-Bozeman, the evaluation tools developed to measure outcome variables: quality, productivity, number of ideas generated, and the number of vertical and lateral transformations. The quality score is on a discrete scale because the quality evaluation form was designed to minimize subjectivity, which limits the accuracy of the evaluation.

Results from this thesis were a good first step in understanding representations in engineering design. This thesis met its research objectives but also shed light on many other aspects of the role of representations in design and also the actual design of the experiment. For one, external representations are not very easy to study and neither is design. Outcomes of design are not easy to evaluate and there are many factors that affect the design process.

To complement this thesis and gain further insight on the effect of external representations on design outcomes, I suggest re-evaluations of subjects' solutions from the experiment and perform another experiment to test the effect of training in notational systems.

Re-evaluation of subjects' solutions by building the circuit and testing its functionality may create a more the quality measure. This would also involve developing a more precise way to define the point system for functionality. The same analysis performed in this thesis should then be done on the new quality and productivity measures to see if the results differ.

The second recommendation for future work is to design an experiment to test the effect of training on outcome variables. The low R^2 of the models and lack of constant variance suggest the presence of other factors affecting the outcome measures. One of the factors may be that students are pre-programmed to use notational systems during design and have not been formally taught to use non-notational and discursive systems. So, the experiment would have two groups of students. One group of students would be trained to work with block diagrams, response curves and text, and another one would serve as a control group. Both groups would then solve a design problem. The solutions would then be evaluated and a statistical analysis would then determine the effect training has on design quality, and student productivity.

Another recommendation is to perform analysis of covariance. This analysis may help reveal some of the unknown factors that are currently affecting the outcome variables. Analysis of covariance involves the outcome variables together with an extraneous variable such as grade point average (GPA). It will determine whether the GPA affects the outcome variable or not. A linear relationship should exist between the outcome variable and the extraneous variable for this analysis to be valid.

Future work is not limited to these three recommendations. The complete experiment can be implemented again to compare results, new tools can be developed to evaluate all the outcome variables, and the same experiment can be run with other engineering fields such as mechanical engineers to look for similar patterns.

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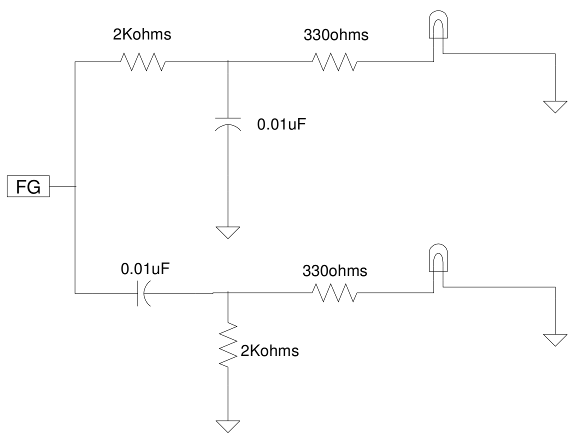
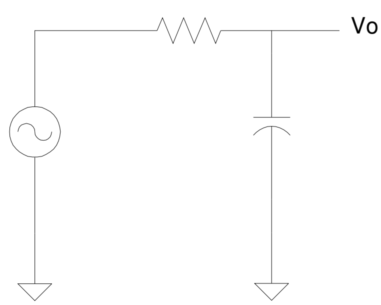
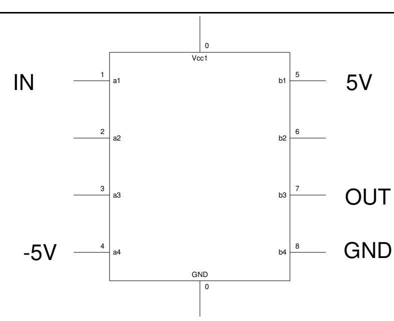
APPENDICES

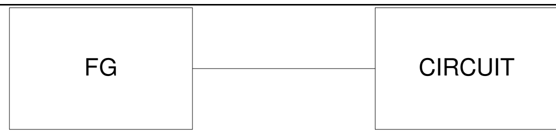
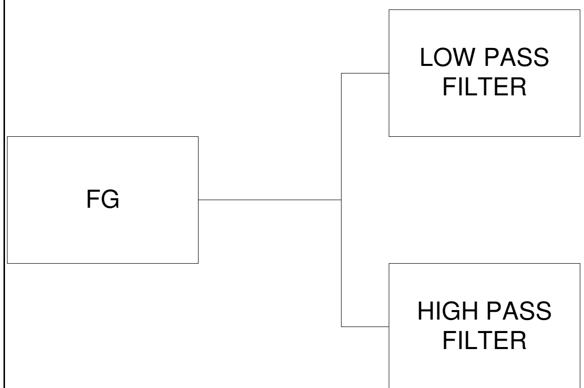
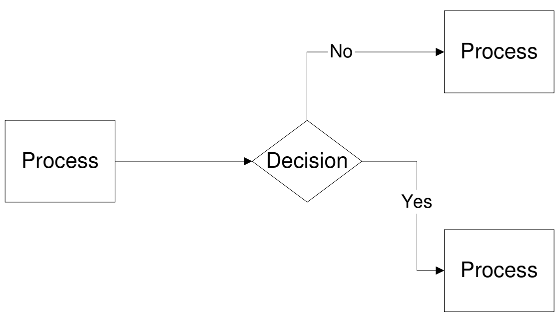
APPENDIX A

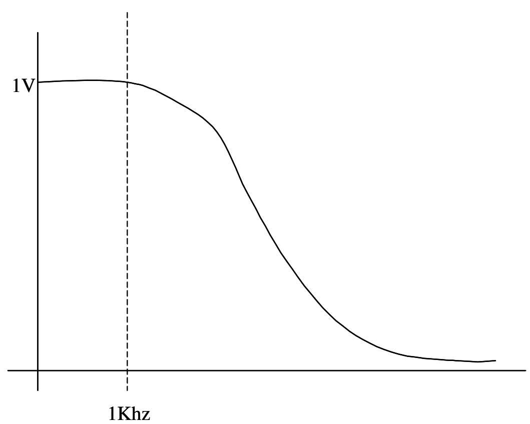
ELECTRICAL ENGINEERING

REPRESENTATIONS CLASSIFED

REPRESENTATION MATRIX

Representation	Goel's Classification	Rationale
 	Notational	1. Meets syntactic criteria because all characters are unique and differentiable. 2. Meets semantic criteria because there is no more than one class of compliant for the components. It maps onto reality clearly.
 	Notational	1. Meets syntactic criteria because we can differentiate between components and they are unique classes of marks. 2. Meets semantic criteria even though the exact value of R or C is not known because the compliant class is the same, i.e. the symbol for a resistor is still a resistor event though the value is not given.
 	Notational	1. Meets syntactic criteria because the marks are unique and differentiable. 2. Meets the semantic criteria because there is no ambiguity regarding the configuration and connection
Block Diagram:	Discursive	1. Meets the syntactic criteria because characters are unique and can be differentiated from one another.

		2. Does not meet the semantic criteria because "circuit" has more than one complaint class
Block Diagram: 	Discursive	1. Meets syntactic criteria because characters are unique and can be differentiated. 2. Does not meet the semantic criteria because "LP Filter" does not specify whether is it with a capacitor or with an inductor, hence there is more than one compliant
Flow Chart: 	Discursive	1. Meets the syntactic criteria because every character is unique and differentiable. 2. Does not meet the semantic criteria because activity and decision in the box can still be ambiguous.
LP Filter Equation: $W_c = 1/RC$ where $W_c = 2*pi*f_c$	Notational	1. Meets syntactic criteria because each mark is unique and can be differentiated from one another. 2. Meets semantic criteria because there is no ambiguity regarding what the equation represents, especially because it stems from a notational system.
"Technical jargon" For example: - Frequency generator - Product specifications	Notational	1. Meets syntactic criteria because it is a language and therefore same syntactic rules apply. 2. Meets semantic criteria because the words do not have

		more than one compliant class
Computer code or Pseudo code	Notational	1. Meet syntactic criteria because every mark is unique and differentiable. Plus it is written using language so the same syntactic rules apply. 2. Meets the semantic criteria because there is no ambiguity and hence no more than one compliant class
Regular Language - Written explanation of a circuit	Discursive	1. Meets syntactic criteria because every character is unique and differentiable 2. Does not meet the semantic criteria because language is inherently ambiguous
Response Curve:  	Non-notational	1. Does not meet syntactic criteria because there is no single character (point on the graph) that is unique, plus they cannot be differentiated from each other. 2. Does not meet the semantic criteria because a character does not have one compliant, plus if you cannot differentiate them then you cannot even determine their complaints.

