A representation for teaching product architecture design

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Abstract. A variety of representations are used throughout the design process to promote efficiency in design tasks ranging from synthesis and exploration to modeling and analysis of design solutions. This paper focuses on the design phase where solutions are transformed from function to form: product architecture design. The architecture domain is generally ill-defined in current engineering curricula and in engineering practice. Product layouts are typically developed implicitly during concept generation activities. To address this problem, we present a representation that facilitates documentation, observation, and manipulation of product architecture. The hypothesis of this paper is that a formal architecture representation can be more effective in generating concept solutions than conventional practice. Our representation is evaluated through experiments with undergraduate mechanical engineering students at both the freshman and senior level. Results show that use of this representation offers a significant advantage in developing conceptual solutions in an educational setting.

Keywords: design representation, engineering education, architecture design

1.0 Introduction

Architecture design is the act of transforming a design solution from function to form. It is a relatively difficult design phase for students experiencing open-ended design problems for the first time. The capacity to educate engineering students on the theory and practice of design is limited in part by the current lack of an effective design language in which we can generate, analyze, and reflect upon a set of conceptual design solutions. Overcoming this deficiency should promote enhanced learning in the classroom and lead to improved design skills in industry. This section illustrates the challenges of architecture design in particular and suggests how a representation can be used to answer to those challenges.

1.1 Architecture Design in Engineering Education

A typical undergraduate design experience incorporates elements of customer needs, functional specification, concept generation, rough form or layout development, and detailed design. Looking beyond architecture design, several abstractions and techniques for the various design stages, as shown in Table 1, have been developed in the past to support both the instruction and execution of the mechanical design process.

Table 1 Existing Design Representations

Design Task	Existing Representation Aids
Problem Clarification & Definition	Customer needs analysis results Mission statement Benchmarking QFD
Industrial Design	External illustrations Foam models
Functional Modeling	Black box Function structure with functional models identified
Physical Solution Generation	Morphological matrix of schematic physical solutions Solution description in textual format
Physical Solution Combination – Concept Layout Generation	Rough geometric schematic ***Architecture notation needed here*** Mathematical models Proof of concept physical prototypes
Manufacturing and Assembly Design	Manufacturing data, selected processes, source of material Bill of materials Assembly tree Force flow diagram
Final Form Specification	CAD, solid models with complete specifications of all parts

Architecture emerges informally during the concept generation phase and becomes an explicit concern during configuration or layout design (Ulrich and Eppinger, 2000). Given the geometric and spatial constraints associated with form solutions, a large number of design issues arise during this stage such as part number and complexity, manufacturing and assembly, product family variety, standardization, modular vs. integral, interfaces, serviceability, and industrial design. The task of architecture design becomes very complex as the designer attempts to keep track of these items. Without clear direction, the search for solutions is a cumbersome and inefficient path.

In other stages of the design, modeling and analysis activities play a prominent role. When one considers conceptual design, however, there is a glaring lack of modeling and analysis generally used in practice. For example, students can apply principles of machine elements to rigorously address the detailed design question of "How big should this shaft be to support some load?" On the other hand, if a student is faced with the problem of developing an initial layout that includes major modules and components, the number of relevant and appropriate tools in the designer's toolbox now seem to dwindle to a much smaller set. Students often apply ad hoc techniques like sketching out a few alternatives that appear to be good according to their tacit knowledge that is based on their prior experience. The prototypical engineer is famous for solving problems in a logical and rigorous style. Unfortunately, the engineer's modeling and analysis capabilities are not fully used in architecture design. This is one principle motivation for developing a representation for architecture design.

1.2 Artifacts of Architecture Design

So far the discussion refers mainly to the ***process*** of architecture design with little mention of the substance of architecture itself. What exactly does product architecture look like? What is the result of performing architecture design? There are several valid answers depending on one's viewpoint. Consider a tangible perspective–visual inspection of a device as dissected in Figure 1. Two similar power screwdrivers with different architectures are shown.

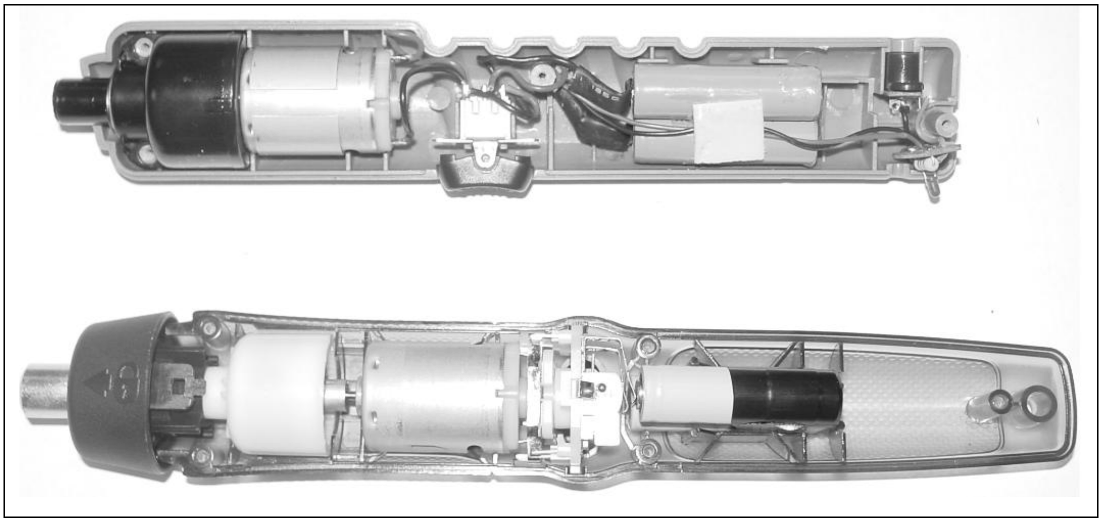


Figure 1 Example of two different architectures

One can extract a great deal of design knowledge from the photograph in Figure 1 including material choice and dimensional considerations. If this detailed design information is removed, what is left in terms of architecture? ***Fundamentally, architecture is about a set of items and how they are arranged.*** But what are the items, and how is their arrangement described? One can argue that the physical modules such as the chuck, gearbox, motor, switch, batteries, and housing form a set of elements, and the spatial layout as shown defines their arrangement. One could even create an abstraction such as a graph to represent this description of architecture. This approach is one of many valid perspectives, representing a significant challenge of architecture design today. There is no widely accepted formal vocabulary and grammar for describing product architecture.

Previous research has left us with several versions of architecture constructs including modules (Stone, 1997), interfaces (Sosa et al. 2000), working principles (Pahl and Beitz, 1996), wirk elements (Jensen, 2000), etc. Most of these concepts have some advantages such as the ability to represent some specific aspect of architecture design like function sharing. However, in the interest of describing product architecture with respect to all its principle elements, a basic problem still remains: product architecture is an ill-defined design stage, and there is a need for a representation that captures the aspects which can improve student learning and designer designing.

This lack of an architecture language is one reason for the roundabout design path that describes architecture design. Specifically, the problem is that the designer must consider a large set of issues without a vehicle for incrementally describing and thus keeping track of the design situation. This scenario is analogous to one attempting to develop a Broadway show without having such a thing as a casting list, action script, or map of the stage. It is simply difficult to manage the leap from function to form without a language for describing and thus keeping track of the design situation.

1.3 Goal and Vision

The motivation for this research is based on three main premises. The first is that architecture design is an important aspect of design, whether original or redesign, deserving of techniques that facilitate effective and efficient search and development of design solutions. Recent prior work supports the importance of architecture design (Cutherell, 1996; Otto and Wood, 2000; Stone et al., 2000; Ulrich and Eppinger, 2000). The second premise is that current architecture design techniques do not measure up to the standard of effective and efficient execution compared with other modeling and analysis techniques for other phases of the design process, such as functional design, Design for Manufacturing and Assembly, Robust design, etc. The third premise is that a formal representation for architecture design is an effective solution to help steer the designer toward solutions. We know, based on previous efforts involving reverse engineering techniques (Jensen et al., 2001), that students benefit from reverse engineering exercises in which students utilize an existing device as a reference for redesign opportunities. The goal of this research is to develop a non-physical representation for architecture design that facilitates a systematic, incremental, and reasonably direct path from function to form. The fundamental improvement sought is a reduction in design effort required to establish product architecture design solutions. A direct result of this advancement should be the improved teaching capability of educators in treating the material normally associated with conceptual design.

2.0 Related Work

In the recent past, techniques of varying levels of formalism have been developed to represent different levels of a product design solution. Two of the many representations will be highlighted: i) function based, and ii) form based. Function based representations allow designers to enjoy the benefits of form independent representations of design solutions. Formal definitions for function structure elements and the function structure generation process have been developed and continue to be refined (Hirtz et al., 2002). On the other end of the spectrum, CAD conceptual modelers (Thompson, 2001) and shape grammar work have focused on representing physical form in terms of its basic property–shape (Stiny, 2001).

Welch and Dixon (1992) developed behavior graphs that are based on research in qualitative physics. A solid contribution of this work is a representation that explicitly defines the connectedness of physical embodiments using functional parameters. One deliverable of this research is the concept of a functional parameter and an embodiment. For purposes of conceptual design, this behavior graph approach is very capable in terms of defining physical topologies of a conceptual solution. This configuration model supports design activities from concept generation to embodiment. Aguirre-Esponda (1992) similarly developed a configuration model that maps a small set of 'ideal' functional elements to a set of physical device elements. One drawback to both approaches is the lack of substantial spatial information regarding the partitioning of spatial regions into components and modules. Welch and Dixon's work in particular is limited somewhat by the single input, single output scheme that is used. Campbell (2000) extends upon Welch and Dixon's (1992) work to facilitate multiple inputs and multiple outputs in addition to allowing parallel embodiments within the conceptual solution. This framework strongly supports automated design.

