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# An Experimental Investigation of the Effect of Functional Ordering on Morphological Chart Exploration

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# AN EXPERIMENTAL INVESTIGATION OF THE EFFECT OF FUNCTIONAL ORDERING ON MORPHOLOGICAL CHART EXPLORATION

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ABSTRACT

Morphological Charts are tools used to systematically explore the design solution space. It consists of a table with first column listing the functions that define the design problem and subsequent columns enumerating means (solutions) to achieving each function. Combining one means for each function produces an integrated design concept solution. The potential number of integrated design concept solutions which can be generated from a morphological chart increase when adding rows or columns. However, limited guidelines are available to aid in curbing this combinatorial explosion while identifying high quality concepts. In addition, instructions to systematically arrange functions and means in the chart are missing.

In this research, an experiment is conducted to understand how morphological charts are explored and what impact functional arrangement has on it. The motive behind this experiment is to develop guidelines and recommendations which can help designers in generating novel high-quality concepts. The experiment consisted of two problem statements, each with five different functional arrangements: 1) Most to Least Important Function, 2) Least to Most Important Function, 3) Input to Output Function, 4) Output to Input Function, and 5) Random. Sixty-seven junior mechanical engineering students were provided a prepopulated morphological chart and asked to generate integrated design concepts. The generated concepts were analyzed to determine how frequently a given means is selected, how much of the chart is explored, what is the sequence of exploration, and finally the influence of function ordering on them. Experimental results indicate a selection frequency of 27-35% from column one, 17-26% from column two, 15-21% from

column three, 12-19% from column four, and 8-18% from column five. Hence, results suggest a tendency to focus more on the initial columns of the morphological chart. The effect of function ordering on selection frequency along rows seems insubstantial, though further experiments are necessary for validation. Results also suggest lower chances of design space exploration with both Input-to-Output and Output-to-Input functional arrangements.

## DEDICATION

I would like to dedicate this thesis to my family, whose support and wisdom has shaped my personality. Every achievement is a result of the guidance and freedom they gave to explore my interests.

## ACKNOWLEDGEMENT

I would like to thank my advisor Dr. Joshua D. Summers for his support and guidance in completing this research. His patience, work ethic and constructive criticism has improved me as a researcher and accelerated my professional development. I would like to thank my committee members, Dr. Mocko and Dr. Paredis, for their time and assistance in reviewing this work. I would also like to thank CEDAR lab members, who have helped me conduct experiments, document this research, and engage in productive conversations. The quality time spent with everyone at Clemson has made this journey a memorable experience.

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# Chapter One
# MORPHOLOGICAL CHARTS: USAGE AND GUIDELINES

The purpose of this research is to contribute towards effective representation and exploration of morphological charts (morph charts). An experiment is conducted to investigate the effect of function ordering on frequency, coverage and sequence of means generation within morph charts. This chapter will provide information on the following morph chart facets

- What are Morph Charts?
- Where are Morph Charts used?
- How to use Morph Charts?

## 1.1 What are Morph Charts?

Morph Charts are design tools used to systematically combine solution means to generate large number of integrated design concept solutions (Dym and Little 2000). Originally proposed by Zwicky in (Zwicky 1967), a morph chart, also known as menu matrix (Niku 2008), or concept combination table (Ulrich and Eppinger 2000), is an organization of the functions and the corresponding solution means in a tabular form. A sample morph chart for four functions of a burrito-folding machine is shown in Table 1. In this example, the functions are listed in a column in the left side of the table and solution means to the right of each function. In this thesis, the solutions for specific functions are defined as "*means*", though different terms such as working principles (Pahl, Wallace, and Blessing 2007) or design parameters (Cross 2008) have been used in the literature.

**Table 1: Sample Morph Chart** (Gregory Smith et al. 2012)

| Functions | Means | | |
|---|---|---|---|
| Receive Tortilla | Table | Locating Plate | Tortilla Stack |
| Receive Filling | Hopper | Packets | Tube |
| Combine Materials | Filling on Tortilla | Tortilla on Filling | Synchronous Dispensing |
| Fold Tortilla | Spatula | Hinged Surface | Rolling Tube |

An integrated design concept solution is formed by combining one means selected for each function. As an example, an integrated design concept solution would include Table-Packets-Tortilla on Filling-Rolling Tube, shown by blue lines and dots in Table 1. Another integrated design concept example of Tortilla Stack-Hopper-Filling on Tortilla-Spatula is shown by red lines and dots. The possible number of combinations in the chart represents the size of the chart; essentially measuring the size of the design space. For example, the given morph chart of a burrito-folding machine has a size of 3x3x3x3 = $3^4$ = 81. Adding one row (one function with three means) to the morph chart increases its size exponentially to $3^5$ = 243, whereas adding one column (one means to each function) to the morph chart increases its size to $4^4$ = 256. Such a radical change in the theoretically possible number of combinations limits the capability to explore the design space efficiently, a concern frequently expressed in literature (Dym and Little 2000; Cross 2008; Ölvander, Lundén, and Gavel 2009).

## 1.2 Where are Morph Charts Used?

Conceptual design is often considered the most important phase in the engineering design process. Such a viewpoint exists due to its notable influence on product cost, function, performance and customer need satisfaction (Kurtoglu, Swantner, and Campbell 2010; Shang, Huang, and Zhang 2009; W. Hsu and Woon 1998). The phase of conceptual design begins once the design problem statement is defined, and the requirements are translated into high-level functions. These high-level functions are then divided into various lower-level functions through the process of functional decomposition. The next step involves generating means to achieve each function individually with the help of idea generation methods such as brainstorming (Dym and Little 2000), Method 6-3-5 (Pahl, Wallace, and Blessing 2007) or collaborative sketching (C-sketch) (SHAH et al. 2001). The generated means are selected and combined on the basis of compatibility to form a set of integrated design concepts. Finally, the solution set is further reduced through evaluation and the remaining principal solutions are explored in the embodiment and detail design phase (Pahl, Wallace, and Blessing 2007).

Morph chart is a form of idea generation method which supports means generation along with the combinatorial aspects to form integrated design concepts. It is classified as an intuitive idea generation method, and can be used either individually or in a group (Shah 1998). Figure 1 illustrates the conceptual design phase and the tools used to support each step. A function structure is a block diagram used to represent the functional decomposition process using functions and input-output flows (Pahl, Wallace, and Blessing 2007).

Decision matrices are used to compare and rank design concepts against a set of evaluation criteria (Ulrich and Eppinger 2000).

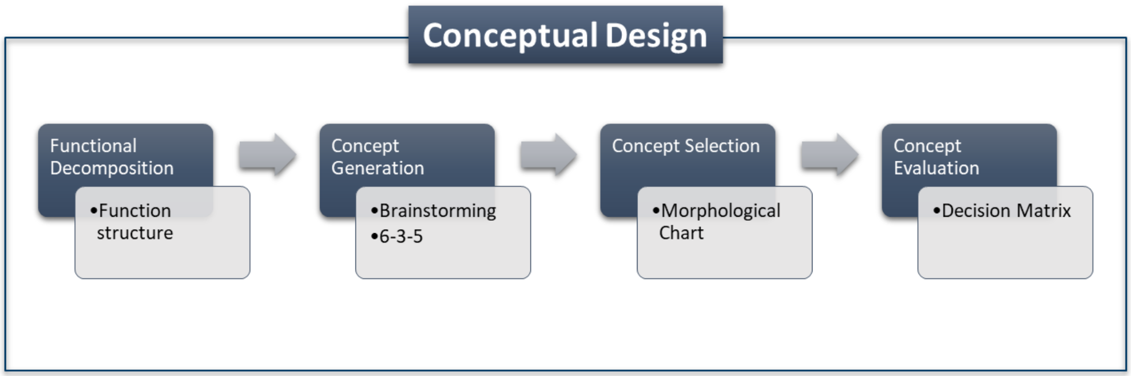



**Figure 1: Conceptual Design Process**

1.3 <u>How to use Morph Charts?</u>

Design tools are often accompanied with instructions on how to use them. These instructions help to ensure that the tool has value with the ultimate purpose of aiding the designer. For example, when using an ideation tool such as brainstorming to search for novel and high-quality design concepts, it is advised not to criticize any sort of idea during the concept generation process, so as to ensure a free flow of ideas (Dym and Little 2000). When using decision making tools such as use-value analysis to evaluate design concepts, requirements-driven evaluation criteria is chosen and ranked, in order to satisfy the constraints and improve decision making (Pahl, Wallace, and Blessing 2007).

Morph charts are decision-making tools which contain guidelines. However, these guidelines are incomplete in addressing the range of possible choices present to the designer or lack sufficient experimental evidence to validate their claims. Despite being prevalent in popular textbooks (Pahl, Wallace, and Blessing 2007; Ulrich and Eppinger

2000; Niku 2008; Cross 2008; Dym and Little 2000; Voland 2003; Adams 1990) and design research (Gregory Smith et al. 2012; Richardson III, Summers, and Mocko 2011; T. Ritchey 2006; A. de W. and T. Ritchey 2007; Gero, Jiang, and Williams 2012a; Kannengiesser, Williams, and Gero 2013), morph charts lack a standardized method for representing and exploring. It is critical to know how morph chart guidelines impact the designer and the decision-making process.

### 1.3.1 Functions in Morph Charts

To construct a morph chart, the first step is to compile a list of different functions or goals that should be achieved. All functions should be expressed at the same level of detail (Cross 2008). Expressing functions at different detail levels will only produce layers of the same morph chart at a varied hierarchical level (George, Renu, and Mocko 2013). However, the guidelines on listing the number of functions is often vague, such as "*list of functions or features should be of a reasonable, manageable size*" (Dym and Little 2000). Though some textbooks give a range of four to eight functions (Cross 2008), no concrete evidence is present to bolster the claim. To address this ambiguity in representation size, an experiment was conducted by researchers to study how the number of functions and means affect the quality of integrated design concept solutions (Gregory Smith et al. 2012). The outcome of the study shows that the quality of concepts was higher in the chart with more means than functions, in comparison to its opposite. The findings also suggest that adding functions to the morph chart did not contribute significantly towards concept quality. Figure 2 provides a graphical summary of the experimental study results.