APPENDIX B

SUPPLEMENTARY MATERIALS FOR EXPERIMENTAL DEISGN

PERSONAL INFORMATION QUESTIONNAIRE

Spring 2004

Responses to this questionnaire are considered confidential and therefore individual responses will not be released, shared, or published. Rather questionnaire results will be reported in aggregate form only.

First Name: ______________________________ Last Name: ______________________________

Gender: ☐M ☐F

Age: ☐20-22 ☐23-25 ☐26-29 ☐30+

Cumulative GPA: ☐4.0-3.5 ☐3.49-3.0 ☐2.99-2.5 ☐< 2.49

Ethnicity: (optional)
☐Asian
☐European
☐Hispanic
☐Native American
☐White

1. Have you held an internship position in the past?

   ☐Yes ☐No

   If yes:
2. How many times have you been on an internship?

   ☐1 ☐2 ☐3 or more

3. What internship experiences have you had and for how long? (you can answer more than one)

   Product designer ______________________________ months
   Technical support ______________________________ months
   Product testing ______________________________ months
   Others (please mention) ______________________________ months

4. Have you had technical employment experience other than the internship? In what technical field?

   ☐Yes ☐No Tech. Field: ______________________________

   If yes:
5. What technical employment experience have you had and for how long?

   Product designer ______________________________ months
   Technical support ______________________________ months
   Product testing ______________________________ months
   Others (please mention) ______________________________ months

6. Check the classes you have completed and made a grade of "C" or better:

   ☐ EE 206 ☐ EE 216 ☐ EE 308 ☐ EE 261
   ☐ EE 207 ☐ EE 316 ☐ EE 371 ☐ EE 262

Design Problem

EE 391, Spring 2004

Name: ________________________

Date: ________________________

Objective:
Design a system (analog, digital, or mixed – designer's choice) to distinguish between two different ranges of frequency.

Specifications:

- Light an LED whenever the incoming signal frequency is below 600 Hz
- Light a different LED whenever the incoming signal frequency is above 12 kHz
- You can choose the LED's switching point (frequency point) within the specified range
- Only one LED is to be lit up at a time. One LED must be lit at all times whenever there is an incoming signal

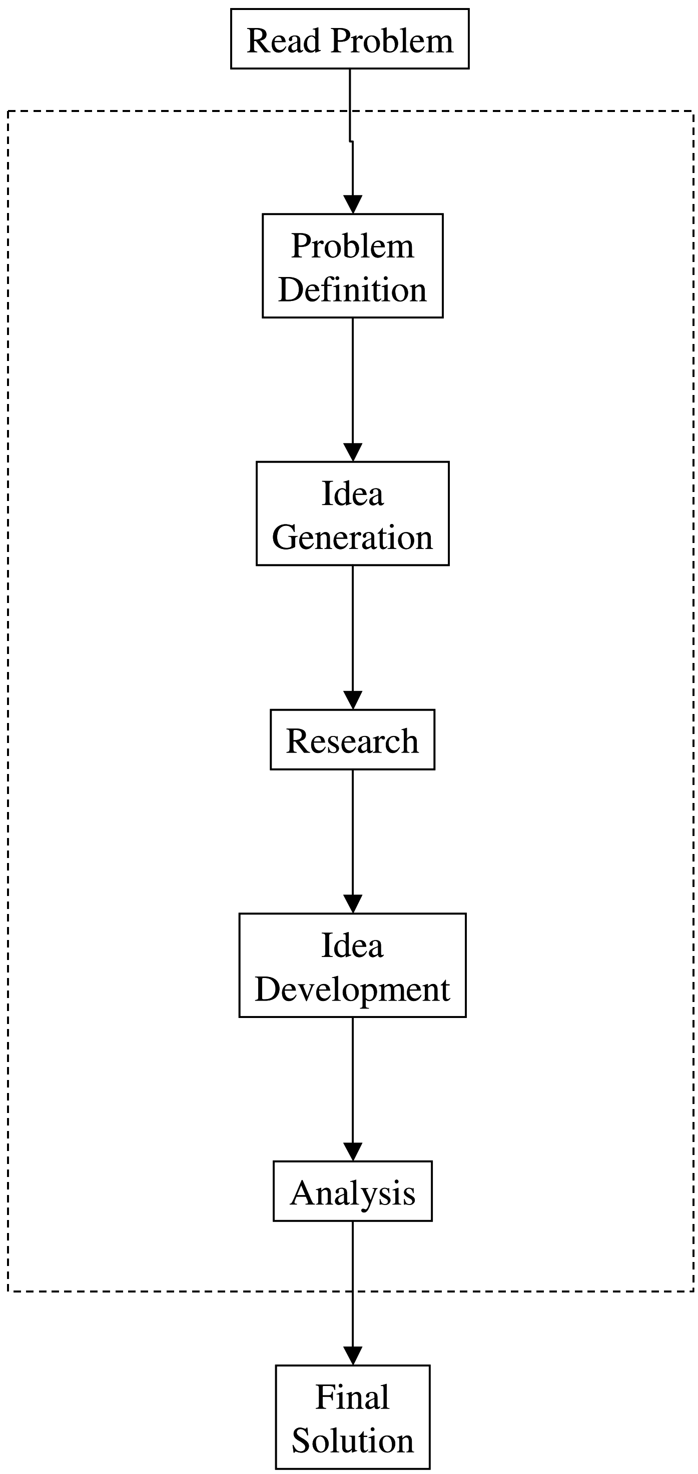
Deliverables:

- Produce a circuit diagram for your design by following the specific instructions presented to you.
- Label the circuit diagram with all the relevant information including:
  - The LED that turns on below 600Hz as: 600Hz LED
  - The LED that turns on above 12kHz as: 12kHz LED
  - Record the switching point

Evaluation:

- Functionality score is based on how well the design meets the design objectives
- Component Score
  - Since electronic designs benefit from low part count, your design will be scored according to the following:
    - Resistors: 1 point each
    - Capacitors: 2 point each
    - Diodes and LEDs: 2 points each
    - Transistors: 6 points (2 points per pin)
    - ICs: 1.5 points per pin
  - A lower score is better

DESIGN PROTOCOL



INSTRUCTIONS FOR TREATMENT COMBINATIONS

(I)

1.

Think of the concepts and constraints presented in the problem statement (but don’t write anything)

2.

Think of as many ideas as you can to solve this problem (but don’t write anything)

3.

Research and keep in your memory any useful information from the texts (don’t write anything)

4.

Develop every idea generated up till now to solve this problem (but don’t write anything)

5.

Analyze every idea in as many ways as you can (but don’t write anything)

6.

Choose the best idea from the ones generated and draw a circuit diagram for it.

A

1.

Represent the problem statement concepts in the form of a graph.

2.

Think of as many ideas as you can to solve this problem (but don't write anything).

3.

Research and record any useful:
Block diagrams and/or graphs from the text

4.

Draw block diagrams for all ideas generated up till now

5.

Draw input and output graphs of what might be expected for every idea

6.

Choose the best idea from the ones generated and draw a circuit diagram for it.

B

1.

Write notes regarding the problem statement

2.

Write a list of as many ideas as you can think of.

3.

Research and record any useful:

Statements from the text

4.

Explain (in writing) the:

Block diagrams for all ideas up till now

AND/OR

All the ideas up till now

5.

Write pros and cons for every idea
AND/OR
Describe (in writing) how might all the ideas work
AND/OR
Describe (in writing) the graphs you might expect for every idea

6.

Choose the best idea from the ones generated and draw a circuit diagram for it.

C

1.

Think of the concepts and constraints presented in the problem statement (but don't write anything).

2.

Think of as many ideas as you can to solve this problem (but don't write anything).

3.