Rosen (1996) takes a different approach by developing a combinatorial method to address configuration design in terms of three discrete design spaces including material compatibility, connections (physical contacts between components), and covers (the relationship of covering a component with others). Rosen's framework is intriguing because he applies the tools of discrete mathematics to the architecture problem and therefore brings to bear a rich set of manipulation techniques to architecture design. This discrete perspective is not required however as Harada et al. (1995) have dealt with transitions between discrete and continuous manipulations of floor layout models.

In addition to the type of analytical frameworks adaptable to architecture design, prior work also demonstrates differences in scope chosen for an approach to the architecture design problem. While the scope is generally focused on the transition from function to form, the emphasis and granularity of previous approaches varies. As a precursor to later developments, a line of work from Chakrabarti (1994) is focused on configuration design in which alternative physical solutions are determined based on spatial constraints. This work develops a representation consisting of functional elements, generic objects, and standard objects. Generic objects are a basic class of several morphological solutions that satisfy a functional element while standard objects are a specific physical solution which satisfies its generic object (Liu et al., 1999). This representation facilitates progressive development of a design solution although the technique is not entirely practical for rapid implementation and is probably best reserved for computational tools which use the technique. In contrast, Allen and Carlson-Skalak (1998) developed a method that is less involved to implement. They developed a system function structure that is a variation of a traditional function structure. Here the system function structure defines the flow of energy, material, and signals among modules established from reverse engineering the product. This approach is attractive in some settings in particular because the representation format requires very little overhead in terms of putting the representation into practice.

A range of terminology and basic concepts is also evidenced in prior work. Erens and Verhulst (1997) decompose the architecture design phase into three domains: function, technology, and physical. Sander and Jantsch (1999) propose a skeleton map design model that uses a functional description as a skeleton for preliminary hardware layouts. Jensen (2000) addresses the spatial mapping of function to form by means of wirk elements, which are based on German design theory. A contribution of this wirk element approach is the capability of decomposing spatial regions and part surfaces that contribute to a given function or functions.

Each of the above references bring some useful concepts to bear on the architecture representation problem. In addition to considering these previous engineering perspectives, this work also looks at the field of psychology. Many fields of study employ the use of models and representations. One approach is to investigate models from other fields such as mathematics, business, or economics. For purposes of getting to the roots of the representation problem, this work also examines the field of cognitive psychology which is, among other things, focused on understanding and explaining how people think in terms of representations.

2.1 Influences from Cognitive Psychology

The purpose of developing an architecture representation is to make architecture design easier. However, this representation venture has a potentially hazardous side effect. Hayes (1989) points out that the manner of representation will have a significant impact on the task. He refers to experiments where a given problem can be over an order of magnitude harder to solve depending on the problem representation. Norman (1983) also argues that one's perspective of the world and the tasks one is required to perform depends strongly on the representation used. While this variation in difficulty depends on the case at hand, it demonstrates how important the representation is to the task. A set of requirements for architecture design are developed in a later section, but for now it suffices to present the architecture design task as a creative process to synthesize physical solutions based on design requirements and functional design information. The following discussion develops the concepts used to develop the product architecture representation.

One useful model of creative cognitive processes such as architecture design is the Geneplore (Generation – Exploration) model developed by Finke, Ward, and Smith (1992). This model is based on the notion that creative activities generally follow a three step process of i) generating so called 'preinventive structures,' ii) exploring those structures, and iii) iterating this process while applying product constraints. Benami and Jin (2002) use this Geneplore structure to develop a cognitive model of conceptual design. Since one objective in the present work is to generate a representation, the notion of 'preinventive structures' is most relevant here. Several types of preinventive structures exist although this work focuses on one particular structure as the foundation for the representation. The next sections develop this concept.

A representation can generally have four components as shown in Table 2. Markman (1999) discusses several levels of representations that are available in increasing levels of sophistication: spatial (includes some element of space), featural (property) based, network models (a graph – a set of connected elements), structured representations that may include visual, causal, and temporal information, and mental models (inclusion of future or potential representation states that are not in existence currently). The mental model concept will be explored because it appears as the most comprehensive and appropriate for the problem of representing physical systems in the context of an active design exercise.

Table 2 General Representation Components (Markman, 1999)

Component	**Description**
Represented world	The actual system domain
Representing world	The modeled system domain
Representing rules	Relations that map the represented world to the representing world
Representation Process	A method that uses the representation

The background for mental models stems from two main areas (Gentner, 1983). The first is cognitive psychology and those related areas that investigate the mind. Second, artificial intelligence research also provides theories about knowledge representation and processing. While different mental models have been developed to represent different problem domains, here the discussion focuses on mental models of physical systems to understand how a mental model can be used in architecture design.

Generally a mental model consists of three items: a set of objects that represent items of interest in the actual system, a set of relations and properties among the objects, and a notation for the objects (Markman, 1999). A simple drive train in Figure 2 serves as an example of these three items. The drawing itself is the notation. The objects are a base, two bearings, motor, shaft, pulley, belt, driven pulley, driven shaft, and some of the design variables as shown.

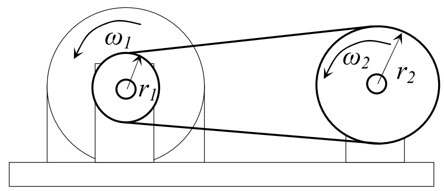


Figure 2 Example set of objects for a mental model of a physical system.

Table 3 Example set of relations for a mental model of a drive train.

ω_2 will increase with a decrease in r_1
ω_2 will increase with an increase in r_2
output torque will increase with motor torque

As the name suggests, mental models are observed, manipulated, and reasoned by the mind. Studies of mental models by Williams, Hollan, and Stevens (1983) have shown that people tend to reason about such models using relatively simple qualitative relationships such as those given in Table 3. White and Frederiksen (1990) argue that people think about physical systems with zero-order models, (whether or not an item is present or not), and first-order models (the direction of change of a parameter in the system). Additionally, White and Frederiksen indicate that quantitative relations in mental models are generally not used to mentally determine the degree of change. This suggests that it is reasonable to gear the architecture representation toward a format that facilitates this type of first order analysis and reasoning of the design.

3.0 Method

Based on the concept of a mental model, there are two key pieces of information essential in developing an architecture representation. First, a set of elements or objects that represents the architecture must be established. Secondly, there must be a set of rules to govern the use of those objects. We present a set of three diagrams each with a nomenclature and rules for describing how to implement each.

In terms of nomenclature, many design abstractions such as those in Table 1 are rich in terms of their visual content and this has advantages based on work from Kremer (1998) who presents several reasons for using visual languages as opposed to relatively linear text: Abstract reasoning is pictorial in nature and has two and three dimensional aspects and so it is logical that visual reasoning may be more efficient than linear verbal language. Visual organizations are efficient for chunking information and thus mitigate short-term memory limitations. Thought operations may be transformations of images and images are analogous to tasks, while linear languages generally bear no analogous relation to the task they describe. For all these reasons, a highly graphical notation is adopted in this work.

Table 4 gives an overall view of the three architecture diagrams. Each of the three diagrams is defined in the next section and includes a set of nomenclature and a procedure for specifying each. The procedures are mainly geared for an original design although the redesign case can be handled using the same procedures by simply including appropriate constraints that follow from the existing device. A Skil Twist power screwdriver is used as an example to illustrate the three diagrams. A few definitions are relevant to diagram terminology:

<u>Spatial Diagram</u>: A notation that represents the product space overall or regions of material in the product space. The diagram may be realized with a sketch, solid model, or appropriate data structure.

<u>Product space</u>: The spatial volume bounded by a product.

<u>Region</u>: A closed volume including the interior and edges. A region can be either the product space or a subset of the product space.

Table 4 Summary of Representation Diagrams

Layout Diagram	Description	Minimum Inputs	Outputs
Spatial Constraints Diagram	A diagram mapping spatial constraints to spatial regions	Customer needs, Requirements, Functional Model, One Physical Solution choice	Spatial constraints External Physical interfaces
Function Layout Diagram	A diagram mapping functions to spatial regions	Spatial Constraints Diagram Physical product (if redesign)	Function to form mapping Candidate physical modules and partition choices
Physical Solution Diagram	A conceptual physical solution for a subset of the spatial diagram	Function Layout Diagram Alternative physical solution choices	Spatial layout of physical solution Relative motion

3.1 Spatial Constraints Diagram (SCD)

The purpose of the spatial constraints representation is to show geometric constraints of the product. Supporting concepts for this notation include industrial design themes since these have a high content of spatial information. Table 5 provides the general nomenclature, and Figure 3 shows the spatial constraints diagram for the Skil Twist screwdriver. The diagram is a silhouette of the product much like a control volume. External flows show the main interactions with the environment and the dimensions give some idea about the scale and known constraints. This diagram mostly involves decisions about how the customer needs are manifested on the external shape of the product.

<u>Definition</u>: The spatial constraints diagram consists of a roughly sized product boundary, all external energy, material, and signal flows oriented in space, and known geometric constraints specified.

Table 5 Spatial Constraints Nomenclature

Notation	Definition	Rule Set
	Energy, Material, or Signal flows external to the product boundary	Show flows relative to the product boundary in terms of position and orientation Flows are equivalent to the flows on the black box diagram
	Boundary of some product region.	Position and orient according to approximate geometry of a selected set of physical solutions (the current physical solution topology) Boundary of a region is sized according to the energy and material throughput at that region Multiple boundaries of regions collectively form the product boundary
Text	Dimensions or descriptions of geometric constraints	Spatial information shown where relevant

<u>Diagram Generation Procedure</u>:

1. Reproduce the functional black box.
2. In order of importance, spatially orient the energy, material, and signal flows based on requirements information, functional information, and the currently selected set of physical solutions.
3. Establish a product boundary by reshaping the black box boundary according to the magnitude and direction of the energy flows and the size, shape, type, and amount of the material flows and their relative location.
4. Identify and label dimensional constraints.