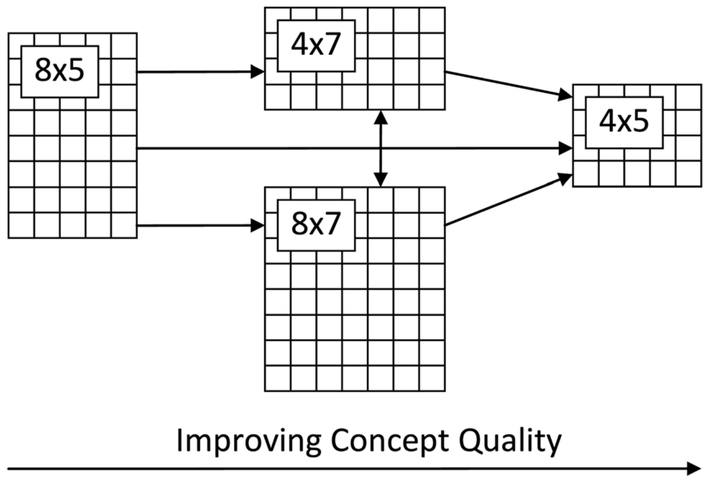



**Figure 2: Effect of Morph Chart size and shape on Concept Quality**
(Gregory Smith et al. 2012)

In another such study, researchers have analyzed how the functional representation in a morph chart affects the novelty and variety of generated means (Richardson III, Summers, and Mocko 2011). The results of this study indicate that the novelty and variety of generated means is not dependent on the experimented forms of function representation (function lists and function structure). However, the order of listing functions in the morph chart was not studied. A common organization of a morph chart after listing functions is given in Table 2. The remaining morph chart is filled with means as detailed in next section.

**Table 2: Morph Chart with Functions**

| **Functions** | |
|---|---|
| $F_1$ | |
| $F_2$ | |
| $F_3$ | |
| … | |
| $F_N$ | |

### 1.3.2 Means in Morph Charts

The next step in constructing the chart is to list possible means for each function at the same level of abstraction. It is not necessary to have the same number of functions and means in a morph chart. Again, specific guidelines on how to represent the means is wanting. Different representations of the means in the cells can be found in the literature, such as textual (Ulrich and Eppinger 2000; Voland 2003), graphical (L. H. Hsu and Chen 2006; Lo, Tseng, and Chu 2010), or hybrid (Dym and Little 2000; Cross 2008), but no consensus exists on which is the most suitable method. The sequence to fill means, either row-wise or column-wise, is also not addressed in the literature. The process of filling means may involve using a dedicated method (brainstorming, Method 6-3-5, C-Sketch) or using the morph chart itself. Even though the experiment in this research solely concerns concept selection using morph charts, morph charts have been employed for concept generation activities as well (Gero, Jiang, and Williams 2012a; Kannengiesser, Williams, and Gero 2013). Currently, no guidelines exist to prescribe the use of any single concept generation technique to obtain means for filling the morph chart.

Table 3 gives the completed morph chart after listing means in front of each specified function, so the means for functions $F_1$ are $M_{1.1}$, $M_{1.2}$ … $M_{1.m}$, the means for function $F_2$ are $M_{2.1}$, $M_{2.2}$ … $M_{2.m}$, and so on. The given morph chart is rectangular (same number of means for each function), although, this is not an explicit requirement in constructing a morph chart. Each function can have a different number of means associated with it. The size of the given morph chart is $n$ x $m$, where $n$ is the number of functions identified and $m$ is the number of means for each function.

**Table 3: Morph Chart with Functions and Means**

| Functions | Means | | | | |
|---|---|---|---|---|---|
| $F_1$ | $M_{1.1}$ | $M_{1.2}$ | $M_{1.3}$ | … | $M_{1.m}$ |
| $F_2$ | $M_{2.1}$ | $M_{2.2}$ | $M_{2.3}$ | … | $M_{2.m}$ |
| $F_3$ | $M_{3.1}$ | $M_{3.2}$ | $M_{3.3}$ | … | $M_{3.m}$ |
| … | … | … | … | … | … |
| $F_N$ | $M_{5.1}$ | $M_{5.2}$ | $M_{5.3}$ | … | $M_{n.m}$ |

1.3.3 Exploring Morph Charts

To begin exploring the chart, a common practice is to first prune the initial chart for discarding infeasible means. The incompatibility between means of different functions is also accounted for, in order to potentially reduce the number of concept solutions. One such pruning approach commonly suggested is the compatibility matrix (Pahl, Wallace, and Blessing 2007). A compatibility matrix is used to evaluate the suitability of combining means of one function with another. Table 4 provides the compatibility matrix for two functions taken from Table 1. The three states ☑, ☒ and ? depicted in the compatibility matrix indicate that means are compatible, means are not compatible, and means may be compatible, respectively. For example, a tube selected to "receive filling" allows dispensing "filling on tortilla" and thus the means are compatible. However, a tube selected to "receive filling" interferes with wrapping the "tortilla on filling" and thus means are not compatible. For the given morph chart in Table 1, the total number of compatibility matrices required is 6 and the number of compatibility checks required is 6x3x3 = 54. It is

clear that the high number of compatibility evaluations required make this process tedious, and as a result, impede manual exploration of the morph chart in a complete manner.

**Table 4: Sample Compatibility Matrix** (Gregory Smith et al. 2012)

| | | Receive Filling | | |
|---|---|---|---|---|
| | | Hopper | Packet | Tube |
| **Combine Materials** | Filling on Tortilla | ☑ | ☑ | ☑ |
| | Tortilla on Filling | ☑ | ? | ☒ |
| | Synchronous Dispensing | ☒ | ? | ☑ |

The experiment conducted in this research is another effort aimed at methodically investigating the representation and exploration of morph charts. The objective is to find out what effect different functional arrangements have on selection of means, in terms of frequency, coverage, and exploration sequence. The experiment consisted of two design problem statements and a prepopulated morph chart with five different functional arrangements for each problem. The problems chosen for this study are: 1) Design of an Automatic Ironing Device, and 2) Design of an Automatic Recycling Sorter, expressed in more detail in Chapter 3. The five functional arrangements for each individual morph chart are 1) Most to Least Important Function, 2) Least to Most Important Function, 3) Input to Output Function, 4) Output to Input Function, and 5) Random.

Similar studies have been conducted in the past and have echoed the need for more specific guidelines in using morph charts (Gregory Smith et al. 2012; Richardson III, Summers, and Mocko 2011). The developed guidelines will aid designers in manual

construction and usage of morph charts. The insights obtained from this research will also contribute towards design automation. Before automated systems can be deployed to aid designers in concept generation and evaluation, experiments like this will help to understand human design decision-making and underline its shortcomings. A gap exists in the current literature in instructing the arrangement of functions within morph charts. Hence, the experiment conducted in this study will work towards filling the gap.

# Chapter Two
# MORPHOLOGICAL CHARTS: MOTIVATION AND LITERATURE REVIEW

The previous chapter summarized morph charts and their context of usage within engineering design. Morph charts are widely recognized tools in engineering design applications and research. Morph charts follow the approach of decomposing a main task into smaller manageable sub-tasks for individual solution finding, a technique central to problem solving in general. This chapter will summarize current literature on morph charts (pertinent to engineering design research), and consequently, elucidate the importance of studying morph charts.

## 2.1 Morph Chart Literature

A morph chart is a tool which encompasses a large solution space qualitatively. The list of functions identified for the design problem and the means (solutions) to realize each function, together represented in a table connect the problem space with the solution space. Hence, morph charts offer a concise delineation of the design problem and its solution. Owing to this compactness, morph charts have been used, modified and researched extensively to solve engineering design problems. Figure 3 provides a graphical structure of literature concerning morph charts, in the context of engineering design application and research. The underlying research theme in the sub-categories of Manual and Automated is explained in the following sub-sections respectively.

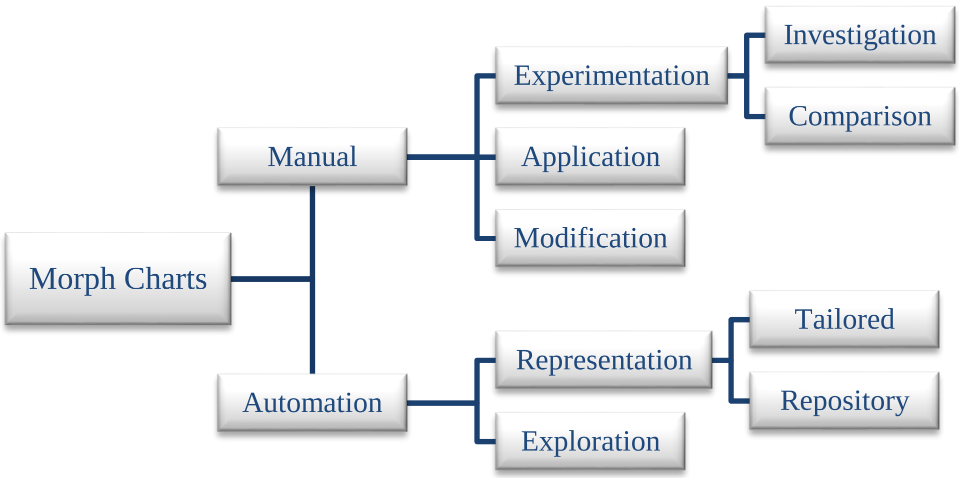



**Figure 3: Morph Chart Literature Map**

2.1.1 Manual

Within the manual category, researchers have exploited morph charts in a number of different ways. Experiments have been conducted with morph charts either to investigate their characteristics, or compare them to other idea generation techniques. Examples of the former sub-category include a study by Smith et al. (Gregory Smith et al. 2012), which investigates the effect of morph chart size and shape on concept generation, and a study by Richardson et al. (Richardson III, Summers, and Mocko 2011), which focuses on the effect of function representation within morph charts on design concepts' novelty and quality. Within the sub-category of comparison, a study (Gero, Jiang, and Williams 2012a) experimentally compares the differences in design cognition of students while using three different concept generation techniques, namely morph charts, brainstorming and TRIZ. Another such study (Kannengiesser, Williams, and Gero 2013) identifies the similarities in

concept generation between morph charts, brainstorming and TRIZ, using the function-behavior-structure (FBS) protocol. The experimental research study in this thesis falls under the sub-category of investigation. Various studies exist that depict the usage of morph charts for different engineering applications, such as multidisciplinary building design (Zeiler and Savanovic 2009), automotive parking brake lever (Mansor et al. 2014) or modular system design (Levin 2009; Levin 2016). Another subset of studies modifies the morph chart to suit their particular application demands. Examples of such studies include the Geometric Integration Concept Generation Chart (Teegavarapu et al. 2009) for design of low-gap automotive body panels, and options matrices for aiding concept generation in general (George, Renu, and Mocko 2013).