Research and record any useful:
Equations and/or circuit diagrams from the text

4.

Draw circuit diagrams for all ideas generated up till now
AND/OR
Write relevant equations for all circuit diagrams drawn

5.

Solve relevant equations on paper (use calculator) for all ideas

6.

Choose the best idea from the ones generated and draw a circuit diagram for it.

AB

1.

Write notes regarding the problem statement
AND
Represent the problem statement concepts in the form of a graph.

2.

Write a list of as many ideas as you can think of.

3.

Research and record any useful:

Block diagrams and/or graphs from the text

AND

Statements from the text

4.

Draw block diagrams for all ideas generated up till now

5.

Explain (in writing) the:

Block diagrams for all ideas up till now

6.

Draw input and output graphs of what might be expected for all ideas

7.

Write pros and cons for every idea

AND/OR

Interpret (in writing) all the graphs generated

8.

Choose the best idea from the ones generated and draw a circuit diagram for it.

AC

1.

Represent the problem statement concepts in the form of a graph.

2.

Think of as many ideas as you can to solve this problem (but don't write anything).

3.

Research and record any useful:

Block diagrams and/or graphs from the text

AND

Equations and/or circuit diagrams from the text

4.

Draw block diagrams for all ideas generated up till now

5.

Draw circuit diagrams for all ideas generated up till now

AND/OR

Write relevant equations for all circuit diagrams drawn

6.

Solve relevant equations on paper (use calculator) for all ideas
AND
Generate relevant graphs for all circuits diagrams

7.

Choose the best idea from the ones generated and draw a circuit diagram for it.

BC

1.

Write notes regarding the problem statement

2.

Write a list of as many ideas as you can think of.

3.

Research and record any useful:
Statements from the text
AND
Equations and/or circuit diagrams from the text

4.

Draw circuit diagrams for all ideas generated up till now
AND/OR
Write relevant equations for all circuit diagrams drawn

5.

Explain (in writing) the:
Circuit diagrams for all ideas generated up till now

6.

Solve relevant equations on paper (use calculator) for all ideas

7.

Write pros and cons for every idea
AND/OR
Describe (in writing) the relevant graphs you might expect for every idea
AND/OR
Interpret (in writing) the results from solving the equations for every idea

8.

Choose the best idea from the ones generated and draw a circuit diagram for it.

ABC

1.

Write notes regarding the problem statement
AND
Represent the problem statement concepts in the form of a graph.

2.

Write a list of as many ideas as you can think of.

3.

Research and record any useful:
Block diagrams and/or graphs from the text
AND
Statements from the text
AND
Equations and/or circuit diagrams from the text

4.

Draw block diagrams for all ideas generated up till now

5.

Draw circuit diagrams for all ideas generated up till now
AND/OR
Write relevant equations for all circuit diagrams drawn

6.

Explain (in writing) the:

Block diagrams for all ideas generated up till now

AND/OR

Circuit diagrams for all ideas generated up till now

7.

Solve relevant equations on paper (use calculator) for all ideas

AND

Generate relevant graphs for all circuits diagrams

8.

Write pros and cons for every idea

AND/OR

Interpret (in writing) all the graphs generated

AND/OR

Interpret (in writing) the results from solving the equations for every idea

9.

Choose the best idea from the ones generated and draw a circuit diagram for it.

EXPLANATION TO STUDENTS BEFORE EXPERIMENT

1.	Follow the instructions given on top of every page. It is very important for the analysis of the experiment.
2.	When an instruction is “do X AND Y”, you have to do both.
3.	When an instruction is “do X OR Y”, you do one or the other, make your choice depending what will help you solve the problem.
4.	When an instruction is “do X AND/OR Y”, you choose to do both ore just one, make your choice depending on what will help you solve the problem.
5.	Do not look ahead. Tackle one instruction at a time and do exactly what it tells you to do.
6.	Once you have worked on one instruction, you cannot go back to add or change anything.
7.	You can go back to refer to what you have done so far.
8.	You may be asked to do some research. There are two texts provided for research. When you are done with research, you have to close the texts. You cannot go back to the texts.
9.	If you are asked to “think” then you cannot write anything down.
10.	Try to solve the problem as best as you can given the experimental conditions and instructions.
11.	Ask questions through the process.
12.	You can use PSPICE wherever you think it is appropriate.
13.	If you need more time it is okay.
14.	Design the solution considering the evaluation criteria.
15.	More paper is available on the workstation is you need.
16.	The experiment involves two phases. The first phase requires you to solve the problem and the second phase are additional questions.

QUALITY EVALUATION FORM

Quality Evaluation Form
Spring 2004

Number: ________________ Phase: ________________

Date: ____________________

Circuit diagram is complete and reasonably neat to read (5pts): ________________________

Functionality Score:
If no component values assigned:

- Only one LED is on at all times (10pts): ____________________
- LEDs will switch within correct frequency range if correct values are assigned (10pts): ____________________

If component values are assigned:

- Only one LED is on at all times (10pts): ____________________
- One LED is on for frequency signal below 600Hz (10pts): __________
- Another LED is on for frequency signal above 12kHz (10pts): ____________

Total Functionality Score: ________

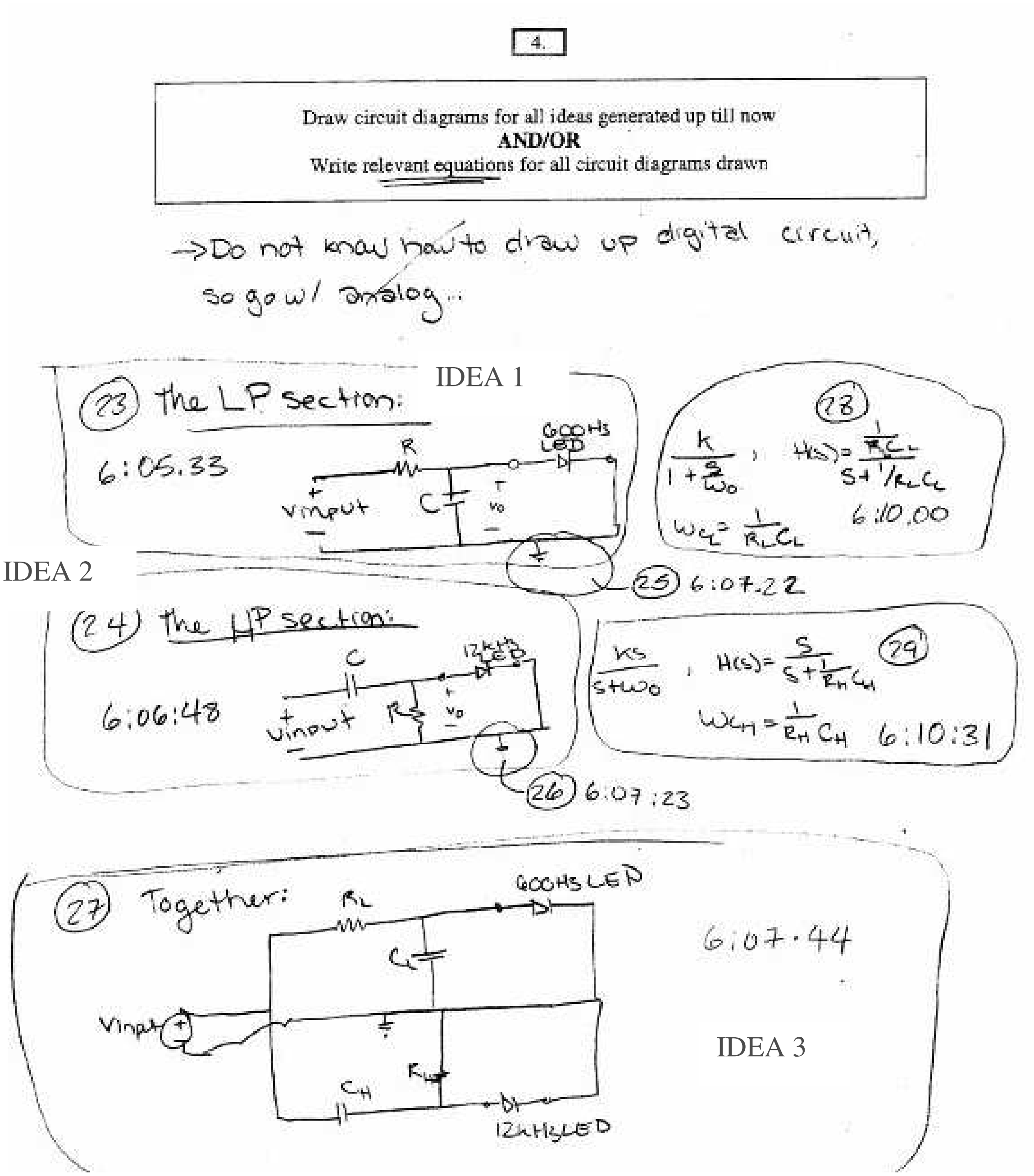
Component Score:
Use the following point assignment to calculate the component score:

- Resistors: 1 point each
- Capacitors: 2 point each
- Diodes and LEDs: 2 points each
- Transistors: 6 points (2 points per pin)
- ICs: 1.5 points per pin

Components	Quantity	Points
Resistors		
Capacitors		
Diodes and LEDs		
Transistors		
ICs		

Total Component Score: ________

EXAMPLE OF DIFFERENT IDEAS



APPENDIX C

ANOVA RESULTS

QUALITY

Quality 100/0: Functionality (100) & Component (0)

Factors	Description	High	Low
A	Non-notational	Use	Not use
B	Discursive	Use	Not use
C	Notational	Use	Not use

Std. Order	A	B	C	Rep1	Rep2	Rep 3	Rep 4	Total
(I)	-	-	-	0.00	66.67	50.00	50.00	166.67
A	+	-	-	50.00	0.00	66.67	33.33	150.00
B	-	+	-	50.00	50.00	33.33	0.00	133.33
Ab	+	+	-	16.67	16.67	0.00	33.33	66.67
C	-	-	+	66.67	44.44	16.67	50.00	177.78
Ac	+	-	+	83.33	66.67	66.67	0.00	216.67
Bc	-	+	+	16.67	33.33	66.67	16.67	133.33
Abc	+	+	+	50.00	66.67	66.67	0.00	183.33
			Sum of Blocks:	333.33	344.44	366.67	183.33	

$y_{...}$ = 1227.78
$\bar{y}_{...}$ = 38.36806

Blocks =4 2^3=8
N =32
alpha =0.15

Source of Variance	df	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	3			2618.634	872.878	1.257	0.315
A	1	5.556	0.347	0.965	0.965	0.001	0.971
B	1	-194.444	-12.153	1181.520	1181.520	1.702	0.206
C	1	194.444	12.153	1181.520	1181.520	1.702	0.206
AB	1	-38.889	-2.431	47.261	47.261	0.068	0.797
AC	1	172.222	10.764	926.890	926.890	1.335	0.261
BC	1	38.889	2.431	47.261	47.261	0.068	0.797
ABC	1	61.111	3.819	116.705	116.705	0.168	0.686
Error	21			14580.440	694.307		
Total	31			20701.196			

Block effect is relatively small
No significant factors

Quality 75/25: Functionality (75) & Component (25)

Factors	Description	High	Low
A	Non-notational	Use	Not use
B	Discursive	Use	Not use
C	Notational	Use	Not use

Std. Order	A	B	C	Rep1	Rep2	Rep 3	Rep 4	Total
(I)	-	-	-	22.19	69.58	57.08	60.63	209.48
A	+	-	-	56.25	0.00	50.63	47.92	154.79
B	-	+	-	60.42	53.96	43.75	18.54	176.67
Ab	+	+	-	32.19	36.04	23.33	46.46	138.02
C	-	-	+	70.83	51.74	31.67	52.71	206.94
Ac	+	-	+	76.25	69.17	72.08	14.90	232.40
Bc	-	+	+	28.13	48.75	72.92	35.83	185.63
Abc	+	+	+	59.58	69.38	72.92	22.71	224.58
			Sum of Blocks:	405.83	398.61	424.38	299.69	

$y_{\ldots}$ = 1528.51

$\bar{y}_{\ldots}$ = 47.76584

Blocks =4 2^3=8

N =32

alpha =0.15

Source of Variance	df	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	3			1176.860	392.287	0.870	0.472
A	1	-28.924	-1.808	26.143	26.143	0.058	0.812
B	1	-78.715	-4.920	193.628	193.628	0.429	0.519
C	1	170.590	10.662	909.408	909.408	2.017	0.170
AB	1	29.549	1.847	27.285	27.285	0.061	0.808
AC	1	157.743	9.859	777.590	777.590	1.725	0.203
BC	1	20.451	1.278	13.071	13.071	0.029	0.866
ABC	1	-2.535	-0.158	0.201	0.201	0.000	0.983
Error	21			9468.701	450.891		
Total	31			12592.886			

Block effect is relatively small

No significant factors

Quality 50/50: Functionality (50) & Component (50)

Factors	Description	High	Low
A	Non-notational	Use	Not use
B	Discursive	Use	Not use
C	Notational	Use	Not use

Std. Order	A	B	C	Rep1	Rep2	Rep 3	Rep 4	Total
(I)	-	-	-	44.38	72.50	64.17	71.25	252.29
A	+	-	-	62.50	0.00	34.58	62.50	159.58
B	-	+	-	70.83	57.92	54.17	37.08	220.00
Ab	+	+	-	47.71	55.42	46.67	59.58	209.38
C	-	-	+	75.00	59.03	46.67	55.42	236.11
Ac	+	-	+	69.17	71.67	77.50	29.79	248.13
Bc	-	+	+	39.58	64.17	79.17	55.00	237.92
Abc	+	+	+	69.17	72.08	79.17	45.42	265.83
			Sum of Blocks:	478.33	452.78	482.08	416.04	

$y_{...}$= 1829.24

$\bar{y}_{...}$= 57.16363

Blocks =4 2^3=8

N =32

alpha =0.15

Source of Variance	df	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	3			347.414	115.805	0.357	0.784
A	1	-63.403	-3.963	125.622	125.622	0.387	0.540
B	1	37.014	2.313	42.813	42.813	0.132	0.720
C	1	146.736	9.171	672.859	672.859	2.075	0.164
AB	1	97.986	6.124	300.040	300.040	0.925	0.347
AC	1	143.264	8.954	641.392	641.392	1.978	0.174
BC	1	2.014	0.126	0.127	0.127	0.000	0.984
ABC	1	-66.181	-4.136	136.871	136.871	0.422	0.523
Error	21			6809.483	324.261		
Total	31			9076.621			

Block effect is relatively small

No significant factors

Quality 25/75: Functionality (25) & Component (75)

Factors	Description	High	Low
A	Non-notational	Use	Not use
B	Discursive	Use	Not use
C	Notational	Use	Not use

Std. Order	A	B	C	Rep1	Rep2	Rep 3	Rep 4	Total
(I)	-	-	-	66.56	75.42	71.25	81.88	295.10
A	+	-	-	68.75	0.00	18.54	77.08	164.38
B	-	+	-	81.25	61.88	64.58	55.63	263.33
Ab	+	+	-	63.23	74.79	70.00	72.71	280.73
C	-	-	+	79.17	66.32	61.67	58.13	265.28
Ac	+	-	+	62.08	74.17	82.92	44.69	263.85
Bc	-	+	+	51.04	79.58	85.42	74.17	290.21
Abc	+	+	+	78.75	74.79	85.42	68.13	307.08
			Sum of Blocks:	550.83	506.94	539.79	532.40	

y…= 2129.97

$\bar{y}$…= 66.56141

Blocks =4 2^3=8

N =32 2^2=4

alpha =0.15 2^1=2

Source of Variance	df	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	3			130.297	43.432	0.138	0.936
A	1	-97.882	-6.118	299.402	299.402	0.952	0.340
B	1	152.743	9.546	729.076	729.076	2.319	**0.143**
C	1	122.882	7.680	471.874	471.874	1.501	0.234
AB	1	166.424	10.401	865.526	865.526	2.753	**0.112**
AC	1	128.785	8.049	518.297	518.297	1.648	0.213
BC	1	-16.424	-1.026	8.429	8.429	0.027	0.872
ABC	1	-129.826	-8.114	526.715	526.715	1.675	0.210
Error	21			6602.786	314.418		
Total	31			10152.403			