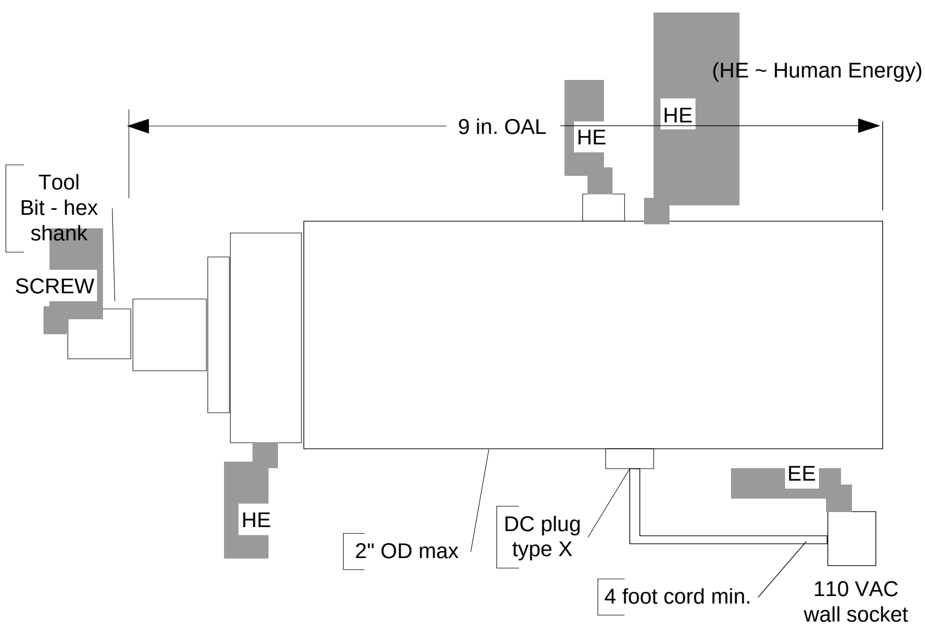


Figure 3 Spatial Constraints Diagram for a cordless screwdriver

3.2 Function Layout Diagram (FLD)

The function layout is based somewhat on the wirk element concept (Jensen, 2000) in that spatial regions are associated with some functionality. The main purpose of this notation is to show the basic internal functions and flows in a spatial format. Table 6 gives the nomenclature, and an example of a function layout is given in Figure 4. One outcome of this particular notation is the ability to predict candidate physical modules in a manner not previously reported. The FLD is where several architectural decisions are made and many options are considered. In fact, one can create many candidate FLD's for the same SCD.

<u>Definition</u>: The function layout diagram consists of a product boundary, all flows external and internal to the device, layout elements, and layout intersections.

Table 6 Function Layout Nomenclature

Notation	Definition	Rule Set
	Energy, Material, or Signal flows external and internal to the product boundary	Show flows relative to the product boundary in terms of position and orientation Show flows from input to output along the same function path as the function structure
	Layout element – a region that corresponds to some function	Position and orient according to approximate geometry of a selected set of physical solutions (the current physical solution topology) Boundary of a region is sized according to the energy and material throughput at that region
	Layout intersection - A region that is a unique intersection of two or more layout elements.	Position and orient according to approximate geometry of a selected set of physical solutions (the current physical solution topology) Boundary of a region is sized according to the energy and material throughput at that region
Text	Flow and function descriptions	Function information is shown for each layout element and layout intersection All functions from the function structure should be identified

<u>Diagram Generation Procedure</u>:

1. Reproduce the product boundary based on the spatial constraints diagram and include the flows but do not include dimensions.
2. In order of flow importance, establish regions for each functional module first and then each function while maintaining the same functional topology from the function structure.
    a. Establish a layout intersection (dashed line) for each functional module identified in the function structure. Module identification in the function structure is described by Stone (1997).
    b. Establish a layout element (solid line) for each function in the function structure.
    c. Establish internal flows that connect layout elements and layout intersections.

d. Size the layout elements and intersections based on the physical solutions size, the magnitude and direction of the energy flows, and the size, shape, type, and amount of the material flows and their relative location.

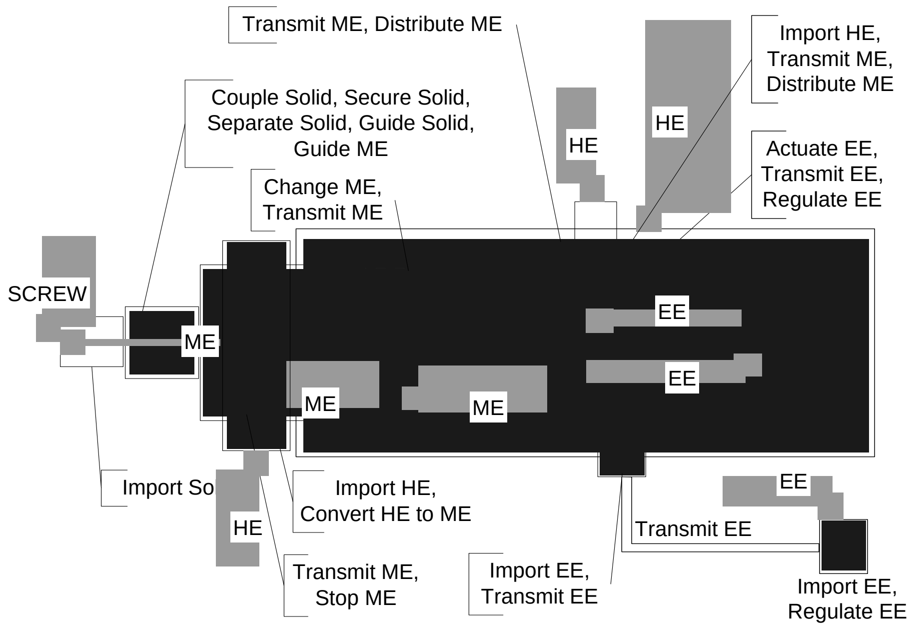


Figure 4 Function Layout Diagram for a cordless screwdriver

3.3 Physical Solution Diagram (PSD)

The physical solution diagram is intended to address the choices from the morphological matrix (Zwicky, 1948) for a set of functions and the relative spatial arrangement of those morphological choices. This particular notation is derived in part from Chakrabarti's (1994) work in that relative motions are shown. Table 7 provides the nomenclature, and an example is given in Figure 5. Note that gross motions are given while some, such as the motion of the planetary gear set, are not. One reasonable threshold for selecting those motions to include is to consider how significant the motion is to the physical solution. This allows the designer to be flexible when including physical motions. This diagram is important since it provides the designer with a check to see if the corresponding FLD is feasible.

Definition: The physical solution diagram consists of a product boundary, physical solution descriptions (text, schematic, or sketch) and arrows indicating motion of parts.

Table 7 Physical Solution Nomenclature

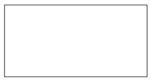
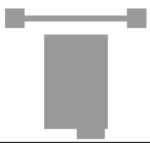
Notation	Definition	Rule Set
	Layout element – a region that corresponds to some function	Position and orient according to approximate geometry of a selected set of physical solutions (the current physical solution topology) Boundary of a region is sized according to the energy and material throughput at that region
	Layout intersection - A region that is a unique intersection of two or more layout elements.	Position and orient according to approximate geometry of a selected set of physical solutions (the current physical solution topology) Boundary of a region is sized according to the energy and material throughput at that region
	Relative motion of a region	Indicates a significant relative motion corresponding to a physical solution at some region May generally be translation or rotation
Text	Physical solution descriptions	Indicates one or more physical solutions that are consistent with a spatial region Alternative physical solutions can be indicated on the same layout provided that both solutions share approximately the same geometric specifications

Diagram Generation Procedure:

1. Identify a layout element or layout intersection.
2. Indicate (with text, schematic, or sketch) the physical solution that performs the functionality of that layout element or layout intersection.
3. Repeat steps 1 and 2 for all layout elements and layout intersections.
4. Identify regions in the device that exhibit relative motion.
5. Label those relative motions using an arrow to indicate direction.

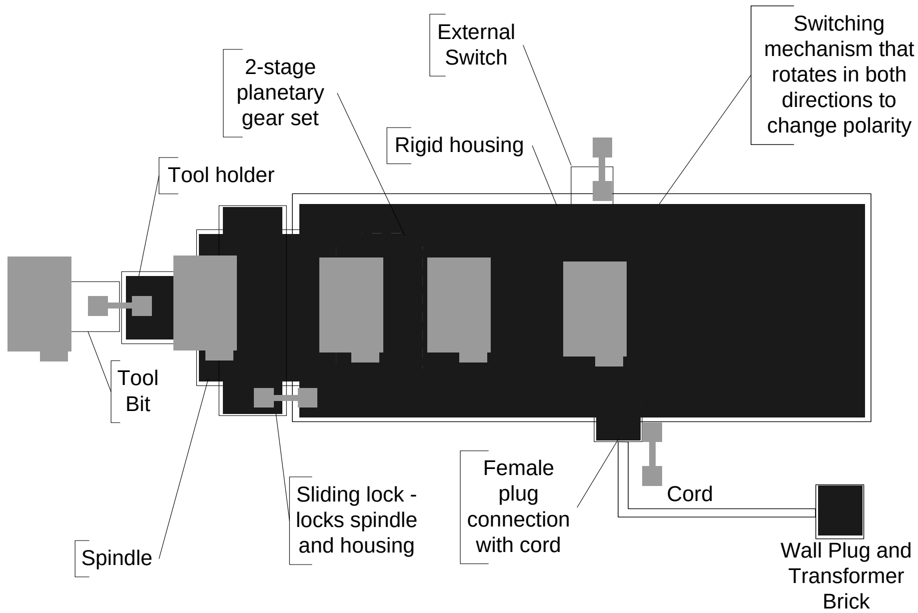


Figure 5 Physical Solution Diagram for a cordless screwdriver

In this power screwdriver diagram, one can clearly illustrate multiple options for different functional elements and intersections. For example, one may choose to include alternatives to the 2-cell NiCad pack. A second leader with description can document these alternatives to include such items as a lithium battery or alkaline battery.

4.0 Method Validation

In order to evaluate method effectiveness, two separate experiments were performed with undergraduate students. The first test involved senior mechanical engineering students at the University of Texas at Austin and the second was performed with freshman engineering students at the University of Missouri-Rolla.