### 2.1.2 Automated

Several approaches have emerged addressing the challenge of using morph charts in automatic representation and exploration of the design space. One of the early attempts in representation involved the development of a web-based morph chart analysis method to support collaborative product development (Huang and Mak 1999). A prototype system is introduced capable of functional analysis, concept generation using morph charts, and concept assessment using Pugh's selection matrix. More recently (C. R. Bryant et al. 2007), Bryant et. al. present an interactive morphological matrix, a product of preliminary research efforts: an automated morphological search (M. R. Bohm, Vucovich, and Stone 2005) and a computational concept generator (C. Bryant et al. 2006). The automated morphological search draws knowledge stored in a web-based design repository to populate morph charts (M. Bohm, Stone, and Szykman 2005). The computational concept generator accepts user-

input high level functional description of the product, and generates a list of filtered and ranked design concept variants. This is achieved by first converting the functional description to a matrix of inter-functional relationships. Finally, solutions are generated using the function-component mapping and component-component compatibility stored in the design repository. The interactive morphological search is a combination of these two methods. While these approaches provide web-based solution accessibility and connectivity information, the limited amount of design knowledge in the repository precludes their widespread implementation. Also, the large set of solutions produced by the automated concept generator poses a significant hurdle for evaluation.

For automation in exploring solutions, Tiwari et al. (Tiwari et al. 2009) use a Genetic Algorithm (GA) based search and optimization to automatically explore morph charts. In this approach, the problem of obtaining solutions (combinations of means) is formulated as a combinatorial multi-objective optimization problem. Hence, optimum values of each criterion can be obtained to give overall high-performance solutions. A similar GA based approach was taken by Barnum and Mattson in (Barnum and Mattson 2009). Olvander et al. (Ölvander, Lundén, and Gavel 2009) also introduce a formal mathematical framework for quantification of morphological matrix, but instead use a Tabu search based optimization strategy. The positive aspects of such an approach include less computational complexity, active designer input, quick feedback to designer, and ability to accommodate input variations. On the contrary, the downsides include considerable designer effort, inability to quantify non-behavioral characteristics (i.e., aesthetics), a need for inter-designer input consistency, and the likelihood of ending in local minima. To

address the problem of inconsistent and subjective inputs, Ma et al. (Ma et al. 2017) have developed a non-deterministic morphological matrix based on fuzzy multi-objective optimization model. Poppa et al. (Poppa, Stone, and Orsborn 2010) develop a clustering approach using Principal Component Analysis (PCA), to explore the automated concept generator output and alleviate the aforementioned limitation of unmanageable solution set.

Some researchers have focused on representation and exploration simultaneously. Kang and Tang (Kang and Tang 2013) present a hybrid of the approaches in (C. R. Bryant et al. 2007) and (Tiwari et al. 2009). A morph chart is generated by a self-established repository containing a functional basis, function-component matrix (FCM), and Design Structure Matrix (DSM), whose exploration is guided by an ant colony optimization (ACO) algorithm. Another such approach is given in (Chen et al. 2006), but is specifically aimed at mechanism synthesis. For representation, a catalogue-based knowledge base is created along with an improved morphological matrix, known as motional function matrix (MFM). The exploration is achieved via a performance constraint verification approach that curbs the combinatorial explosion.

Table 5 gives a summary of the research conducted on morph charts in chronological order. While other approaches for automation using graph grammars (C. R. Bryant et al. 2005; Kurtoglu, Swantner, and Campbell 2010) or functional surface (Shang, Huang, and Zhang 2009) exist in literature, these approaches are not directly tied to morph charts and are hence not included in the summary table. Similarly, studies that do not concern engineering design or its applications are also excluded.

**Table 5: Summary of Morph Chart Research**

| Citation | Type of Study | Approach | Application/Focus Area |
|---|---|---|---|
| (W. Hsu and Woon 1998) | Review | | Conceptual Design |
| (Huang and Mak 1999) | AR | Web-based MC | |
| (Strawbridge, McAdams, and Stone 2002) | AR | DR | |
| (M. R. Bohm, Stone, and Szykman 2005) | AR | DR | |
| (L. H. Hsu and Chen 2006) | M | Geometric CAD MC | |
| (C. Bryant et al. 2006) | AR | FCM & DSM | |
| (Chen et al. 2006) | ARE | Motion Functional Matrix & Catalogue | |
| (C. R. Bryant et al. 2007) | AR | DR, FCM & DSM | |
| (Tinsley et al. 2007) | AR | | Biomimetic Design |
| (Zeiler and Savanovic 2009) | A | | Building Design |
| (Barnum and Mattson 2009) | AE | GA | |
| (Ölvander, Lundén, and Gavel 2009) | AE | Tabu Search | |
| (Tiwari et al. 2009) | AE | GA | |
| (Teegavarapu et al. 2009) | M | Concept Generation Chart | Automotive Body Panels |
| (Poppa, Stone, and Orsborn 2010) | AE | Clustering | |
| (Lo, Tseng, and Chu 2010) | M | 3D CAD MC | Variant Design |
| (Chakrabarti et al. 2011) | Review | | CAD Design Synthesis |
| (Richardson III, Summers, and Mocko 2011) | I | | Function Representation |
| (Gero, Jiang, and Williams 2012b) | C | | MC vs BS vs TRIZ |
| (G Smith et al. 2012) | I | | MC Size & Shape |
| (Kannengiesser, Williams, and Gero 2013) | C | | MC vs BS vs TRIZ |
| (Kang and Tang 2013) | ARE | DR, FCM, DSM & ACO | |
| (George, Renu, and Mocko 2013) | M | Options Matrices | Concept Generation |
| (Mansor et al. 2014) | A | | Automotive Brake Lever |
| (Park et al. 2015) | AR | Multi-Modal DR | |
| (Dragomir et al. 2016) | C | | MC vs BS |
| (Levin 2016) | A | | Modular Systems |
| (Ma et al. 2017) | AE | | Fuzzy MC |

| | |
|---|---|
| Type of Study: | Prefix A – Automation; AR – Representation; AE – Exploration; ARE – Representation & Exploration; M – Modification; A – Application; I – Investigation; C – Comparison |
| Approach/Application/Focus Area: | MC – Morph Chart; DR – Design Repository; BS – Brainstorming; GA – Genetic Algorithm; ACO – Ant Colony Optimization; FCM – Function Component Matrix; DSM – Design Structure Matrix |

## 2.2 Why Study Morph Charts?

With morph chart literature sufficiently reviewed, the justification for studying them can be provided. First, morph charts form an integral part of major engineering design textbooks (Ulrich and Eppinger 2000; Dym and Little 2000; Cross 2008; Adams 1990; Carryer, Ohline, and Kenny 2011; Buede 2009; Voland 2003), which is symbolical of their significance in the academic community. Second, the scope of morph charts, or more generally known as morphological analysis, is not only limited to engineering design but also extends to disciplines of operations research, management science, architecture, policy planning, technological forecasting, creativity and design theory (T. Ritchey 2006; Mansor et al. 2014; Zeiler and Savanovic 2009; Zeiler 2013; Gogu 2005; Kannengiesser, Williams, and Gero 2013; Johansen 2018; Williams and Bowden 2013; de Fátima Teles and de Sousa 2017). After all, a morph chart can also be viewed as a method of information processing, not restricted to technical problem solving in particular (Pahl, Wallace, and Blessing 2007).

By studying morph charts using experiments, an opportunity exists to develop guidelines which will aid designers in morph chart representation and exploration, leading to high quality concepts. Moreover, the fact that morph charts are used in the conceptual phase to aid decision-making, increases their relative importance as a design tool since previous research suggests that 70% of product life cycle cost is determined during the conceptual design phase (Hoover and Jones 1991).

### 2.2.1 Conceptual Design Automation using Morph Charts

As evidenced by Table 5, a major portion of research on conceptual design automation relies on morph charts. For design knowledge representation, morph charts have been applied in the form of function-component matrix (FCM) and design-structure matrix (DSM). For exploration, researchers focus on combining morph charts with optimization techniques to effectively explore the solution space. Keeping the same goal of effective design space exploration in mind, an experiment is conducted in this thesis to understand morph chart exploration, and investigate the effect of representation. The insights obtained from the experiment will eventually contribute towards the algorithms being developed for automatically exploring the design solution space.

### 2.2.2 Advantages and Limitations

When it comes to manual concept generation and selection, morph charts possess various advantages and disadvantages that dictate their applicability. Some advantages of morph charts include the possibility of identifying novel designs (Cross 2008), conveying a feel of the design problem/space at hand and illustration of unexpected solution pairings. Disadvantages include the unmanageable size of integrated design concepts, high number of infeasible combinations present, and lack of guidelines to aid exploration.

The experiment conducted in this study directly redresses the guideline limitation, which in turn mitigates the effect of previous two limitations. Studying morph charts offers the benefit of systemizing the intuitive aspects of concept generation and selection. After all, majority of the inventions are in essence new ways of combining old bits and pieces

(Adams 1990), and more than 75% of design activities fall under the category of design modification, variant design, or case-based design (Lo, Tseng, and Chu 2010).