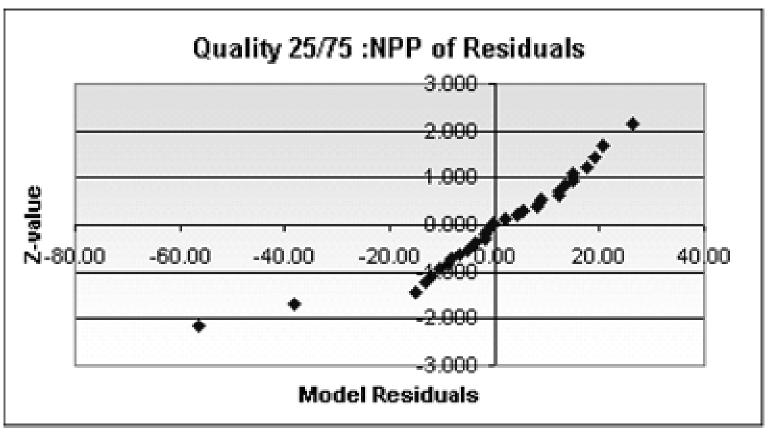
Block effect is relatively small
Factor B and interaction AB are significant

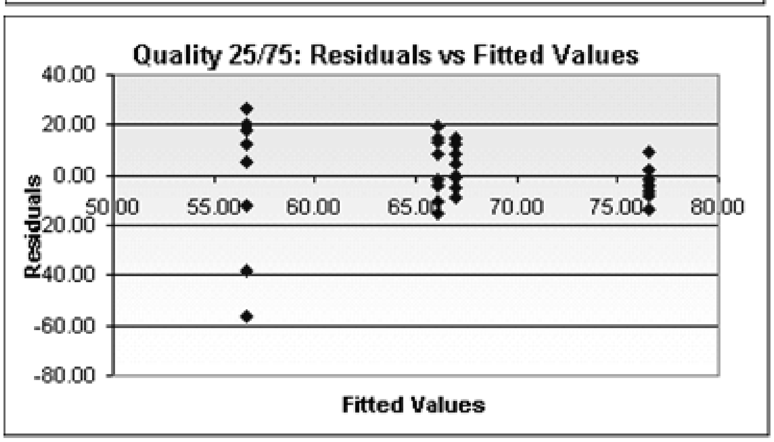
Model 1: Quality 25/75

$$y = \beta_o + \beta_2 x_2 + \beta_{13} x_1 x_2$$

		x_2	x_1x_2	R^2
y =	66.56	4.77	5.20	0.16

Std. Order	y	Residulas Rep1	Rep2	Rep 3	Rep 4
(I)	66.99	-0.43	8.43	4.26	14.89
a	56.59	12.16	-56.59	-38.05	20.50
b	66.13	15.12	-4.26	-1.55	-10.51
ab	76.54	-13.31	-1.74	-6.54	-3.83
c	66.99	12.18	-0.67	-5.32	-8.86
ac	56.59	5.50	17.58	26.33	-11.90
bc	66.13	-15.09	13.45	19.28	8.03
abc	76.54	2.21	-1.74	8.88	-8.41





PRODUCTIVITY

Productivity 100/0: Functionality (100) & Component (0)

Factors	Description	High	Low
A	Non-notational	Use	Not use
B	Discursive	Use	Not use
C	Notational	Use	Not use

Std. Order	A	B	C	Rep1	Rep2	Rep 3	Rep 4	Total
(I)	-	-	-	0.00	56.30	97.30	49.09	202.68
a	+	-	-	76.05	0.00	72.55	41.37	189.96
b	-	+	-	51.27	26.32	26.67	0.00	104.25
ab	+	+	-	15.63	19.32	0.00	31.14	66.09
c	-	-	+	60.20	55.91	34.36	73.17	223.64
ac	+	-	+	47.04	46.81	63.44	0.00	157.30
bc	-	+	+	9.09	57.50	54.41	22.78	143.78
abc	+	+	+	44.36	39.93	107.29	0.00	191.58
			Sum of Blocks:	303.63	302.09	456.02	217.55	
							y…=	1279.27
							$\bar{y}$…=	39.9773

Blocks =4 2^3=8
N =32 2^2=4
alpha =0.1 2^1=2

Source of Variance	df	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	3			3698.313	1232.771	1.501	0.243
A	1	-69.428	-4.339	150.634	150.634	0.183	0.673
B	1	-267.890	-16.743	2242.656	2242.656	2.731	0.113
C	1	153.312	9.582	734.513	734.513	0.894	0.355
AB	1	88.700	5.544	245.865	245.865	0.299	0.590
AC	1	32.338	2.021	32.679	32.679	0.040	0.844
BC	1	176.725	11.045	975.988	975.988	1.188	0.288
ABC	1	139.586	8.724	608.879	608.879	0.741	0.399
Error	21			17245.519	821.215		
Total	31			25935.045			

Block effect is relatively small
No significant factors

Productivity 75/25: Functionality (75) & Component (25)

Factors	Description	High	Low
A	Non-notational	Use	Not use
B	Discursive	Use	Not use
C	Notational	Use	Not use

Std. Order	A	B	C	Rep1	Rep2	Rep 3	Rep 4	Total
(I)	-	-	-	42.42	58.76	111.08	59.52	271.78
a	+	-	-	85.55	0.00	55.09	59.46	200.11
b	-	+	-	61.95	28.40	35.00	27.81	153.16
ab	+	+	-	30.18	41.77	30.91	43.41	146.26
c	-	-	+	63.96	68.79	65.29	77.13	275.18
ac	+	-	+	43.05	48.57	68.60	10.51	170.72
bc	-	+	+	15.34	84.09	59.51	48.97	207.92
abc	+	+	+	52.86	41.56	117.34	23.49	235.25
			Sum of Blocks:	395.30	371.94	542.82	350.31	

y…= 1660.38

$\bar{y}$…= 51.88683

Blocks =4 2^3=8

N =32 2^2=4

alpha =0.1 2^1=2

Source of Variance	df	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	3			2845.624	948.541	1.431	0.262
A	1	-155.693	-9.731	757.506	757.506	1.143	0.297
B	1	-175.197	-10.950	959.186	959.186	1.447	0.242
C	1	117.762	7.360	433.368	433.368	0.654	0.428
AB	1	196.563	12.285	1207.401	1207.401	1.822	0.191
AC	1	1.445	0.090	0.065	0.065	0.000	0.992
BC	1	169.731	10.608	900.266	900.266	1.358	0.257
ABC	1	67.014	4.188	140.339	140.339	0.212	0.650
Error	21			13918.801	662.800		
Total	31			21162.557			

Block effect is relatively small
No significant factors

Productivity 50/50: Functionality (50) & Component (50)

Factors	**Description**	**High**	**Low**
A	Non-notational	Use	Not use
B	Discursive	Use	Not use
C	Notational	Use	Not use

Std. Order	**A**	**B**	**C**	**Rep1**	**Rep2**	**Rep 3**	**Rep 4**	**Total**
(I)	-	-	-	84.84	61.22	124.86	69.95	340.88
a	+	-	-	95.06	0.00	37.64	77.56	210.25
b	-	+	-	72.63	30.48	43.33	55.63	202.07
ab	+	+	-	44.73	64.23	61.81	55.67	226.44
c	-	-	+	67.72	81.68	96.22	81.10	326.72
ac	+	-	+	39.05	50.32	73.75	21.03	184.15
bc	-	+	+	21.59	110.69	64.61	75.17	272.06
abc	+	+	+	61.36	43.18	127.40	46.98	278.92
			Sum of Blocks:	486.97	441.80	629.63	483.08	