4.1 Experiment 1

The focus of this study is to compare the aforementioned diagram approach to a prior technique that is less structured in guiding design activities. The following describes the task required by the control and experimental groups. Both groups are given the same preliminary information describing the design of a nail gun. This includes customer needs, an activity diagram, a black box, a functional model, and a morphological matrix containing physical solutions to each function in the functional model. Table 8 and Figures 6 through 8 illustrate each of these problem elements except for the morphological matrix which is not shown. The experiment is run as an in-class assignment where the students are divided into two groups and further partnered with a classmate to perform the exercise of architecture design. A control group is given a conventional technique while the experimental group is instructed on the three diagrammatical techniques shown in Section 3. The experimental setup is developed to test method effectiveness with respect to three metrics: 1) the quantity of concept alternatives produced, 2) the quality of the solutions, and 3) method efficiency or the quality per the amount of time allocated to each concept.

Table 8 Customer Needs for a nail gun

Low Cost	(< $500)
Light weight	(< 6 lbs)
Utilize 18 Gauge finishing nails	(capacity of 100) (1.5" long – only 18 Gauge nails supplied by a single manufacturer such as Paslode) Nails come in glued together in a strip of 50 – the strip can be either straight or angled – designers choice)
Small size	Able to use in corners No greater than 12" in any dimension
Portable	Can carry on a 1.5" wide belt
Safe	Unable to fire by dropping on ground Unlikely to be fired by children
Last long before energy resupply	Efficient use of energy
One handed nailing operation	Should be able to support firing using one hand at any orientation (ceiling, floor, wall, tight corner, etc.)

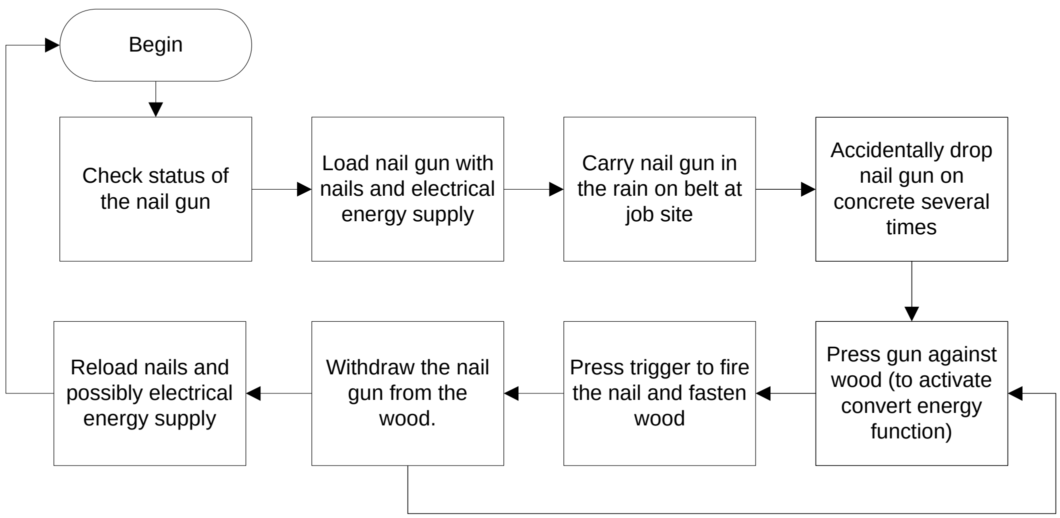


Figure 6 Activity Diagram for a nail gun

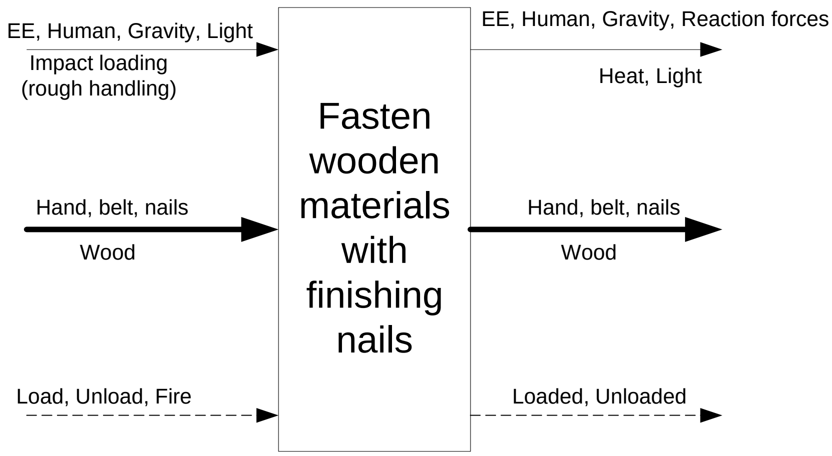


Figure 7 Black Box for a nail gun

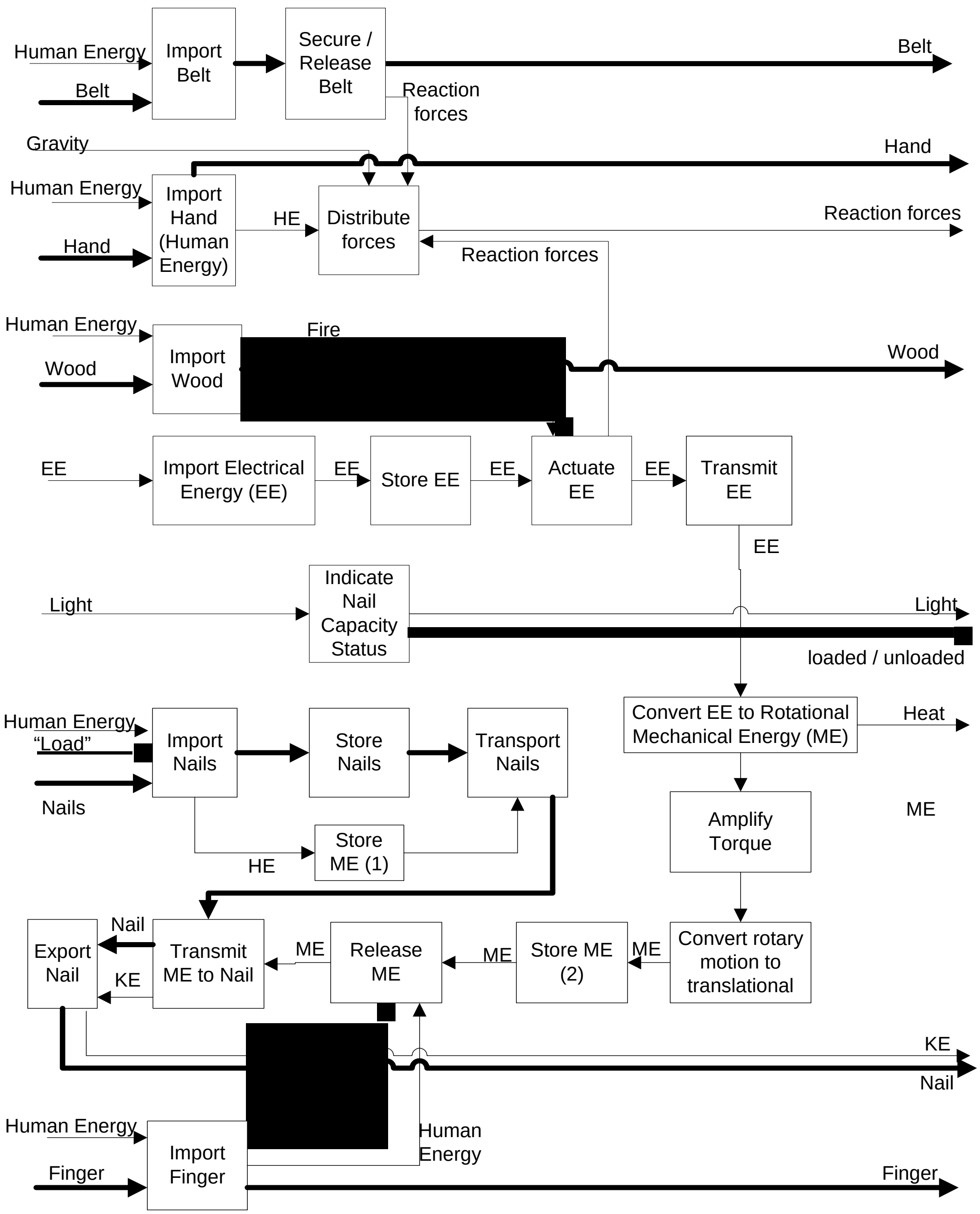


Figure 8 Functional Model for a nail gun

Given the above problem information, both groups are then separated and briefly instructed on the use of their assigned design method. Following this brief introduction to the method, each group works for approximately one hour to generate alternative concept solutions for the nail gun problem. From the student’s perspective, the assignment objective is to be graded on the quantity and quality of the results in addition to following the design procedure set forth by the design method. The control group uses a procedure that is specifically designed to assist in the development of product architecture: the method proposed by Ulrich and Eppinger (2000). This method is a four-step process as described below in Table 9.

This particular technique is chosen for comparison since it is targeted toward architecture design and considered to be at least as good as the nominal level of capability for conventional engineering practices used by engineers today. For the experimental group, the assignment covers development of concepts based on three diagrams in the representation shown earlier: the spatial constraints diagram, function layout diagram, and the physical solutions diagram.

Table 9 Architecture Design Method from Ulrich and Eppinger (2000)

1. Create schematic containing elements of both function and form.
2. Cluster elements of the schematic
3. Create a rough geometric layout
4. Identify fundamental and incidental interactions

The results are encouraging as they show distinct differences between the control and experimental groups. As expected, the experimental group generally demonstrates a greater degree of problem decomposition afforded by the architecture representation. Figures 9 through 11 show the development of one concept layout from one team in the experimental group in terms of spatial constraints, functional layout, and physical solutions.