# Chapter Three
# EXPERIMENTAL METHOD

The objective in this experiment is to discover how does the relative placement of functions (i.e. representation) within a morph chart influence the generated concepts (i.e. exploration). The experiment consisted of two design problems, each consisting of five different functional arrangements. For each design problem, participants were provided with a morph chart of a particular functional arrangement and asked to generate concepts. The generated concepts were analyzed to identify patterns of exploration, and then the patterns of exploration for each functional arrangement were compared. The analysis of exploration pattern consists of frequency, coverage and sequence of means generation.

Conceptual design automation is a burgeoning focus area within design research. Though researchers have developed algorithms to automatically explore the design space, the credibility of these algorithms in helping design decision-making is in question. Before automated systems can help humans explore the design space efficiently, there is a need to understand which specific areas of human decision-making need improvement and computer support. This philosophy motivates us to explore the current decision-making pattern and ability of novice designers by conducting an experimental study, as detailed in subsequent sections.

## 3.1 Research Question and Hypothesis

The research question explored here is: *How does the location of a function in a morph chart affect the selection of means associated with that function?* It is critical to know how functions and means should be arranged in a morph chart, especially when

dealing with mechanical systems. This is because a sizeable variety of means exist to achieve any given function, and function type varies largely such as convert energy to transmit load, or import solid to actuate energy. To create a computational support tool, one must first understand how people explore morph charts. The hypothesis is: *Designers tend to focus relatively more on initial columns of the morph chart, irrespective of functional order*. In other words, changing the location of a function will not alter the pattern of selection of means specific to that function, however, the pattern is expected to be biased towards the first few columns. The bias in selection is justified as this is how English speakers read (left to right; top to bottom), and partly due to design fixation.

Design fixation is a well-documented phenomena which describes the tendency to employ familiar ideas or means to solve a design problem while ignoring better ones (Jansson and Smith 1991; Linsey et al. 2014). While morph charts are recommended methods to discourage design fixation (Linsey et al. 2014; Crilly 2015), no method exists that can eliminate design fixation entirely. This study will reconcile these seemingly contradictory views. Also, the experiment conducted in this study does not ask participants to develop a morph chart from scratch, rather asks to develop concepts from a prepopulated morph chart.

To answer the research question, an experiment is designed containing two problem statements and five different functional arrangements for each problem. Participants are provided with a prepopulated morph chart and evaluation criteria and asked to generate twenty integrated design concepts. The evaluation criteria were usage cost, reliability, and

ease of use, intended to highlight the most critical design requirements. Generated concepts are analyzed for their frequency, exploration sequence, and chart coverage.

### 3.2 Design Problems

The problems chosen for this study are: 1) Design of an Automatic Ironing Device, and 2) Design of an Automatic Recycling Sorter, as summarized in Table 6. The problems have been used before in a research study (Patel et al. 2016), and the difficulty level did not appear as a challenge for the participants' level of expertise. By choosing such novel problems which do not have an existing solution in the market, an additional variable of previous knowledge or preconceived notion is eliminated. The first factor which influenced the decision to choose these problems was complexity, that is to say that junior level mechanical engineering students should be familiar with the device functions and means, and be able to conceive a solution. Since the experiment was planned during normal class hours, the allotted time of 75 minutes was also taken into account. Other influencing factors include real world significance of design problems, cross-cultural consistency, and domain suitability for undergraduate mechanical engineering students.

**Table 6: Problem Statement Prompts** (Patel et al. 2016)

| **Problem 1: Automatic Clothes Ironing Device** |
|---|
| The world is experiencing an accelerated demand for a more automated and connected workplace, one such example of which is the highly competitive service and hospitality industry. A private hotel owner has identified the need for an automated clothes ironing device to reduce manpower cost while ensuring customer satisfaction. Given below is the Morphological Chart of an automatic clothes ironing device for use in hotels. The purpose of this device is to press wrinkled clothes as obtained from clothes dryer and fold them suitably for the garment type. The functions of the automatic clothes ironing device are listed on the first column followed by the respective means. Your goal is to generate twenty promising concepts from the given morphological chart. Space is provided below for the mention of code for each function (F) and corresponding means (M), for example – F3M5, F2M1, etc. The generated concepts will be evaluated on the basis of usage cost, reliability and ease of use. Please keep these criteria in mind when generating concepts for the given product. |
| **Problem 2: Automatic Recycling Sorter** |
| With environmental degradation on the rise, sustainability is the need of the hour. One step towards a sustainable future is the proper segregation and recycling of waste. Given below is the Morphological Chart of an automatic recycling machine for household use. The purpose of this device is to sort plastic bottles, glass containers, aluminum cans, and tin cans. The sorted material items then need to be compressed and stored in separate containers. The functions of this device are listed on the first column followed by the respective means. Your goal is to generate twenty promising concepts from the given morphological chart. Space is provided below for the mention of code for each function (F) and corresponding means (M), for example – F3M5, F2M1, etc. The generated concepts will be evaluated on the basis of usage cost, reliability and ease of use. Please keep these criteria in mind when generating concepts for the given product. |

The problem statement prompts are written to be of similar lengths with problem 1 containing 172 words and problem 2 containing 153 words. Moreover, the structure of the problem statements is also similar, starting first with background motivation and identification of need, followed by the purpose of the device, its morph chart, details on participant's role, and finally evaluation criteria. The problems are similar in principle as both require some form of sensing and actuation, leading towards an electromechanical device. As a result, it is expected that the morph chart exploration or selection pattern

should not differ significantly between the two problems, assuming no other variables affect the outcome.

### 3.3 Experimental Materials: Morph Charts

For each problem statement and morph chart, five different functional arrangements were created. The experimented functional arrangements are: 1) Most Important to Least Important Function, 2) Least Important to Most Important Function, 3) Input to Output Function, 4) Output to Input Function, and 5) Random. From here on, we refer to the different arrangements as Priority, Reverse Priority, Input/Output, Output/Input, and RND respectively. Table 7 gives the Priority morph chart for ironing device problem, and Table 8 gives the Input/Output morph chart for recycling sorter problem. The inter-functional relationships between different arrangements for the two problem statements is given by Table 9 and Table 10.

**Table 7: Problem #1 Priority Morph Chart**

| Function | Means | | | | |
|---|---|---|---|---|---|
| **1) Press Cloth** | 1) Linkage Mechanism | 2) Cam & Follower | 3) Belt or Chain Drive | 4) Screw Mechanism | 5) Rack & Pinion |
| **2) Convert EE to ME** | 1) DC Motor | 2) AC Synchronous Motor | 3) AC Induction Motor | 4) Linear Motor | 5) Electro-Magnetic Switch |
| **3) Turn Cloth** | 1) Cam & Follower | 2) Linkage Mechanism | 3) Gear Drive | 4) Chain Drive | 5) Belt Drive |
| **4) Positioning** | 1) Linkage Mechanism | 2) Cam & Follower | 3) Belt or Chain Drive | 4) Screw Mechanism | 5) Gear Drive |
| **5) Convert EE to Heat** | 1) Heating Element | 2) Thermo-Electric Device | 3) Heat Exchanger | 4) Resistor | 5) Magnetron (Microwave) |
| **6) Fold Cloth** | 1) Linkage Mechanism | 2) Cam & Follower | 3) Belt Drive | 4) Chain Drive | 5) Gear Drive |

**Table 8: Problem #2 Input/Output Morph Chart**

| Function | Means | | | | |
|---|---|---|---|---|---|
| **1) Convert EE to ME** | 1) DC Motor | 2) AC Synchronous Motor | 3) AC Induction Motor | 4) Linear Motor | 5) Electro-Magnetic Switch |
| **2) Translate** | 1) Screw Mechanism | 2) Rack & Pinion | 3) Belt or Chain Drive | 4) Linkage Mechanism | 5) Cam & Follower |
| **3) Convert EE To MagE** | 1) Electro-Magnet | 2) Wire | 3) Permanent Magnet | 4) Ferro-magnet & coil | 5) Super-conducting Magnet |
| **4) Sort Solid** | 1) Machine Vision | 2) 3D Scan & Weight | 3) Acoustic | 4) Infrared | 5) Chemical Analysis |
| **5) Guide** | 1) Linkage Mechanism | 2) Gear Drive | 3) Screw Mechanism | 4) Cam Follower | 5) Rack & Pinion |
| **6) Compress Solid** | 1) Screw Mechanism | 2) Linkage Mechanism | 3) Belt or Chain Drive | 4) Rack & Pinion | 5) Spring |

**Table 9: Function – Code Relations**

| Problem 1 | | Problem 2 | |
|---|---|---|---|
| **Code** | **Function** | **Code** | **Function** |
| F1 | Press Cloth | F1 | Sort Solid |
| F2 | Convert EE to ME | F2 | Compress Solid |
| F3 | Turn Cloth | F3 | Convert EE to ME |
| F4 | Positioning | F4 | Translate |
| F5 | Convert EE to Heat | F5 | Guide |
| F6 | Fold Cloth | F6 | Convert EE to MagE |

**Table 10: Inter-Functional Relations**

| | Priority | Reverse Priority | Input/Output | Output/Input | RND |
|---|---|---|---|---|---|
| **Problem 1** | F1 | F6 | F2 | F6 | F4 |
| | F2 | F5 | F4 | F3 | F1 |
| | F3 | F4 | F5 | F1 | F6 |
| | F4 | F3 | F1 | F5 | F2 |
| | F5 | F2 | F3 | F4 | F3 |
| | F6 | F1 | F6 | F2 | F5 |
| **Problem 2** | F1 | F6 | F3 | F2 | F4 |
| | F2 | F5 | F4 | F5 | F3 |
| | F3 | F4 | F6 | F1 | F2 |
| | F4 | F3 | F1 | F6 | F6 |
| | F5 | F2 | F5 | F4 | F1 |
| | F6 | F1 | F2 | F3 | F5 |

The morph chart is nearly square, of size 6x5, to ensure an appropriate design space (3,125 integrated design concepts) that does not overwhelm participants with combinatorial possibilities. The reason for such a selection also follows from the findings in (G Smith et al. 2012). It can be seen that the functions and corresponding means of the

two design problems are similar, primarily involving some form of energy conversion and mechanical motions.