$y_{...}$ = 2041.48

$\bar{y}_{...}$ = 63.79636

Blocks =4 2^3=8
N =32 2^2=4
alpha =0.1 2^1=2

Source of Variance	df	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	3			2527.068	842.356	1.041	0.395
A	1	-241.957	-15.122	1829.472	1829.472	2.261	0.148
B	1	-82.504	-5.156	212.715	212.715	0.263	0.613
C	1	82.212	5.138	211.211	211.211	0.261	0.615
AB	1	304.425	19.027	2896.084	2896.084	3.580	**0.072**
AC	1	-29.448	-1.840	27.099	27.099	0.033	0.857
BC	1	162.737	10.171	827.601	827.601	1.023	0.323
ABC	1	-5.558	-0.347	0.965	0.965	0.001	0.973
Error	21			16989.959	809.046		
Total	31			25522.175			

Block effect is relatively small
Interaction AB is significant

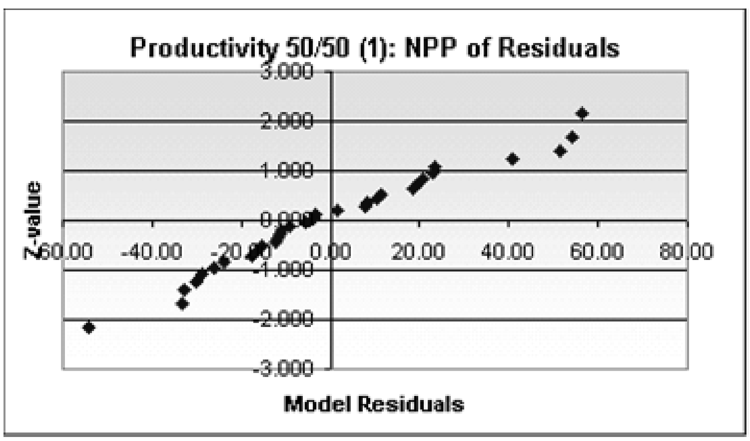
Model 1: Productivity 50/50

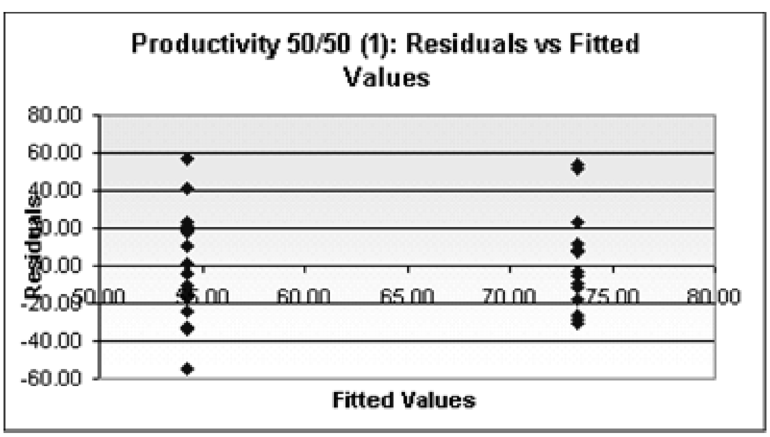
$$y = \beta_o + \beta_{12}x_1x_2$$

		x_1x_2
$y =$	63.80	9.51

R^2	R^2_{Adj}
0.11	0.08

		Residulas			
Std. Order	**y**	**Rep1**	**Rep2**	**Rep 3**	**Rep 4**
(I)	73.31	11.53	-12.09	51.56	-3.36
a	54.28	40.77	-54.28	-16.65	23.28
b	54.28	18.35	-23.80	-10.95	1.34
ab	73.31	-28.58	-9.08	-11.50	-17.64
c	73.31	-5.59	8.37	22.91	7.79
ac	54.28	-15.24	-3.96	19.47	-33.25
bc	54.28	-32.69	56.40	10.33	20.89
abc	73.31	-11.95	-30.13	54.09	-26.33





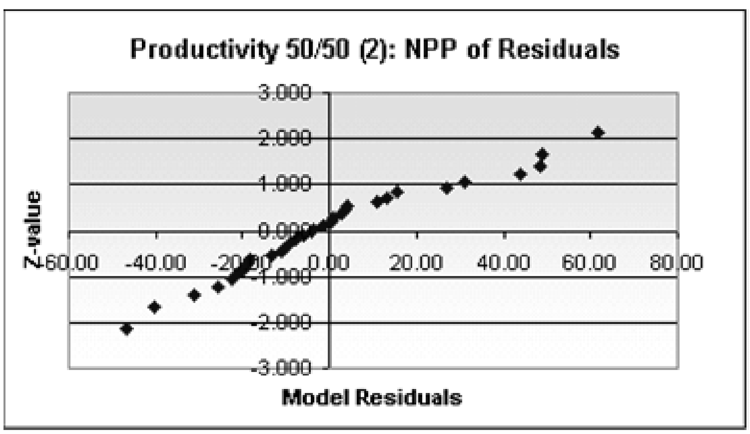
Model 2: Productivity 50/50

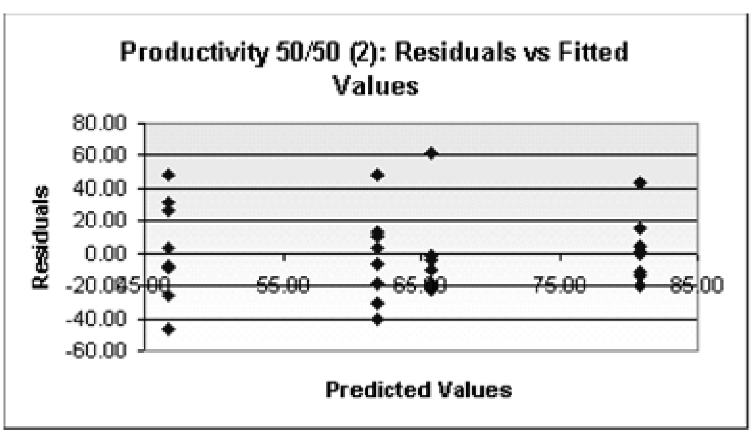
$$y = \beta_o + \beta_1 x_1 \quad \beta_{12} x_1 x_2$$

		x_1	x_1x_2
y =	63.80	-7.56	9.51

R^2	R^2_{Adj}
0.19	0.13

Std. Order	y	Residulas Rep1	Rep2	Rep 3	Rep 4
(l)	80.87	3.97	-19.65	43.99	-10.92
a	46.72	48.34	-46.72	-9.09	30.84
b	61.84	10.78	-31.36	-18.51	-6.22
ab	65.75	-21.02	-1.52	-3.94	-10.08
c	80.87	-13.15	0.81	15.35	0.23
ac	46.72	-7.68	3.60	27.03	-25.69
bc	61.84	-40.25	48.84	2.77	13.33
abc	65.75	-4.39	-22.57	61.65	-18.77





Productivity 25/75: Functionality (25) & Component (75)

Factors	Description	High	Low
A	Non-notational	Use	Not use
B	Discursive	Use	Not use
C	Notational	Use	Not use

Std. Order	A	B	C	Rep1	Rep2	Rep 3	Rep 4	Total
(I)	-	-	-	127.26	63.69	138.65	80.38	409.97
a	+	-	-	104.56	0.00	20.18	95.66	220.40
b	-	+	-	83.31	32.57	51.67	83.44	250.98
ab	+	+	-	59.28	86.69	92.72	67.93	306.61
c	-	-	+	71.48	94.56	127.15	85.06	378.25
ac	+	-	+	35.05	52.08	78.91	31.54	197.57
bc	-	+	+	27.84	137.28	69.71	101.37	336.20
abc	+	+	+	69.86	44.80	137.46	70.47	322.60
			Sum of Blocks:	578.64	511.66	716.44	615.85	

$y_{...}=$ 2422.59

$\bar{y}_{...}=$ 75.70589

Blocks =4 $2^3=8$

N =32 $2^2=4$

alpha =0.1 $2^1=2$

Source of Variance	df	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	3			2742.643	914.214	0.726	0.548
A	1	-328.221	-20.514	3366.533	3366.533	2.672	0.117
B	1	10.189	0.637	3.244	3.244	0.003	0.960
C	1	46.662	2.916	68.041	68.041	0.054	0.818
AB	1	412.288	25.768	5311.915	5311.915	4.216	**0.053**
AC	1	-60.340	-3.771	113.780	113.780	0.090	0.767
BC	1	155.743	9.734	757.993	757.993	0.602	0.447
ABC	1	-78.130	-4.883	190.757	190.757	0.151	0.701
Error	21			26458.993	1259.952		
Total	31			39013.900			