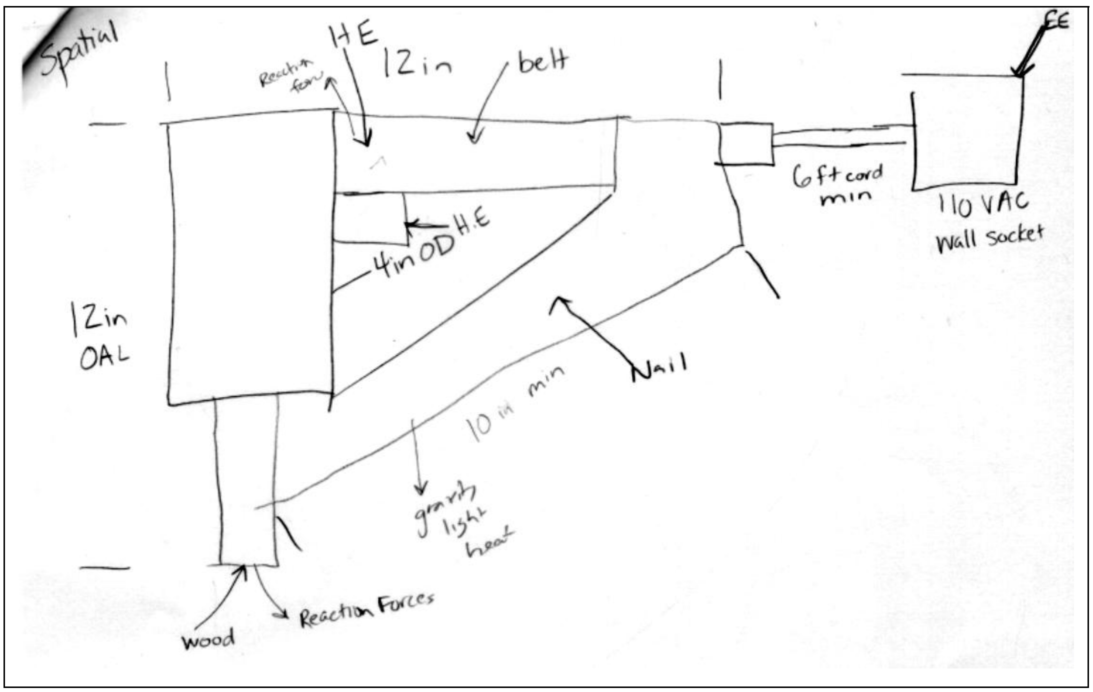


Figure 9 Spatial Constraints Diagram – Experimental Group

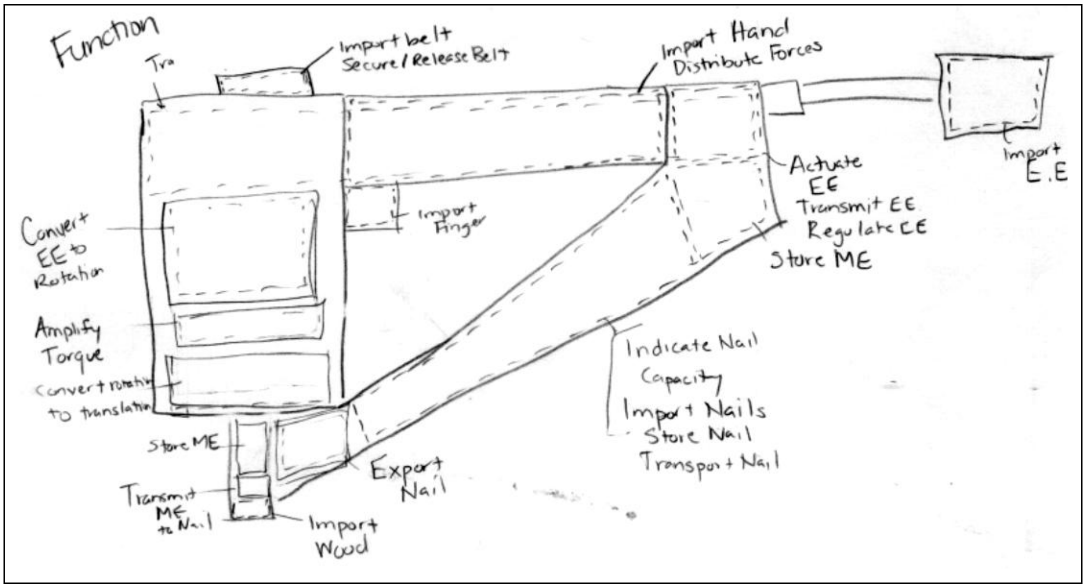


Figure 10 Functional Layout Diagram – Experimental Group

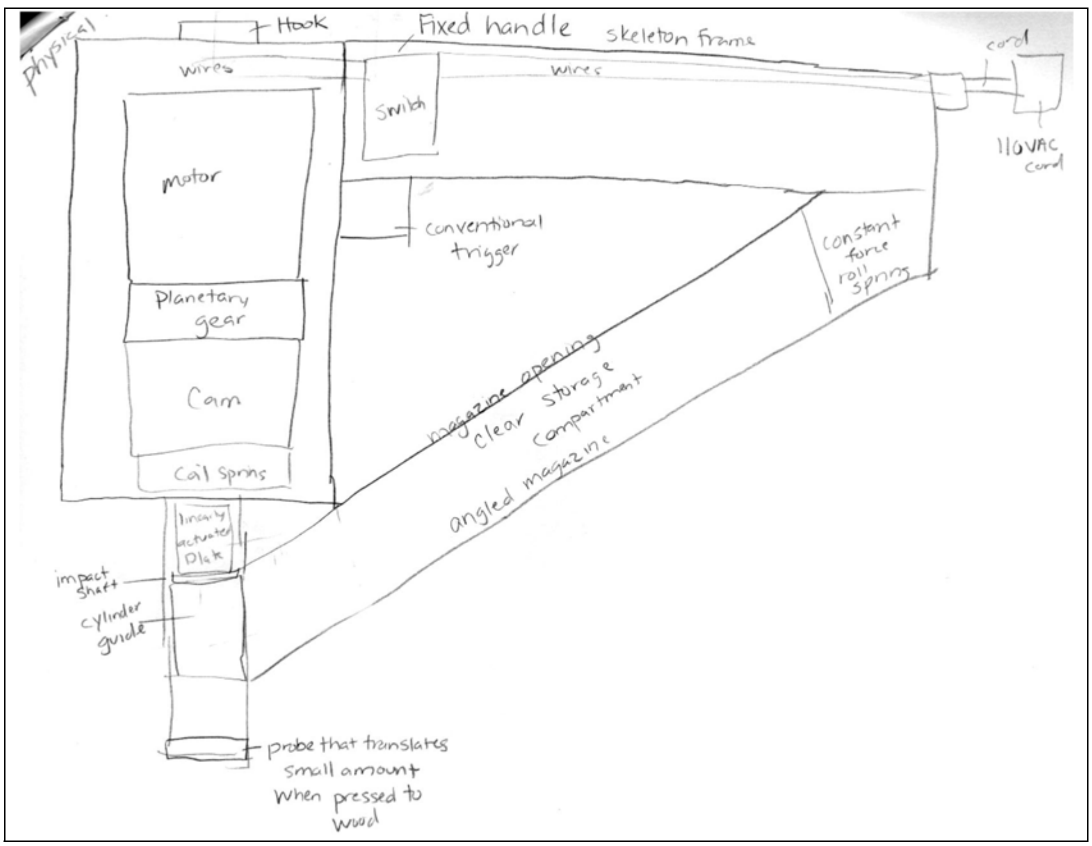


Figure 11 Physical Solution Diagram – Experimental Group

In addition, a second team in the experimental group demonstrates a considerable degree of concept exploration through the generation of multiple spatial constraints diagrams as shown in Figure 12.

This same team takes advantage of the physical solution diagram by explicitly showing alternative candidate solutions within the physical solution diagram given in Figure 13.