The procedure for creating the different arrangements is as follows. First, the Input/Output and Output/Input orders were obtained from the function structures, which can be found in (Patel et al. 2016) (see Appendix A). To obtain the Priority and Reverse Priority arrangements, the relative significance of each function was found using three methods, 1) mapping requirements to functions, 2) counting the input-output flows for each function, and 3) counting the input-output flows for each function with weights assigned to flows. The three results obtained for the relative significance of functions (or function rankings) are provided in Table 11.

**Table 11: Comparison of Function Ranking Results**

| | **Requirements-Function Mapping** | **I/O Count** | **I/O Count (Weights)** |
|---|---|---|---|
| **Problem 1** | Press Cloth | Press Cloth | Press Cloth |
| | Convert EE to Heat | Positioning | Convert EE to ME |
| | Convert EE to ME | Turn Cloth | Turn Cloth |
| | Positioning | Convert EE to ME | Positioning |
| | Fold Cloth | Fold Cloth | Convert EE to Heat |
| | Turn Cloth | Convert EE to Heat | Fold Cloth |
| **Problem 2** | Sort Solid | Sort Solid | Sort Solid |
| | Convert EE to ME | Compress Solid | Compress Solid |
| | Convert EE to MagE | Translate | Convert EE to ME |
| | Compress Solid | Guide | Translate |
| | Translate | Convert EE to ME | Guide |
| | Guide | Convert EE to MagE | Convert EE to MagE |

The procedure followed to get these results is given in Appendix B. Finally, the results obtained from the method of counting the input-output flows for each function with weights assigned was selected owing to objectivity and overlap with one or the other method. The reverse priority arrangement is obtained by inverting the priority arrangement. The justification for assignment of weights to flows is that given the context of the two design problem statements, it appears logical that signal flow does not significantly affect the solution generation, followed by material and energy flow. Hence, an order is needed to capture the relative impact on solution generation. Also, finding an innovative solution with regards to energy flow is much more difficult and consequential in comparison to the other two. The weights assigned for energy, material and signal flows are 9 (high), 3 (medium), and 1 (low) respectively. The RND order, intended to be random in nature, was deliberately structured in a manner to be different from the rest to ensure its significance.

### 3.4 Participants

The participants for this study comprised of mechanical engineering junior level undergraduate students, enrolled in ME 3060 (Fundamentals of Machine Design), a required course Spring 2018 at Clemson University. To guarantee a minimum level of subject understanding, the participants were provided a common leveling tutorial on morph charts (see Appendix C). The total number of participants used in the experiment were 67. The distribution of the different functional arrangements within the participants is given in Table 12.

**Table 12: Participant Distribution**

| Problem 1 | | Problem 2 | |
|---|---|---|---|
| **Order** | **Number of Participants** | **Order** | **Number of Participants** |
| Priority | 13 | Priority | 15 |
| Reverse Priority | 13 | Reverse Priority | 10 |
| Input/Output | 13 | Input/Output | 15 |
| Output/Input | 15 | Output/Input | 13 |
| RND | 13 | RND | 14 |

Participants were randomly assigned to the different morph chart arrangements. The experiment was conducted during normal class hours in order to mitigate discomfort. Thus, the environment, time of day, distractions, and other conditions were held constant for all participants. The participants were awarded extra credit for engaging in the research study. Figure 4 shows an example of the experimental setup.

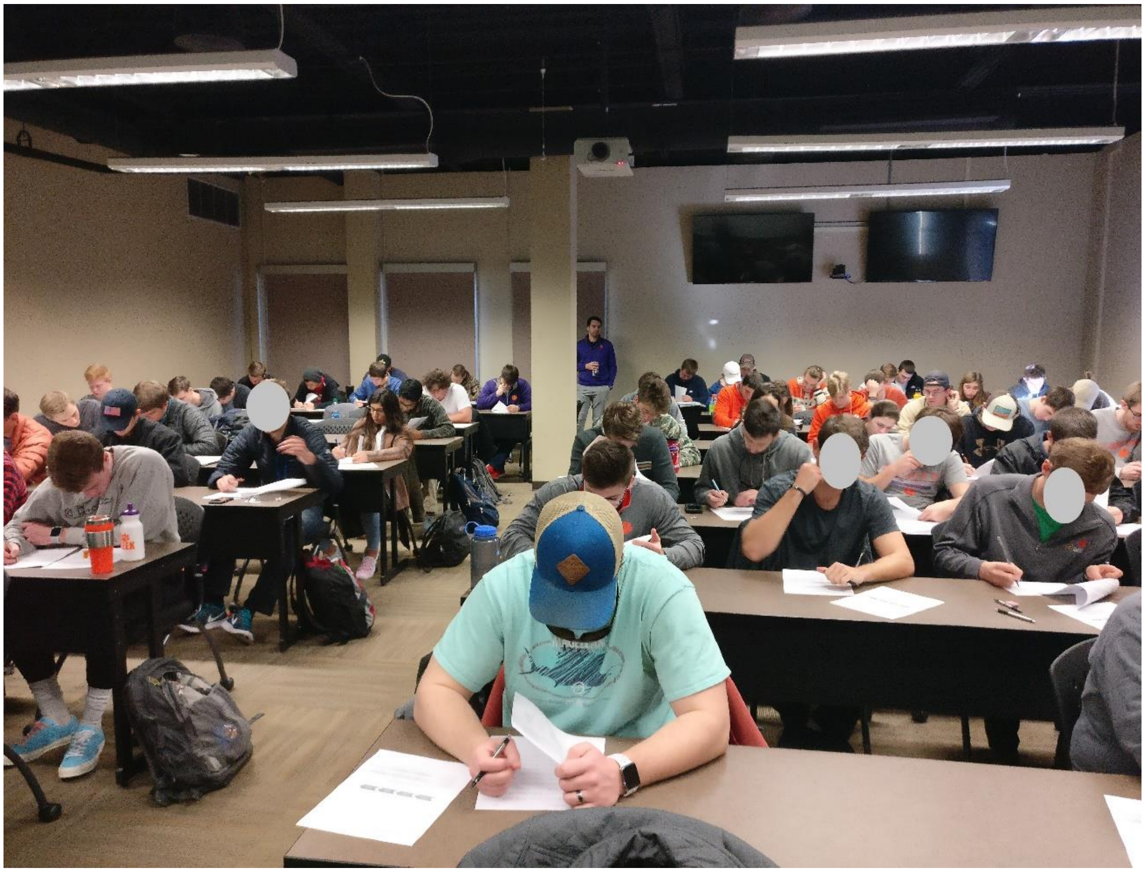


**Figure 4: Setup for Experimental Study**

3.5 Experimental Procedure

The experiment began with an introduction to morph charts and the expected role of participants in the study. Next, a set of handouts were distributed involving a tutorial on the design of an automatic burrito folder, aimed to give an intuitive idea of how design proceeds from a problem statement to functions, means generation and finally integrated design concept solutions (see Appendix C). To disconnect the tutorial from experiment problem, a pre-sketching activity was conducted for five minutes to enhance creativity and reduce mental stress. Previous research illustrates the positive impact of pre-sketching in idea generation (Worinkeng, Summers, and Joshi 2013). The first pre-sketching activity

involved sketching a dream home in Alaska, and the second pre-sketching activity (to disconnect problem one and problem two) involved sketching a personal yacht at the U.S. Virgin Islands. To start with the problem and concept generation activity, two handouts were distributed: one handout containing the problem statement with a prepopulated morph chart, and the second one providing space for recording twenty integrated design concept solutions (see Appendix C). Participants were allowed to ask questions before the activity began, and facilitators were present to answer individual questions during the activity.

For each problem, participants were given twenty minutes to record their integrated design concept solutions. The allotted time seemed to be justified considering that participants were provided with a prepopulated morph chart. Also, the majority of participants were able to develop twenty integrated design concept solutions, and all of them generated at least ten solutions. A summary of the experimental procedure is given in Table 13.

**Table 13: Experiment Summary**

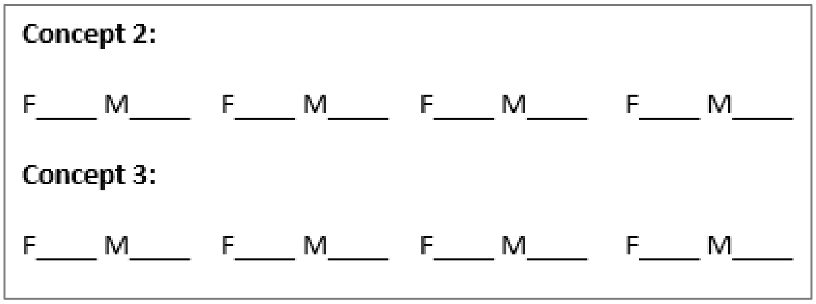
| | |
|---|---|
| **Activities** | Introduction to Morph Charts |
| | Morph Chart Practice Tutorial |
| | Pre-Sketching: Dream Home in Alaska (5 minutes) |
| | Problem #1: Automatic Ironing Device (20 minutes) |
| | Pre-Sketching: Personal Yacht at Virgin Islands (5 minutes) |
| | Problem #2: Automatic Recycling Sorter (20 minutes) |
| **Participants** | Total Number of Participants: 67 |
| | Number of Concepts asked to generate: 20 |
| | Number of Concepts analyzed: 10 |

## Chapter Four
## ANALYSIS PROCEDURE

Three aspects, frequency of means generation, morph chart coverage, and exploration sequence, are analyzed to study the exploration pattern followed by participants while generating integrated design concepts. This chapter summarizes the process of data collection, and the process of analyzing the three aspects (frequency, coverage, exploration sequence) from the collected data.