Block effect is relatively small
Interaction AB is significant

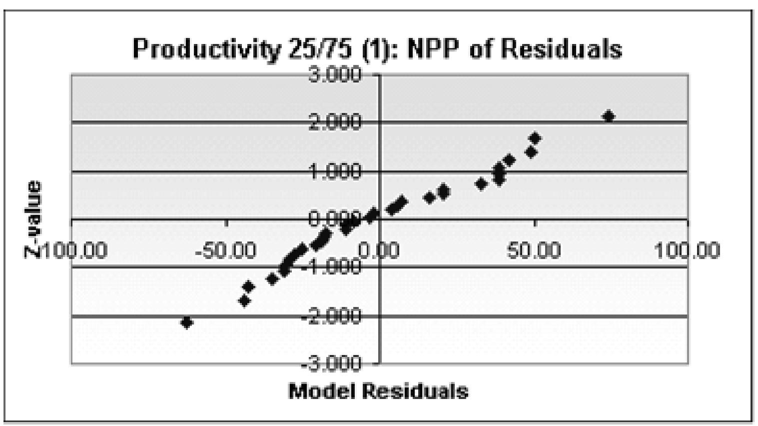
Model 1: Productivity 25/75

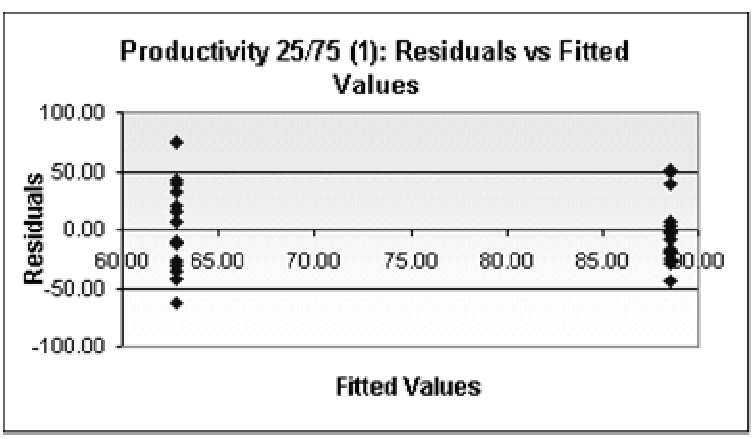
$$y = \beta_o + \beta_{12}x_1x_2$$

		x_1x_2
$y =$	75.71	12.88

R^2	R^2_{Adj}
0.14	0.11

		Residulas			
Std. Order	**y**	**Rep1**	**Rep2**	**Rep 3**	**Rep 4**
(l)	88.59	38.67	-24.90	50.06	-8.21
a	62.82	41.74	-62.82	-42.64	32.83
b	62.82	20.49	-30.26	-11.16	20.62
ab	88.59	-29.31	-1.90	4.13	-20.66
c	88.59	-17.11	5.97	38.56	-3.53
ac	62.82	-27.77	-10.74	16.08	-31.28
bc	62.82	-34.98	74.46	6.89	38.54
abc	88.59	-18.73	-43.79	48.87	-18.12





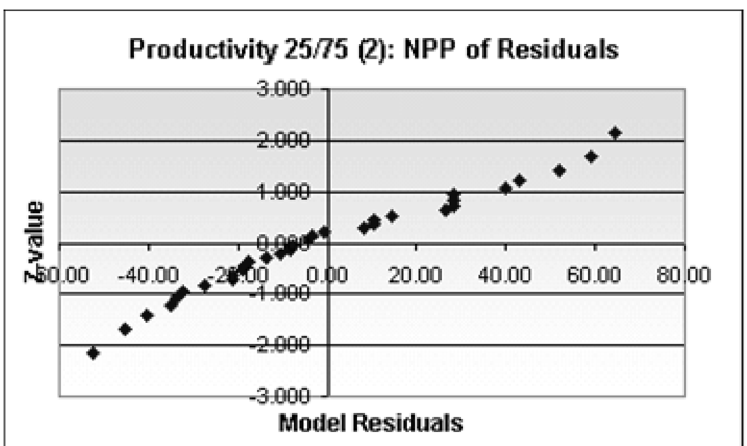
Model 2: Productivity 25/75

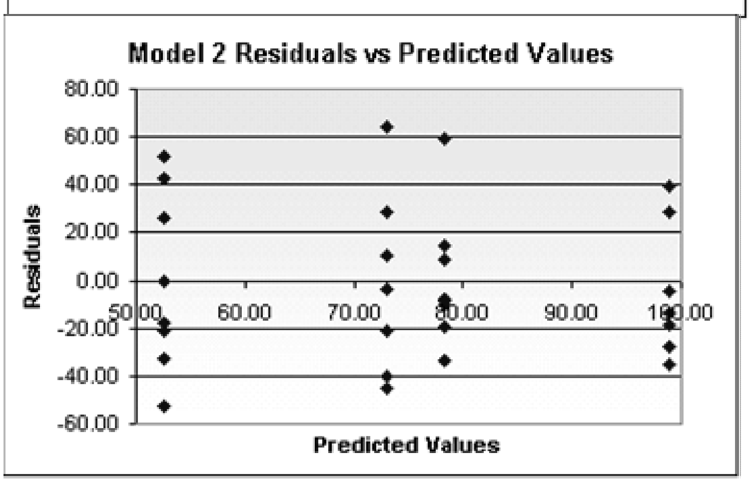
$$y = \beta_o + \beta_1 x_1 \quad \beta_{12} x_1 x_2$$

		x_1	x_1x_2
$y =$	75.71	-10.26	12.88

R^2	R^2_{Adj}
0.22	0.17

Std. Order	y	Residulas Rep1	Rep2	Rep 3	Rep 4
(l)	98.85	28.41	-35.16	39.80	-18.47
a	52.56	52.00	-52.56	-32.39	43.09
b	73.08	10.23	-40.51	-21.41	10.36
ab	78.33	-19.06	8.35	14.38	-10.40
c	98.85	-27.36	-4.28	28.30	-13.79
ac	52.56	-17.52	-0.49	26.34	-21.02
bc	73.08	-45.24	64.20	-3.37	28.29
abc	78.33	-8.47	-33.53	59.13	-7.86





NUMBER OF IDEAS

Number of Ideas

Factors	Description	High	Low
A	Non-notational	Use	Not use
B	Discursive	Use	Not use
C	Notational	Use	Not use

Std. Order	A	B	C	Rep1	Rep2	Rep 3	Rep 4	Total
(l)	-	-	-	5.00	2.00	1.00	1.00	9.00
a	+	-	-	4.00	1.00	3.00	8.00	16.00
b	-	+	-	5.00	2.00	5.00	2.00	14.00
ab	+	+	-	8.00	3.00	3.00	7.00	21.00
c	-	-	+	5.00	6.00	4.00	10.00	25.00
ac	+	-	+	5.00	2.00	5.00	9.00	21.00
bc	-	+	+	6.00	7.00	7.00	6.00	26.00
abc	+	+	+	6.00	4.00	7.00	8.00	25.00
			Sum of Blocks:	44.00	27.00	35.00	51.00	
							y...=	157.00
							$\bar{y}$...=	4.90625

Blocks =4 $2^3=8$

N =32 $2^2=4$

alpha =0.1 $2^1=2$

Source of Variance	df	Contrasts	Effects	SS	MS	F_o	P-value
Blocks	3			41.094	13.698	3.566	**0.031**
A	1	9.000	0.563	2.531	2.531	0.659	0.426
B	1	15.000	0.938	7.031	7.031	1.831	0.190
C	1	37.000	2.313	42.781	42.781	11.139	**0.003**
AB	1	3.000	0.188	0.281	0.281	0.073	0.789
AC	1	-19.000	-1.188	11.281	11.281	2.937	0.101
BC	1	-5.000	-0.313	0.781	0.781	0.203	0.657
ABC	1	3.000	0.188	0.281	0.281	0.073	0.789
Error	21			80.656	3.841		
Total	31			186.719			