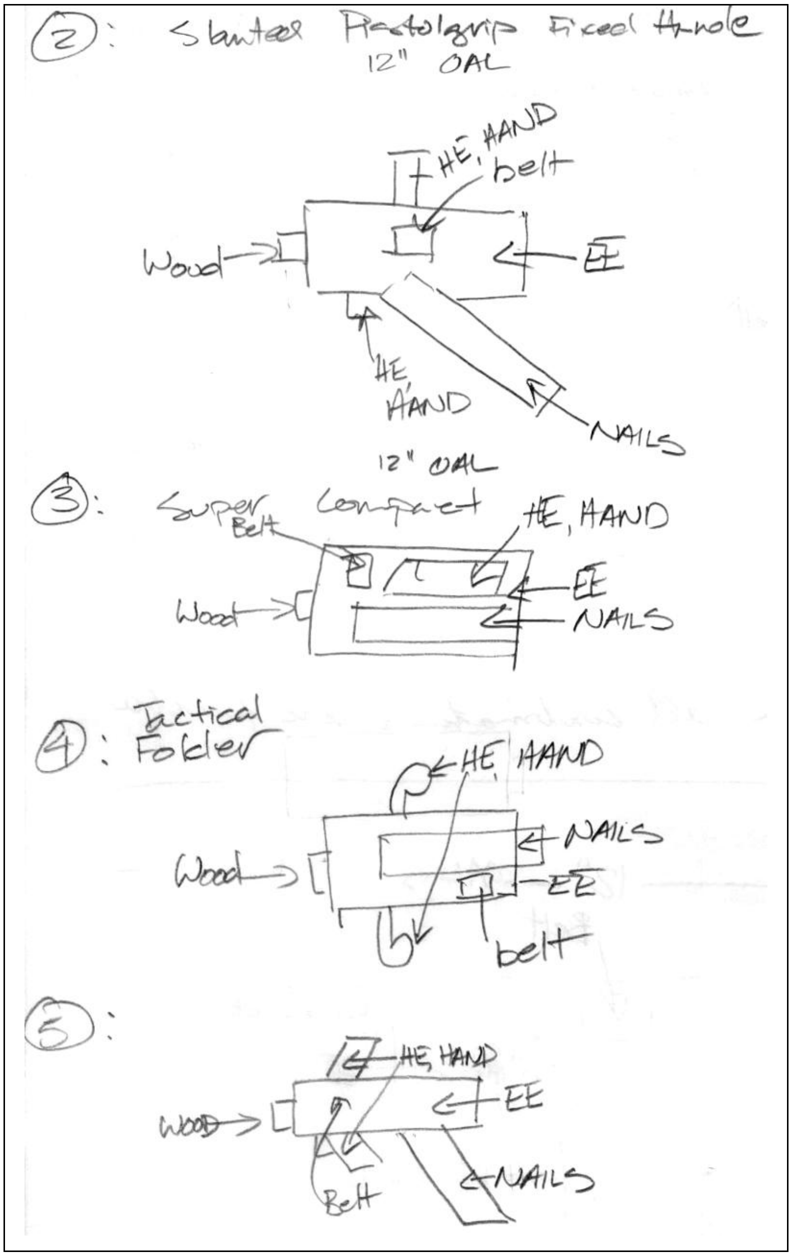


Figure 12 Alternative Spatial Constraint Layouts – Experimental Group

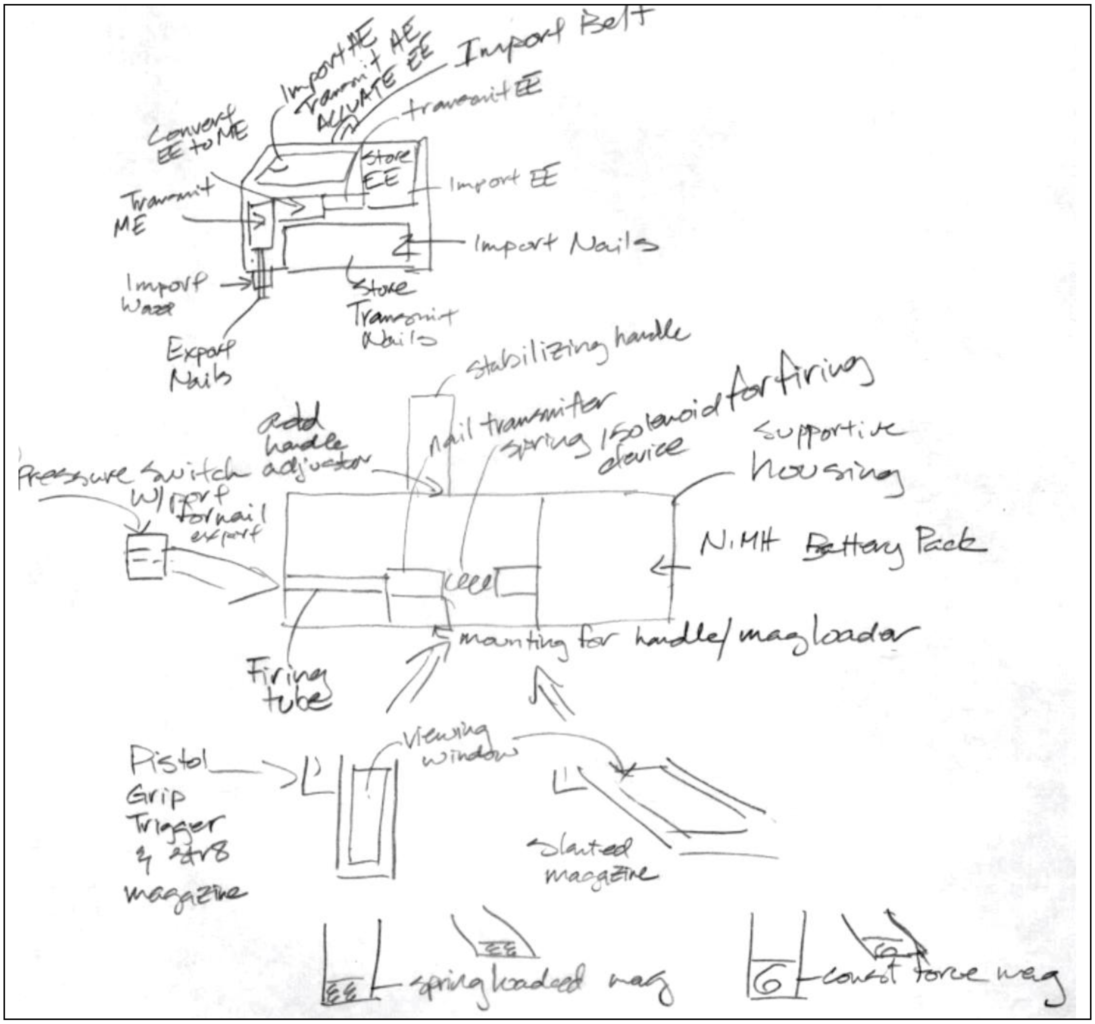


Figure 13 Alternative Physical Solutions – Experimental Group

In contrast to the experimental group, the control group exhibits a greater degree of merging of function and form within the same concept. The schematic layout shown in Figure 14 illustrates this point. Despite the fewer number of alternatives generated by the control group, the quality of solutions in terms of the geometric layouts were relatively good as illustrated in Figures 15 and 16.