### 4.1 Data Collection and Filtering

For each participant, only the first ten integrated design concepts were chosen for analysis. This is because participants were deliberately asked to generate more concepts than originally planned for analysis, so that they are focused and on-time. A similar practice of requesting more concepts than the ones actually being analyzed has been observed in the literature (G Smith et al. 2012). The data collected was manually screened and recorded in Excel for further analysis. The MATLAB script to analyze the results is given in Appendix D. An example of the data recording sheet given to participants is shown in Figure 5. Due to limited space, the given data recording sheet shows only four combination blanks (F_M_). The data recording sheet given to participants contained six combination blanks for the six functions present in the morph chart. Students were only required to fill numbers in front of F (function) and M (means) to form integrated design concepts. An important aspect is that function codes (1 to 6) were not specified and blank spaces were present for filling the means code as well as function code. This was done to see if participants would change the function order given to them.


Concept 2:

F____ M____ F____ M____ F____ M____ F____ M____

Concept 3:

F____ M____ F____ M____ F____ M____ F____ M____

**Figure 5: Data Recording Sheet (snippet) given to Participants**

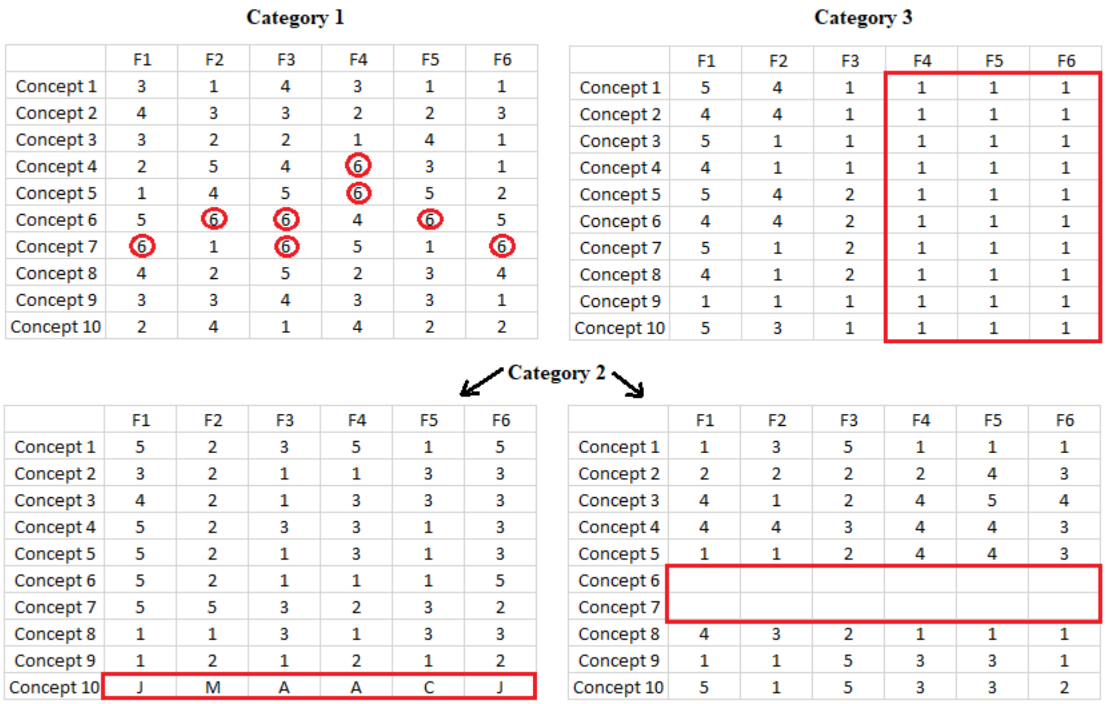
Figure 6 gives the Excel entry for a participant provided with the priority morph chart for problem 1. In the Excel entry shown below, F1 corresponds to function one (Press Cloth), F2 corresponds to function two (Convert EE to ME), and so on. The rows in the Excel entry represent the first ten concepts developed by the participant, and the values in the cells represent the means selected for each function. Concept 1 shown relates to the data recording sheet as F1M5-F2M4-F3M1-F4M1-F5M1-F6M4. Similar Excel entries were created for other participants, and the entries were grouped according to given functional order and problem type.

| | F1 | F2 | F3 | F4 | F5 | F6 |
|---|---|---|---|---|---|---|
| Concept 1 | 5 | 4 | 1 | 1 | 1 | 4 |
| Concept 2 | 3 | 2 | 1 | 5 | 5 | 5 |
| Concept 3 | 2 | 2 | 2 | 2 | 2 | 2 |
| Concept 4 | 3 | 2 | 3 | 2 | 3 | 4 |
| Concept 5 | 2 | 3 | 2 | 4 | 5 | 5 |
| Concept 6 | 4 | 4 | 4 | 4 | 4 | 4 |
| Concept 7 | 5 | 4 | 5 | 5 | 5 | 4 |
| Concept 8 | 2 | 3 | 4 | 2 | 3 | 4 |
| Concept 9 | 5 | 5 | 5 | 5 | 5 | 5 |
| Concept 10 | 1 | 1 | 1 | 1 | 1 | 1 |

**Figure 6: Sample Excel Entry**

Several data sets were excluded from analysis because of the following errors. First, the given morph charts contained six functions and five means. However, some participants confused the coding for functions and means leading to “6’s” in their list of design concepts. Participants with more than two “6’s” in their set of generated concepts were discarded, and the others were converted to “5”. Secondly, concepts which were incomplete (did not include means for one or all the functions), or contained irregularities such as letters (A, B, C) instead of numbers, were also discarded. Thirdly, participants which selected a single means for all ten design concepts across three or more functions, were also rejected to ensure unbiased results. Because out of the six functions given in the morph chart, if participants chose a single means for three or more functions (half or more than half) while generating ten design concepts, it is reasonable to assume that these participants did not make attempts to sincerely explore the design space. Hence, these samples need to be discarded to avoid skewing the results.

Figure 7 illustrates a sample of the Excel entries of the participants/concepts that were excluded from the analysis, grouped according to the categories mentioned above. Table 14 gives the number of discarded participants/concepts for each category and problem. In category 1 and 3, participant samples were entirely discarded and therefore the number of individual concepts discarded is ten times the number of participants affected (ten design concepts per participant) in Table 14. For category 2, only individual concepts were discarded.



Category 1

| | F1 | F2 | F3 | F4 | F5 | F6 |
|---|---|---|---|---|---|---|
| Concept 1 | 3 | 1 | 4 | 3 | 1 | 1 |
| Concept 2 | 4 | 3 | 3 | 2 | 2 | 3 |
| Concept 3 | 3 | 2 | 2 | 1 | 4 | 1 |
| Concept 4 | 2 | 5 | 4 | 6 | 3 | 1 |
| Concept 5 | 1 | 4 | 5 | 6 | 5 | 2 |
| Concept 6 | 5 | 6 | 6 | 4 | 6 | 5 |
| Concept 7 | 6 | 1 | 6 | 5 | 1 | 6 |
| Concept 8 | 4 | 2 | 5 | 2 | 3 | 4 |
| Concept 9 | 3 | 3 | 4 | 3 | 3 | 1 |
| Concept 10 | 2 | 4 | 1 | 4 | 2 | 2 |

Category 3

| | F1 | F2 | F3 | F4 | F5 | F6 |
|---|---|---|---|---|---|---|
| Concept 1 | 5 | 4 | 1 | 1 | 1 | 1 |
| Concept 2 | 4 | 4 | 1 | 1 | 1 | 1 |
| Concept 3 | 5 | 1 | 1 | 1 | 1 | 1 |
| Concept 4 | 4 | 1 | 1 | 1 | 1 | 1 |
| Concept 5 | 5 | 4 | 2 | 1 | 1 | 1 |
| Concept 6 | 4 | 4 | 2 | 1 | 1 | 1 |
| Concept 7 | 5 | 1 | 2 | 1 | 1 | 1 |
| Concept 8 | 4 | 1 | 2 | 1 | 1 | 1 |
| Concept 9 | 1 | 1 | 1 | 1 | 1 | 1 |
| Concept 10 | 5 | 3 | 1 | 1 | 1 | 1 |

Category 2

| | F1 | F2 | F3 | F4 | F5 | F6 |
|---|---|---|---|---|---|---|
| Concept 1 | 5 | 2 | 3 | 5 | 1 | 5 |
| Concept 2 | 3 | 2 | 1 | 1 | 3 | 3 |
| Concept 3 | 4 | 2 | 1 | 3 | 3 | 3 |
| Concept 4 | 5 | 2 | 3 | 3 | 1 | 3 |
| Concept 5 | 5 | 2 | 1 | 3 | 1 | 3 |
| Concept 6 | 5 | 2 | 1 | 1 | 1 | 5 |
| Concept 7 | 5 | 5 | 3 | 2 | 3 | 2 |
| Concept 8 | 1 | 1 | 3 | 1 | 3 | 3 |
| Concept 9 | 1 | 2 | 1 | 2 | 1 | 2 |
| Concept 10 | J | M | A | A | C | J |

| | F1 | F2 | F3 | F4 | F5 | F6 |
|---|---|---|---|---|---|---|
| Concept 1 | 1 | 3 | 5 | 1 | 1 | 1 |
| Concept 2 | 2 | 2 | 2 | 2 | 4 | 3 |
| Concept 3 | 4 | 1 | 2 | 4 | 5 | 4 |
| Concept 4 | 4 | 4 | 3 | 4 | 4 | 3 |
| Concept 5 | 1 | 1 | 2 | 4 | 4 | 3 |
| Concept 6 | | | | | | |
| Concept 7 | | | | | | |
| Concept 8 | 4 | 3 | 2 | 1 | 1 | 1 |
| Concept 9 | 1 | 1 | 5 | 3 | 3 | 1 |
| Concept 10 | 5 | 1 | 5 | 3 | 3 | 2 |

**Figure 7: Sample of Excluded Excel Entry**

**Table 14: Distribution of Discarded Samples**

| | **Problem 1** | | **Problem 2** | |
|---|---|---|---|---|
| | Concepts Discarded | Participants Affected | Concepts Discarded | Participants Affected |
| **Category 1** | 40 | 4 | 40 | 4 |
| **Category 2** | 5 | 4 | 10 | 4 |
| **Category 3** | 70 | 7 | 90 | 9 |

### 4.2 Frequency of Means Generation

The primary research goal was to determine the frequency of a means selection. The secondary goal was to see by how much the frequency altered with a change in functional arrangement. First, a 6x5 (same size as the morph chart) matrix was created for each participant. This matrix records the number of times a given means appeared in the

set of generated concepts. This is defined as a *frequency position matrix*. Table 15 provides the *frequency position matrix* for the Excel entry shown in Figure 6. To clarify, the values in the columns of the Excel entry correspond to the rows in the *frequency position matrix*. The sum of every row in the *frequency position matrix* is equal to the number of design concepts generated.