Blocks are significant

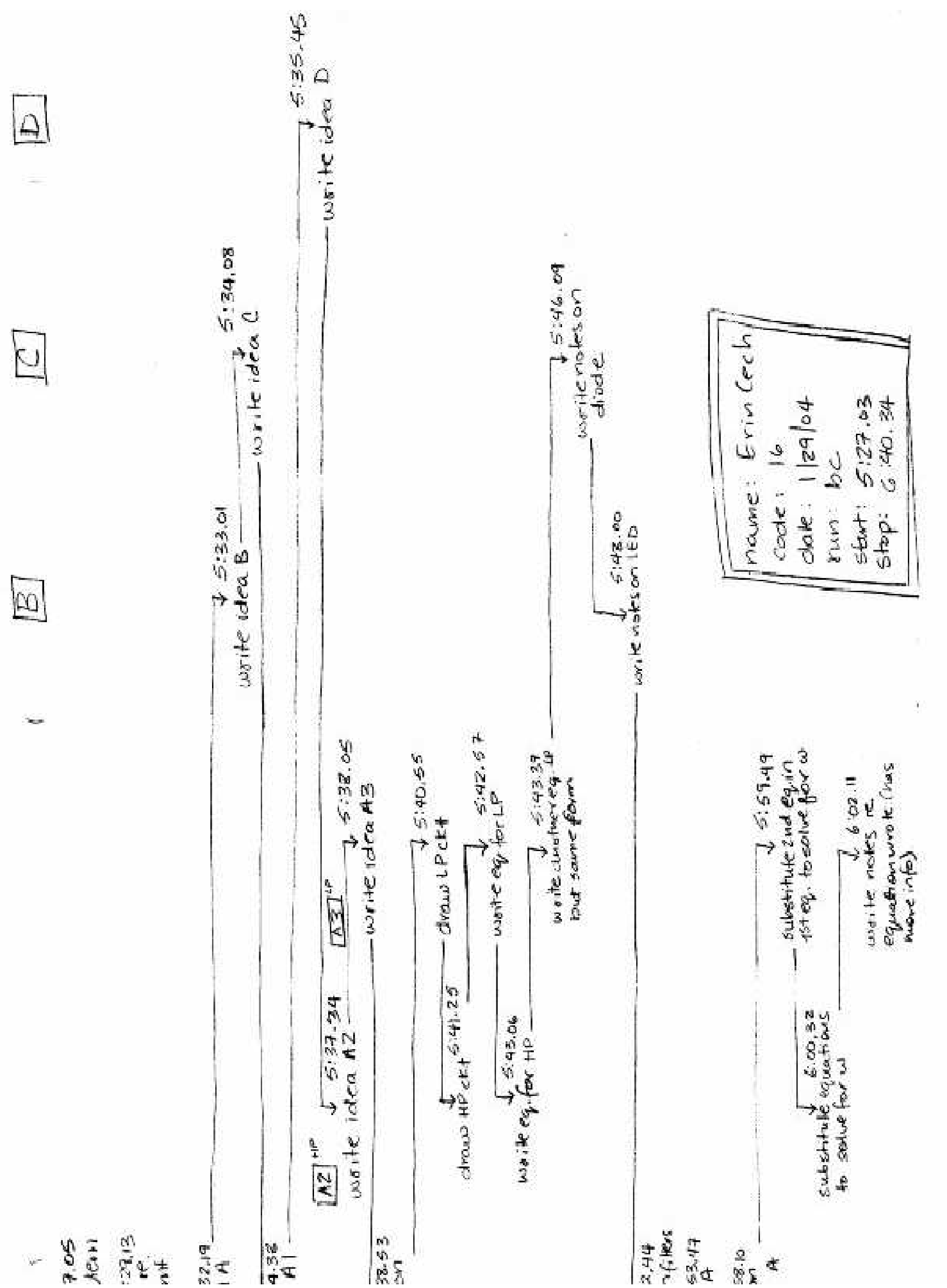
Factor C is significant

APPENDIX D

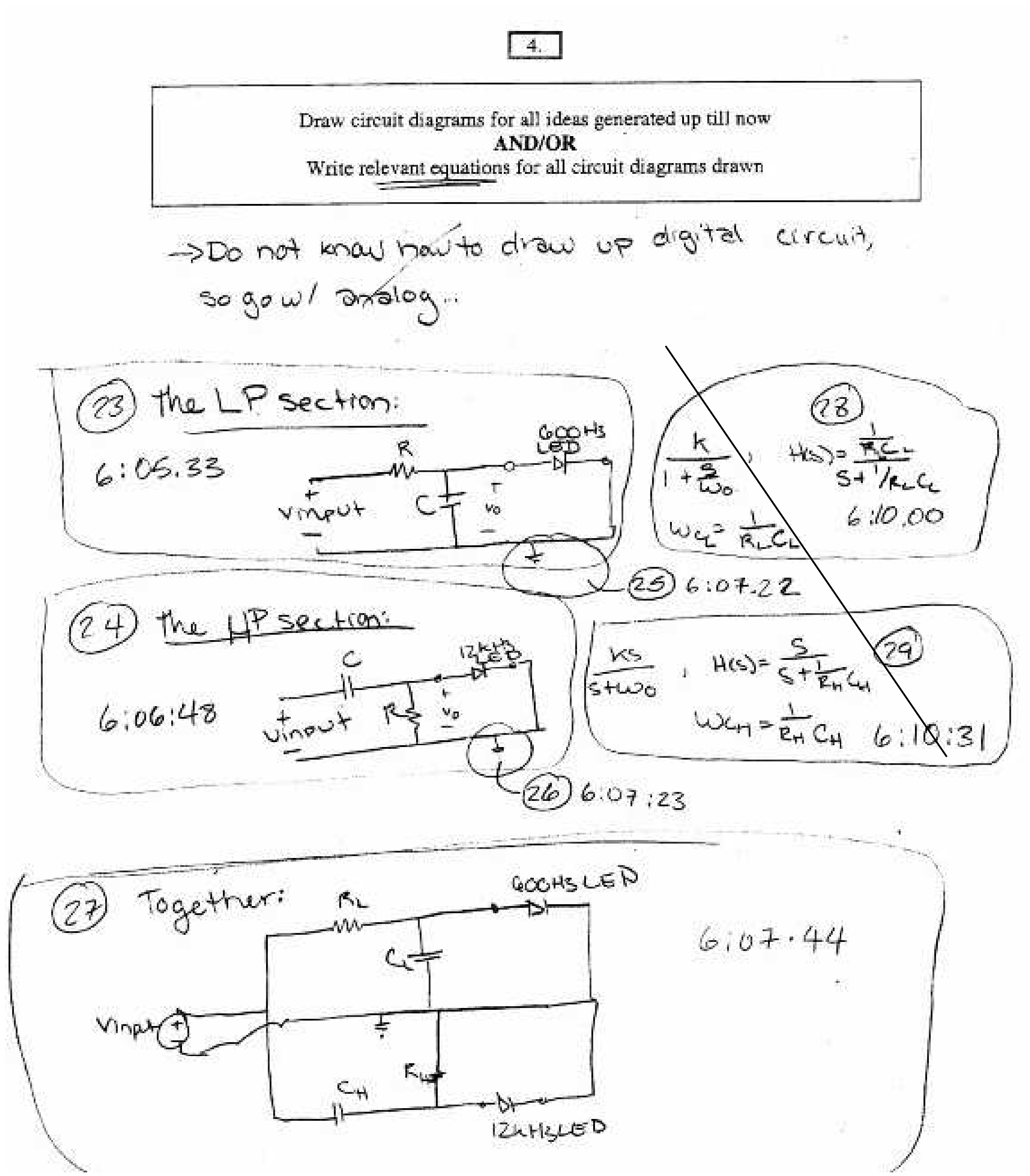
TRANSFORMATION ANALYSIS

MATERIALS

REPRESENTATION FLOW DIAGRAM EXAMPLE



CODING VIDEO EXAMPLE



TRANSFORMATION TIME SHEET

Transformation Time Sheet

Spring 2004

Code: _____________ Run: ___________

Record the time after a transition occurs		Record the start times for every representation				
Vertical	**Lateral**	**Graphs**	**Block Diagrams**	**Text**	**Circuit Diagrams**	**Equations**