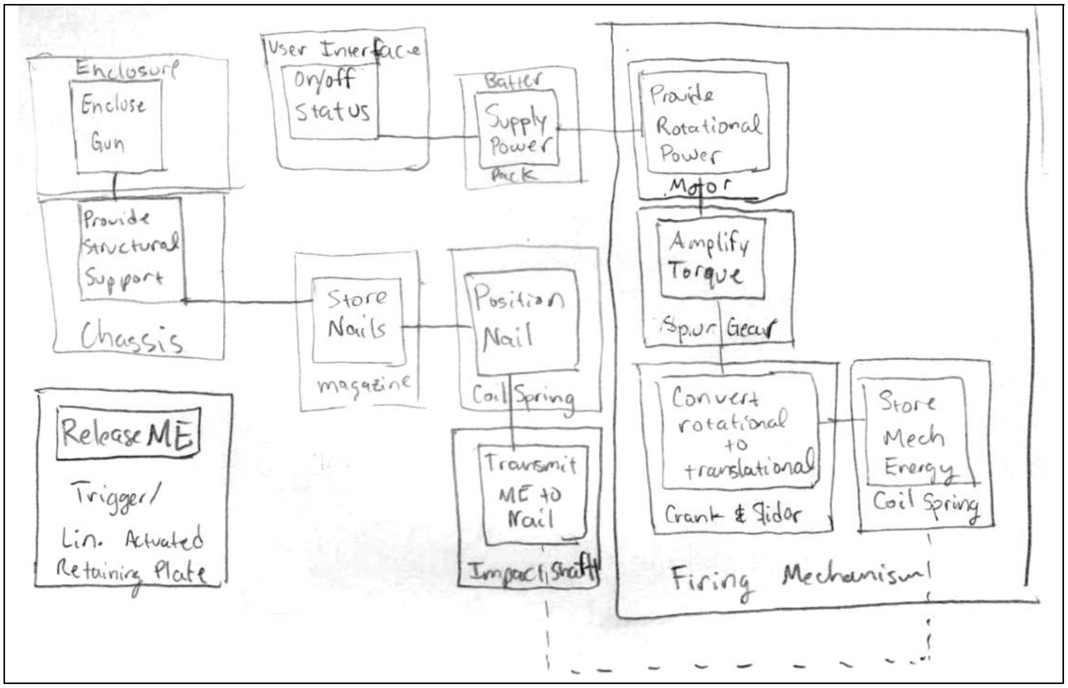


Figure 14 Schematic Layout – Control Group

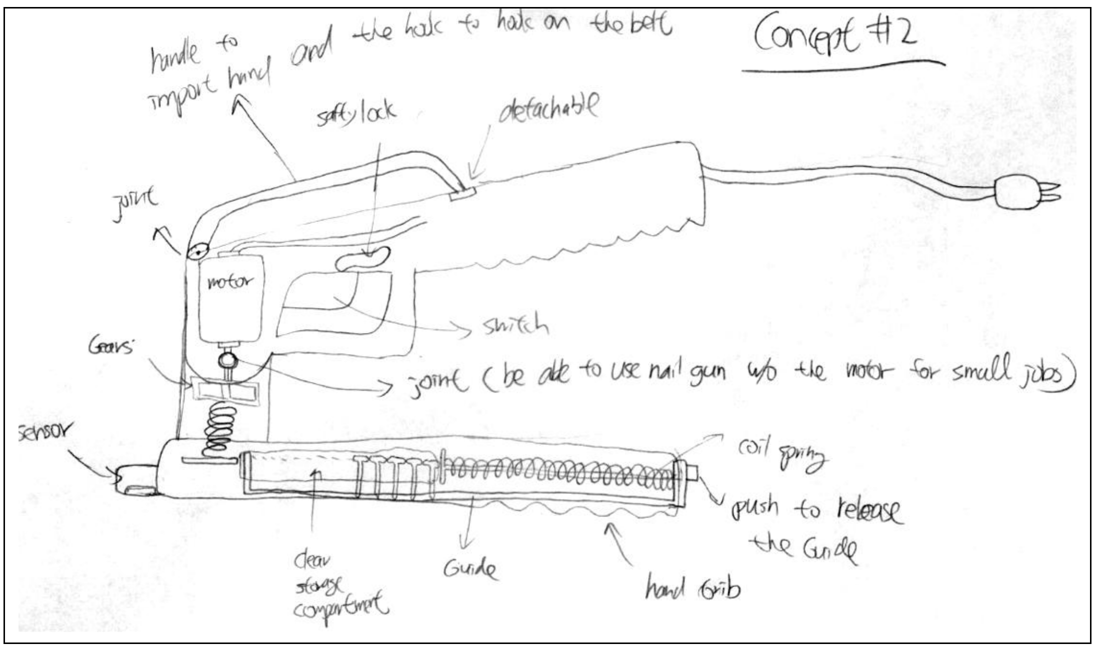


Figure 15 Geometric Layout – Control Group

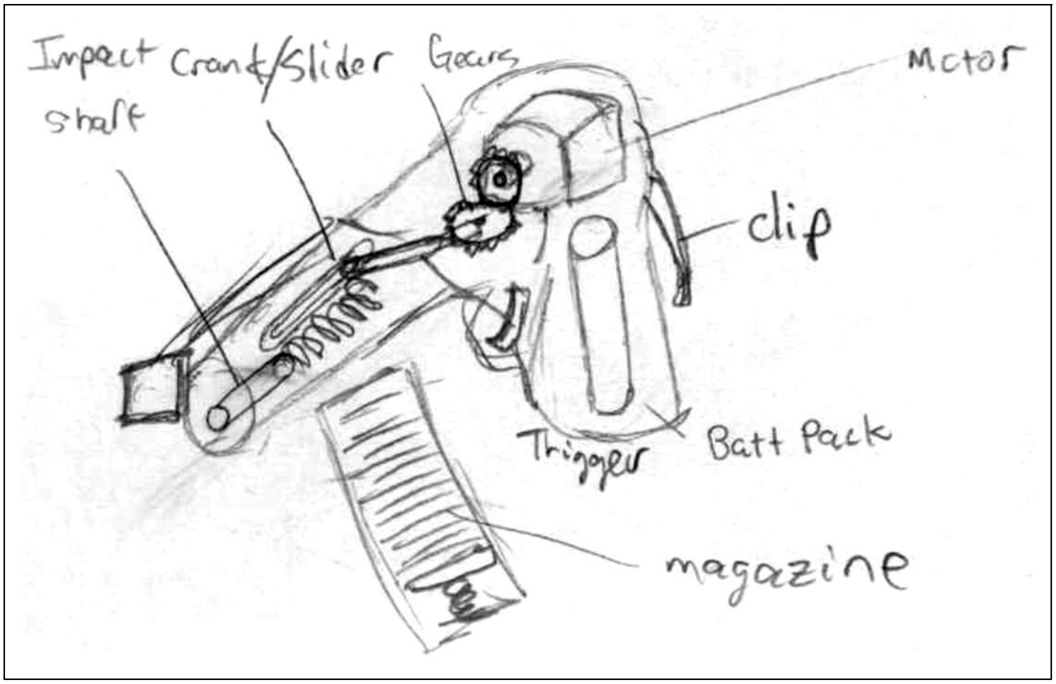


Figure 16 Geometric layout – Control Group

The results are evaluated according to the three metrics: quantity, quality, and method efficiency. Quantity is defined as simply the number of alternative concepts generated. Quality is defined as the worthiness of the concept with respect to customer needs. Method efficiency attempts to capture the "bang to buck" ratio of implementing the methods. Specifically, if one team generates twice as many solutions as another, then the amount of effort expended per solution varies between the two groups. The method efficiency measure is defined as the quality of solutions per the percent time allocated to each solution. If one makes a reasonable assumption that the time allocated to each concept is the total time divided by the number of solutions, then the percentage of time allocated to each concept is (1/quantity). Therefore the method efficiency metric is defined as (quantity)*(quality). Results from the nail gun experiment are given in Table 10.

Table 10 Results from the nail gun design assignment

	TEAM	Quantity	Quality (Q) 1	2	3	Ave Q	Method Efficiency (M.E.) 1	2	3	M.E. Ave
CONTROL	1	6	5.0	3.8	5.7	4.8	30.0	22.8	34.2	29.0
	2	1	5.0	5.0	7.0	5.7	5.0	5.0	7.0	5.7
	3	3	8.3	6.0	8.0	7.4	25.0	18.0	24.0	22.3
	4	2	6.7	6.8	6.0	6.5	13.3	13.5	12.0	12.9
	5	2	5.0	7.5	9.0	7.2	10.0	15.0	18.0	14.3
	6	2	8.3	8.3	8.0	8.2	16.7	16.5	16.0	16.4
	7	2	8.3	8.0	10.0	8.8	16.7	16.0	20.0	17.6
MEAN		2.7	6.4	6.2	7.3	6.6	16.7	15.1	18.5	16.8
		Quantity	1	2	3	**Ave Q**	1	2	3	**M.E. Ave**
EXPERIMENTAL	8	5	6.7	4.4	4.4	5.2	33.3	22.0	22.0	25.8
	9	6	3.3	2.2	4.6	3.4	20.0	13.2	27.6	20.3
	10	8	6.7	3.5	4.9	5.0	53.3	28.0	39.2	40.2
	11	5	5.0	2.2	5.0	4.1	25.0	11.0	25.0	20.3
	12	5	3.3	2.6	5.0	3.6	16.7	13.0	25.0	18.2
	13	5	8.3	7.3	5.2	6.9	41.7	36.5	26.0	34.7
	14	2	10.0	6.0	9.5	8.5	20.0	12.0	19.0	17.0
MEAN		4.3	6.7	4.5	5.5	5.2	30.0	19.4	26.3	25.2
t-test (%)		**97.1**	**13.3**	**94.8**	**100.0**	**86.0**	**93.8**	**64.1**	**87.1**	**89.9**

Since quality is a relatively subjective factor, three people judged the results according to quality on a scale of 1 to 10. The results for the quality of solutions are shown under the “1, 2, 3” headings which indicate the three people evaluating this metric. An average quality is also given as the mean average of these three ratings. Note that in this first experiment, the graders were not blind to the control and experimental groups.

The data is compared in terms of the three metrics directly and by performing an unpaired t-test on the means between the control and experimental groups. This test shows the probability that the means are distinct and as indicated in Table 10, quite high probabilities are found. Clearly, there is high confidence that the proposed method generates a larger number of alternative concepts than the control method. The quality of solutions varies considerably depending on the evaluator most likely because judging designs is quite subjective. However, the control group does exhibit a higher overall quality probably because teams in those groups generally spent more time per concept solution. In terms of method efficiency, the results indicate that the new method shows improvement over the representative conventional technique. Figures 17 through 19 show the same results of the three metrics graphically as a function of each team in the study. Figure 17 visually shows that the experimental group overall produced a greater number of solutions. As one can see from Figure 18, the quality of solutions produced by the control group is generally higher. However, Figure 19 shows that the experimental group demonstrated a higher level of efficiency in developing design solutions.