**Table 15: Sample Frequency Position Matrix**

| | **M1** | **M2** | **M3** | **M4** | **M5** | **Σ** |
|---|---|---|---|---|---|---|
| **F1** | 1 | 3 | 2 | 1 | 3 | **10** |
| **F2** | 1 | 3 | 2 | 3 | 1 | **10** |
| **F3** | 3 | 2 | 1 | 2 | 2 | **10** |
| **F4** | 2 | 3 | 0 | 2 | 3 | **10** |
| **F5** | 2 | 1 | 2 | 1 | 4 | **10** |
| **F6** | 1 | 1 | 0 | 5 | 3 | **10** |

Next, all the *frequency position matrices* for a given functional arrangement were summed. The resultant is a cumulative *frequency position matrix* for each functional arrangement. This cumulative *frequency position matrix* was then re-ordered and normalized to account for difference in functional position and participant distribution respectively. The normalization was done by dividing the matrix values by the summation (number of participants x concepts generated per participant) shown on the rightmost column. The matrices were re-ordered to the priority functional arrangement solely for the purpose of comparison. The obtained normalized *frequency position matrix* provides the percentage of appearance of means for the respective functional arrangement, where sum of every row is one i.e. 100%. A sample normalized *frequency position matrix* is given in Table 16 up to two decimal places. This matrix is shaded over a gradient given in Table 17

to highlight the variations. In a true random state, where each means is selected equally, each value in the normalized *frequency position matrix* should be 0.2 (20%), with the same gradient (Gradient 2) over each cell.

**Table 16: Sample Normalized Frequency Position Matrix**

| | M1 | M2 | M3 | M4 | M5 |
|---|---|---|---|---|---|
| **F1** | 0.31 | 0.21 | 0.14 | 0.20 | 0.15 |
| **F2** | 0.28 | 0.31 | 0.16 | 0.21 | 0.05 |
| **F3** | 0.21 | 0.29 | 0.18 | 0.11 | 0.21 |
| **F4** | 0.30 | 0.19 | 0.18 | 0.21 | 0.13 |
| **F5** | 0.33 | 0.19 | 0.16 | 0.19 | 0.14 |
| **F6** | 0.38 | 0.18 | 0.14 | 0.10 | 0.20 |

**Table 17: Frequency Gradient**

| Normalized Range | Gradient |
|---|---|
| 0.00 to 0.05 | White |
| 0.05 to 0.15 | Gradient 1 |
| 0.15 to 0.25 | Gradient 2 |
| 0.25 to 0.35 | Gradient 3 |
| 0.35 to 0.45 | Gradient 4 |
| 0.45+ | Gradient 5 |

If changes in functional arrangement have no impact on the frequency of means generation, then the normalized *frequency position matrices* should ideally be the same. To evaluate this, the cosine similarity between two *frequency position matrices* is calculated by treating every row as a vector. Table 18 depicts the ten possible combinations for comparing two functional arrangements for their normalized *frequency position matrices*. The matrix in Table 18 has marks only in upper triangle due to symmetry, and the diagonal is representative of comparing the functional arrangements to themselves. The output of

the cosine similarity is a column vector where every row corresponds to a function. After calculating the cosine similarity for every combination given in Table 18, the result is ten six-by-one output column vectors. These output column vectors are then summed and divided by ten (number of possible combinations) to obtain an average output column vector. The resultant average column vector is the average similarity for each function between all the five different functional arrangements.

**Table 18: Combinations for Normalized Frequency Position Matrix Comparison**

| | Priority | Reverse Priority | I/O | O/I | RND |
|---|---|---|---|---|---|
| Priority | | ☑ | ☑ | ☑ | ☑ |
| Reverse Priority | | | ☑ | ☑ | ☑ |
| I/O | | | | ☑ | ☑ |
| O/I | | | | | ☑ |
| RND | | | | | |

4.3 Morph Chart Coverage

Chart coverage denotes the number of means which have been explored by the participant while developing the first ten integrated design concepts. This includes the means from which design concepts have been generated. If means were eliminated explicitly in the chart by participant, there it is assumed that these were explored. Thus, the coverage indicates the degree to which the design space was explored.

For the given 6x5 morph chart, minimum value for coverage is ten. In other words, to develop at least ten different integrated design concepts one has to cover at least ten means from the morph chart. The maximum value for coverage is thirty (size of the morph

chart). Figure 8 depicts a 6x5 morph chart with minimum coverage, where $F_x$ = Function X and $M_y$ = Means Y. Minimum coverage can also be defined as the fewest means used to develop ten unique integrated design concepts. The dots represent the selected means and lines connect the selected means to form integrated design concepts. The pattern of selected means in Figure 8 is not the only pattern to obtain minimum coverage. The list of the integrated design concepts is given in Table 19.

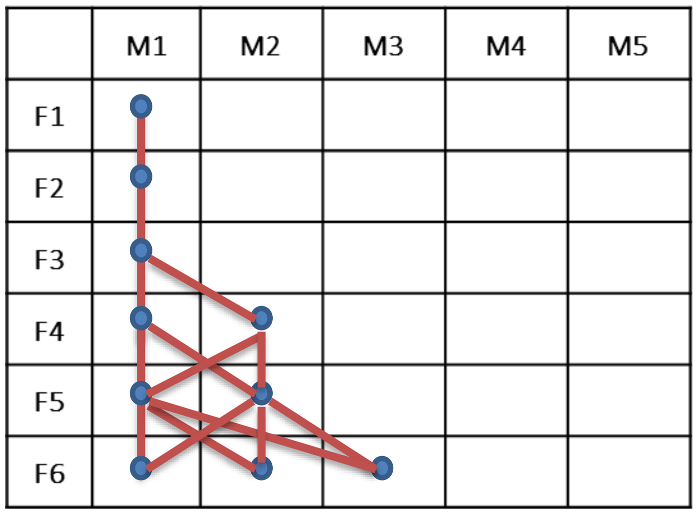



**Figure 8: Minimum Coverage Morph Chart**

**Table 19: List of Integrated Design Concepts for Minimum Coverage**

| | |
|---|---|
| **Concept 1** | F1M1-F2M1-F3M1-F4M1-F5M1-F6M1 |
| **Concept 2** | F1M1-F2M1-F3M1-F4M1-F5M1-F6M2 |
| **Concept 3** | F1M1-F2M1-F3M1-F4M1-F5M1-F6M3 |
| **Concept 4** | F1M1-F2M1-F3M1-F4M1-F5M2-F6M1 |
| **Concept 5** | F1M1-F2M1-F3M1-F4M1-F5M2-F6M2 |
| **Concept 6** | F1M1-F2M1-F3M1-F4M1-F5M2-F6M3 |
| **Concept 7** | F1M1-F2M1-F3M1-F4M2-F5M1-F6M1 |
| **Concept 8** | F1M1-F2M1-F3M1-F4M2-F5M1-F6M2 |
| **Concept 9** | F1M1-F2M1-F3M1-F4M2-F5M1-F6M3 |
| **Concept 10** | F1M1-F2M1-F3M1-F4M2-F5M2-F6M1 |

### 4.4 Exploration Sequence

The sequence of exploration explains how students navigate the morph chart step by step. Exploration sequence was analyzed row-wise (i.e. along functions) and column-wise (i.e. along means). For analyzing the sequence along functions, the number of participants that changed the function order were noted with their respective new function orders. In the case of exploring sequence along rows, a 5x5 matrix was developed for every participant. This matrix, referred to as *exploration matrix*, indicates the number of times the participant navigates from one means to another while generating design concepts.

Table 20 gives the *exploration matrix* for Priority functional arrangement for problem one. The matrix is read considering row as the starting point and column as the ending point. So, for the shown *exploration matrix*, participants when initially at column means two, navigated to means one 37 times, stayed at means two 36 times, navigated to means three 23 times, navigated to means four 13 times, and navigated to means five 17

times. In the next step, the exploration matrix for every participant in a given functional arrangement is summed. The summed *exploration matrix* is then normalized for the basis of comparison. The normalization was done by dividing the matrix row values by the respective summation shown on the rightmost column. A sample normalized *exploration matrix* is given in Table 21 up to two decimal places. As with frequency, if the sequence of exploration along rows is truly random, all the values should be 0.2.

**Table 20: Sample Exploration Matrix**

| | **M1** | **M2** | **M3** | **M4** | **M5** | **Σ** |
|---|---|---|---|---|---|---|
| **M1** | 60 | 35 | 15 | 20 | 23 | **153** |
| **M2** | 37 | 36 | 23 | 13 | 17 | **126** |
| **M3** | 19 | 21 | 18 | 19 | 10 | **87** |
| **M4** | 28 | 19 | 21 | 19 | 10 | **97** |
| **M5** | 17 | 12 | 10 | 16 | 17 | **72** |

**Table 21: Sample Normalized Exploration Matrix**

| | **M1** | **M2** | **M3** | **M4** | **M5** |
|---|---|---|---|---|---|
| **M1** | 0.39 | 0.23 | 0.10 | 0.13 | 0.15 |
| **M2** | 0.29 | 0.29 | 0.18 | 0.10 | 0.13 |
| **M3** | 0.22 | 0.24 | 0.21 | 0.22 | 0.11 |
| **M4** | 0.29 | 0.20 | 0.22 | 0.20 | 0.10 |
| **M5** | 0.24 | 0.17 | 0.14 | 0.22 | 0.24 |

# Chapter Five
# EXPERIMENTAL RESULTS AND DISCUSSION

The results given in this chapter follow the analysis procedure mentioned in the previous chapter. The three analysis aspects (frequency, coverage and exploration sequence) will help answer the question – How did participants explore the morph chart? Comparing the morph charts in terms of the three analysis aspects will determine the effect of functional arrangement on exploration pattern. In addition, the research hypothesis: Participants focus more on the earlier column regions of the morph chart irrespective of functional order, will also be evaluated for its validity.