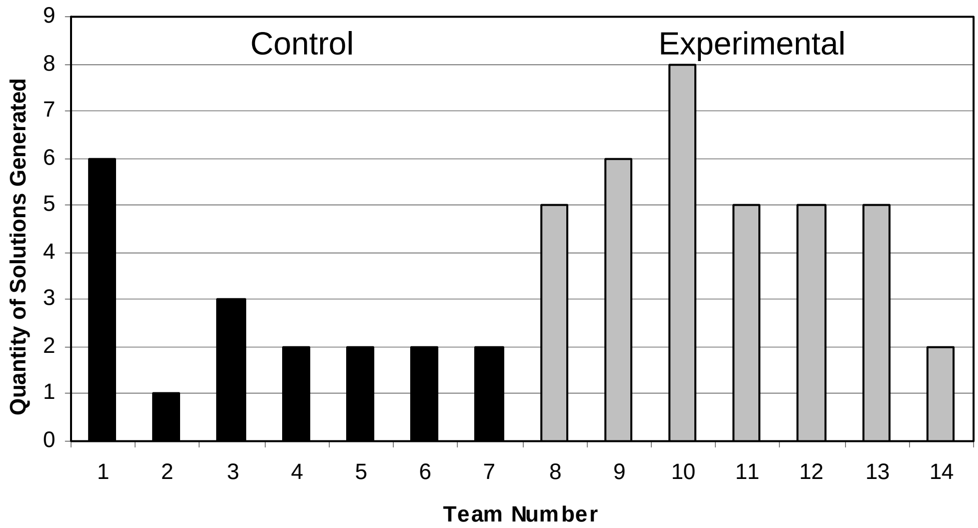


Figure 17 Comparison of solution quantity between test groups

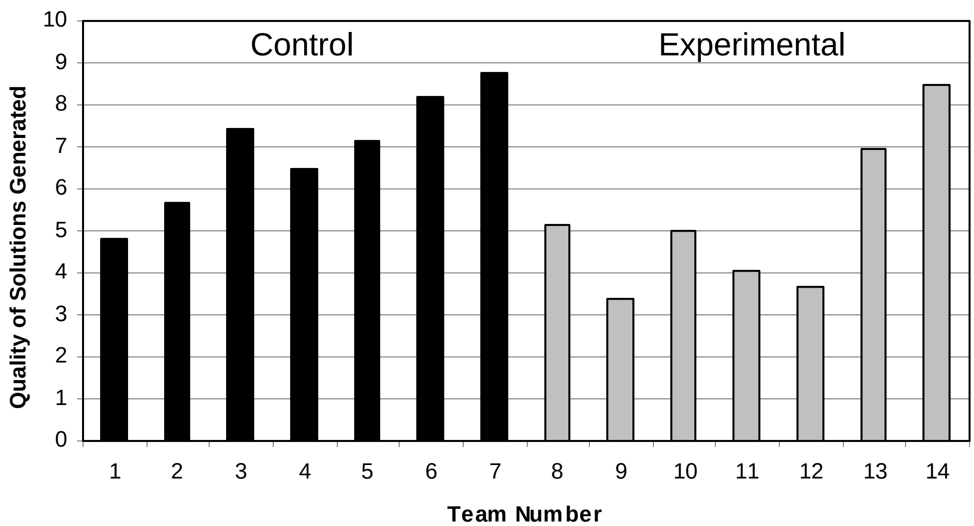


Figure 18 Comparison of mean solution quality

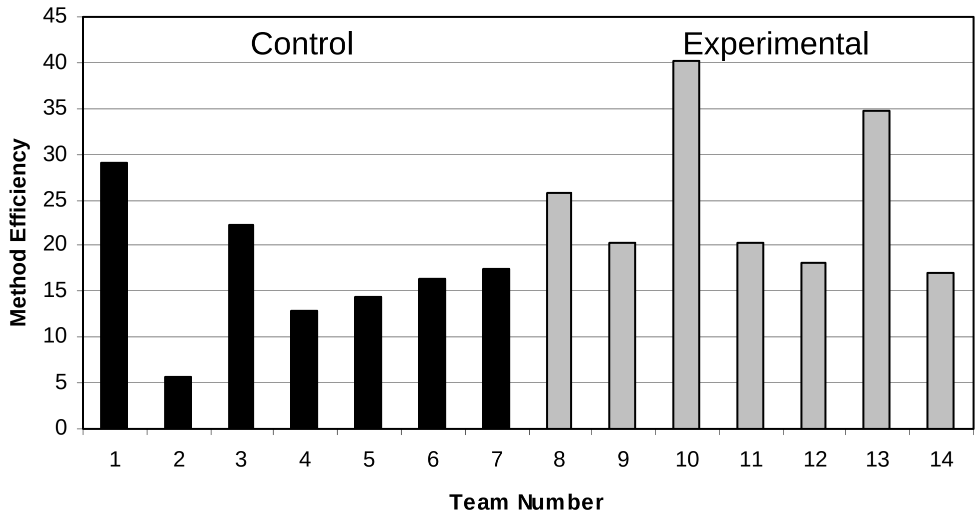


Figure 19 Comparison of mean method efficiency

Based on the above results, the method is clearly useful relative to the Ulrich and Eppinger method in terms of the quantity of solutions generated and the efficiency with which those solutions are derived. Given the controlled conditions of the experiments, the variation between control and experimental groups is attributed to the difference in the two design approaches. One potential source of error that may tend to negate this assertion is the variability with respect to rigorously following method procedure among the design teams. Both groups exhibited some deviation from procedure probably due to a lack of extensive practice with either method. Additionally, the composition of the teams between the two groups may differ somewhat with respect to designer skill level and experience. Given this preliminary study with only seven teams involved from each group, the results provide initial evidence that the representation is useful. A second experiment is performed to further evaluate representation effectiveness.

4.2 Experiment 2

Freshman engineering students from the University of Missouri-Rolla participated in the second experiment where they were divided into three groups. Two person teams were formed within each group. In addition to the experimental technique and Ulrich and Eppinger’s method, a third group was only given a morphological matrix and no architecture technique for developing concept variants. Group make-up is shown in Table 11. A description of a design problem to create a better mouse trap is given to all three groups and is presented in terms of the same information as the first experiment: customer needs, black box, functional model, and morphological matrix.

Table 11 Results from the nail gun design assignment

Group	Method Used	No. of Teams
Control 1	No method	17
Control 2	Ulrich & Eppinger's technique	18
Experimental	Presented in this paper	18

Evaluation metrics for the second experiment differ slightly from the first. Instead of judging quality as a lumped metric, each concept was evaluated according to three measures: feasibility, originality, and detail. Results from this second experiment were evaluated by averaging the ratings as judged by several graduate engineering students at the University of Texas at Austin (a different institution from where the experiment was run) who were blind to the knowledge of which concepts were associated with a given test group. Based on the results, it is clear that the student performance of the experimental group with respect to generating feasible and detailed solutions was better than both control groups. A t-test on the data shows no statistical difference between any groups in terms of originality of solution. However, the same test verifies a significant difference between experimental and both control groups in terms of detail and feasibility of solutions. Figure 20 illustrates the results and Table 12 shows the probability that the means between the test groups are distinct.

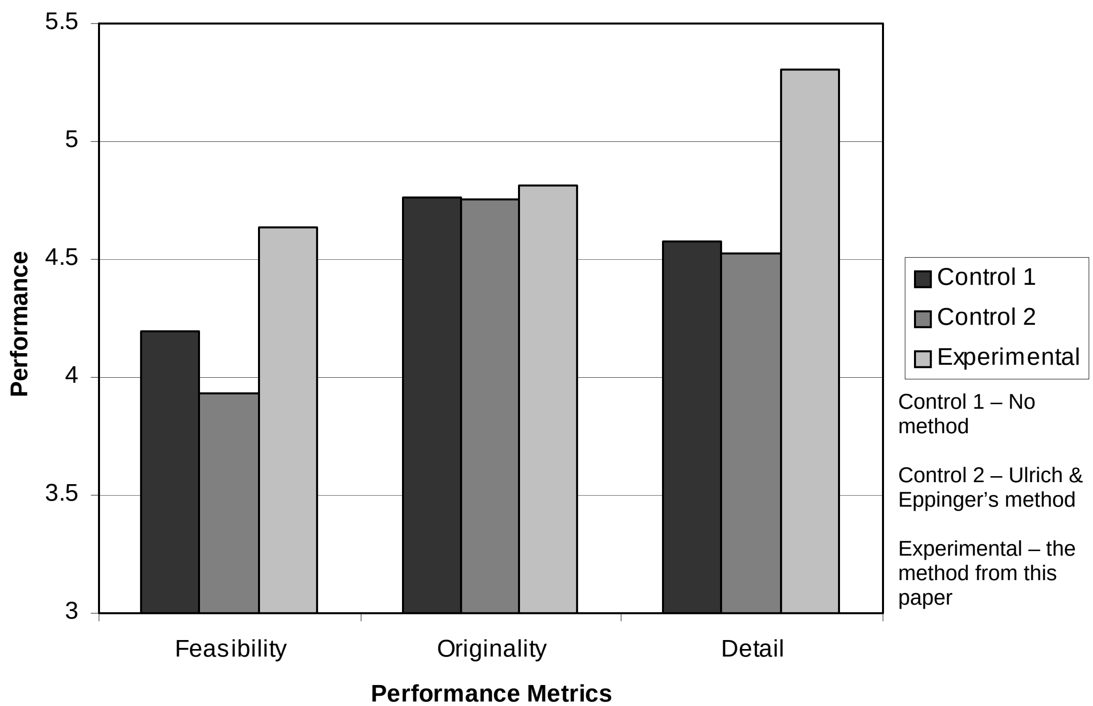


Figure 20 Experiment 2 results

Table 12 Probability of distinct results in experiment 2

	Feasibility	Originality	Detail
Comparative Groups	t-test (%)	t-test (%)	t-test (%)
Experimental / Control 1	89	20	97
Experimental / Control 2	98	19	97
Control 1 and Control 2	62	2	15

Comparisons among the three groups in terms of quantity, overall quality, and method efficiency showed only minor differences which, according to a t-test, was found to be within the noise of the comparison. Table 13 provides the results of experiment 2 with respect to these measures. In this case, overall quality is found as the sum of the feasibility, originality, and detail measures. In experiment two, the information afforded by the three metrics of quality seem to individually offer a more insightful view of representation performance than the overall quality measure used in evaluating the first experiment. Clearly, the students armed with the experimental method presented in this paper produced designs in greater detail and feasibility to those of the control group. Furthermore, the structured method dispels the notion that such rigorous approaches thwart creativity as the measure of originality is not significantly different among the three methods.

Table 13 Additional results from experiment 2

Test Group	Quantity	Overall Quality	Method Efficiency
Control 1	5.5	13.5	74.4
Control 2	5.1	13.2	66.8
Experimental	4.9	14.8	72.9

5.0 Discussion and Conclusions

This work offers a view of how educators can use a design representation to positively impact the quality of design solutions from both freshman and senior level students. One of the particular difficulties in design, especially in the case of novice engineers, is integrating conceptual ideas into a full concept variant. We know from work based on reverse engineering concepts that students benefit from having a concrete reference that can aid in reflecting and observing potential design avenues (Jensen et al., 2001). Specifically, the "design through redesign" approach relies on a physical artifact, the original product, for the designer to observe and consider potential changes. The representation in this paper is analogous as it implements an abstraction of the design to facilitate designer observation and reflection. By using this representation, the students are able to begin with known information and proceed forward in an incremental manner rather than a single jump from function to form. We expect, and the experiments support, that students can more effectively design with the representation than without it.

Results from the first experiment are very encouraging in terms of demonstrating a high level of efficiency with the proposed technique. However, the fact that the same results were not evidenced in the second experiment raises some questions about both representation performance and the method of testing the representation. There are potentially many arguments for reconciling this discrepancy although the reason will probably not be clear until additional repeated experiments indicate the effects taking place. Possible suspects for the discrepancy include an inherent different performance level of the seniors and freshman. Perhaps the difference in design problems between the two groups also played a role. At this point it is best that the reader simply be aware of the differences and to also note the additional information assessed in the second experiment.

Instead of simply measuring overall quality, the second experiment considered feasibility, originality, and detail of solution. Given the sequence of steps in the representation development which call for a considerable amount of detail, it is not surprising that the detail of the solutions developed with the proposed method is higher. The high level of feasibility exhibited with the experimental group is consistent with the expected likelihood that it is beneficial to provide the designer with a reference to observe, consider, and develop potential design solutions. In this case, the advantage takes the form of more feasible solutions. Interestingly, there was little difference in the originality of solutions among all three groups. This suggests that fortunately, the proposed representation does not hinder creativity but maintains a reasonable level of openness to novel ideas. Additionally, one clear benefit of the representation is the relatively short learning curve required for suitable execution.

The main contribution of this work is in demonstrating that students exhibit improved performance in developing concept variants when using a representation that progresses systematically and incrementally from known information to full concepts. The representation presented in this paper is one solution that seems to be promising although it is not clear what type of representation is most effective relative to the complete set of potential abstractions and design languages. In the psychology literature it is noted that people sometimes perform very well with incomplete models and representations (Markman 1999). Perhaps this is true for design representations as well and perhaps we should explore the effect of different representations on the performance of designers in order to find a suitable threshold between complete and incomplete representations. Future work might seek a representation that is robust in the sense of performing well across the spectrum of designers and design problems. No doubt there is much work to be done and this is only with respect to that stage of architecture design or, somewhat more broadly, conceptual design. Embodiment design may indirectly benefit from this work given the similarities in the processes of architecture design and embodiment design. These similarities suggest that an improved method for embodiment design might utilize similar design representations as those presented in this work. While embodiment design is one area of opportunity leading from this research, the main foundation developed in this study is in establishing that a highly creative and nonlinear task like architecture design can be supported effectively with an incremental approach through a design representation.

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