## 5.1 Frequency of Means Generation

### 5.1.1 Frequency of Individual Means

The normalized *frequency position matrices* indicate the frequency of means selection. As stated earlier, these matrices are shaded over a gradient (specified in Table 17) to highlight variation. The results for problem one (Table 22, Table 23, Table 24, Table 25, Table 26) and problem two (Table 27, Table 28, Table 29, Table 30, Table 31) are given below. Darker means cells indicate higher percentage of appearance in the integrated design concepts, and lighter means cells indicate lower percentage of appearance in the integrated design concepts. If all the means appeared in the integrated design concepts equally, the percentage of appearance for each means would be 20% (0.2 cell value), and hence the shaded normalized *frequency position matrix* would only contain Gradient 2. As a reminder, cells are shaded White if the value is between 0.00 and 0.05, Gradient 1 if the value is between 0.05 and 0.15, Gradient 2 if the value is between 0.15 and 0.25, Gradient

3 is the value is between 0.25 and 0.35, Gradient 4 if the value is between 0.35 and 0.45, and Gradient 5 if the value is above 0.45. Values are only given for cells with Gradient 3, 4 and 5 (i.e. all the gradients above the expected gradient range of 0.15 to 0.25).

**Table 22: Problem #1 Priority**

| | | | | |
|---|---|---|---|---|
| 0.31 | | | | |
| 0.28 | 0.31 | | | |
| | 0.29 | | | |
| 0.30 | | | | |
| 0.33 | | | | |
| 0.38 | | | | |

In Table 22, Gradient 4 is present in one cell (in column one) and Gradient 3 is present in six cells (four in column one, two in column two).

**Table 23: Problem #1 Reverse Priority**

| | | | | |
|---|---|---|---|---|
| 0.32 | | | | |
| 0.43 | | | | |
| | 0.35 | | | |
| 0.31 | | | | |
| 0.46 | | | | |
| 0.45 | | | | |

In Table 23, Gradient 5 is present in one cell (in column one), Gradient 4 is present in three cells (two in column one, one in column two) and Gradient 3 is present in two cells (in column one).

**Table 24: Problem #1 Input/Output**

| | | | | |
|---|---|---|---|---|
| | 0.34 | | | |
| 0.40 | | | | |
| | 0.42 | 0.25 | | |
| 0.34 | | 0.25 | | |
| 0.43 | | | | |
| 0.52 | | | | |

In Table 24, Gradient 5 is present in one cell (in column one), Gradient 4 is present in three cells (two in column one, one in column two) and Gradient 3 is present in four cells (one in column one, one in column two, two in column three).

**Table 25: Problem #1 Output/Input**

| | | | | |
|---|---|---|---|---|
| 0.26 | | | | |
| 0.39 | | | | |
| | 0.30 | | | |
| 0.30 | | 0.26 | | |
| 0.35 | | | | |
| 0.29 | 0.25 | | | |

In Table 25, Gradient 4 is present in two cells (in column one) and Gradient 3 is present in six cells (three in column one, two in column two, one in column three).

**Table 26: Problem #1 RND**

| | | | | |
|---|---|---|---|---|
| | | | | |
| 0.41 | | | | |
| 0.26 | | | | |
| 0.33 | | | | |
| 0.41 | | | | |
| 0.47 | | | | |

In Table 26, Gradient 5 is present in one cell (in column one), Gradient 4 is present in two cells (in column one) and Gradient 3 is present in two cells (in column one).

**Table 27: Problem #2 Priority**

| | | | | |
|---|---|---|---|---|
| 0.31 | 0.27 | | | |
| 0.30 | | | | |
| 0.28 | | | | |
| | | | 0.31 | |
| 0.34 | | | | |
| 0.34 | | | | |

In Table 27, Gradient 3 is present in seven cells (five in column one, one in column two, one in column four).

**Table 28: Problem #2 Reverse Priority**

| | | | | |
|---|---|---|---|---|
| 0.35 | 0.38 | | | |
| 0.38 | | | | |
| 0.38 | | | | |
| 0.30 | | 0.25 | | |
| 0.28 | | | | |
| 0.35 | | | | |

In Table 28, Gradient 4 is present in five cells (four in column one, one in column two) and Gradient 3 is present in three cells (two in column one, one in column three).

**Table 29: Problem #2 Input/Output**

| | | | | |
|---|---|---|---|---|
| | | | 0.29 | |
| 0.35 | | | | |
| 0.47 | | | | |
| | | 0.42 | | |
| 0.30 | | | | |
| 0.57 | | | | |

In Table 29, Gradient 5 is present in two cells (in column one), Gradient 4 is present in two cells (one in column one, one in column three) and Gradient 3 is present in two cells (one in column one, one in column four).

**Table 30: Problem #2 Output/Input**

| | | | | |
|---|---|---|---|---|
| 0.31 | | 0.28 | | |
| 0.38 | | | | |
| 0.25 | | | | 0.25 |
| | | 0.26 | | |
| | 0.37 | | | |
| 0.32 | | | | |

In Table 30, Gradient 4 is present in two cells (one in column one, one in column two) and Gradient 3 is present in six cells (three in column one, two in column three, one in column five).

**Table 31: Problem #2 RND**

| | | | | |
|---|---|---|---|---|
| | | | 0.31 | |
| 0.35 | | | | |
| 0.40 | | 0.26 | | |
| | 0.31 | 0.33 | | |
| 0.32 | | | | 0.31 |
| 0.43 | | | | |

In Table 31, Gradient 4 is present in two cells (in column one) and Gradient 3 is present in seven cells (two in column one, one in column two, two in column three, one in column four, one in column five).

Observations made after collectively analyzing the results are as follows:

- High gradient values (above 0.35) typically occur in column one and two
- Gradient 5 is found rarely and only present in first column

- Exploration patterns of problem one and two are comparable, when considering respective functional arrangements
- Highest distribution uniformity exists in the Priority functional arrangement, followed by Output/Input functional arrangement
- The Priority and Output/Input functional arrangements show similarity in exploration pattern for both problems. Similar inference can be drawn for Reverse Priority and Input/Output functional arrangements.

### 5.1.2 Frequency of Means Columns

Now that the frequency of each individual means is analyzed, the next step involves analyzing the frequency of each means column. To obtain a column-wise comparison of means selection frequency, the normalized *frequency position matrix* for each functional arrangement was summed along columns. The result is a one-by-five row vector for each functional arrangement, where every value corresponds to a means column. The resulting values are given in Table 32. Note that the values of the one-by-five row vector for every functional arrangement are given in column format in Table 32, in front of their respective means column numbers. Table 33 gives the percentage distribution of values provided in Table 32. As an example, for problem 1 the selection percentage of Means Column 1 (M1) is equal to 1.81/(1.81+1.26+0.95+1.01+0.87) = 30%. The percentage range specifies the lowest to highest percentage of means column selection across all functional arrangements for a given problem. While taking problem one and problem two both into consideration, the percentage range for M1 is 27-35%, for M2 it is 17-26%, for M3 it is 15-21%, for M4 it is 12-19%, and for M5 it is 8-18%. Figure 9 depicts the results for problem one whereas

Figure 10 depicts the results for problem two. The results indicate a decline in selection frequency when moving from left to right on the morph chart, regardless of functional arrangement and problem type. The values affirm the inferences drawn previously and corroborate the hypothesis that participants will tend to focus more on the initial columns of the morph chart irrespective of functional arrangement.

**Table 32: Means Column Selection Frequency (Normalized)**

| | | Priority | Reverse Priority | I/O | O/I | RND |
|---|---|---|---|---|---|---|
| **Problem 1** | **M1** | 1.81 | 2.13 | 2.01 | 1.80 | 2.13 |
| | **M2** | 1.26 | 1.28 | 1.57 | 1.20 | 1.10 |
| | **M3** | 0.95 | 0.89 | 1.15 | 1.14 | 0.95 |
| | **M4** | 1.01 | 0.87 | 0.81 | 0.97 | 0.93 |
| | **M5** | 0.87 | 0.83 | 0.46 | 0.89 | 0.89 |
| **Problem 2** | **M1** | 1.78 | 2.05 | 2.10 | 1.63 | 1.89 |
| | **M2** | 1.22 | 1.33 | 1.02 | 1.10 | 1.16 |
| | **M3** | 1.13 | 1.05 | 1.27 | 1.18 | 0.97 |
| | **M4** | 1.08 | 0.73 | 0.96 | 1.17 | 0.92 |
| | **M5** | 0.79 | 0.83 | 0.65 | 0.93 | 1.05 |

**Table 33: Means Column Selection Percentage**

| | | Priority | Reverse Priority | I/O | O/I | RND | Percentage Range |
|---|---|---|---|---|---|---|---|
| **Problem 1** | **M1** | 30% | 35% | 34% | 30% | 35% | 30-35% |
| | **M2** | 23% | 21% | 26% | 20% | 18% | 18-26% |
| | **M3** | 16% | 15% | 19% | 19% | 16% | 15-19% |
| | **M4** | 17% | 15% | 14% | 16% | 15% | 14-17% |
| | **M5** | 14% | 14% | 8% | 15% | 15% | 8-15% |
| **Problem 2** | **M1** | 30% | 34% | 35% | 27% | 32% | 27-35% |
| | **M2** | 20% | 22% | 17% | 18% | 19% | 17-22% |
| | **M3** | 19% | 18% | 21% | 20% | 16% | 16-21% |
| | **M4** | 18% | 12% | 16% | 19% | 15% | 12-18% |
| | **M5** | 13% | 14% | 11% | 16% | 18% | 11-18% |

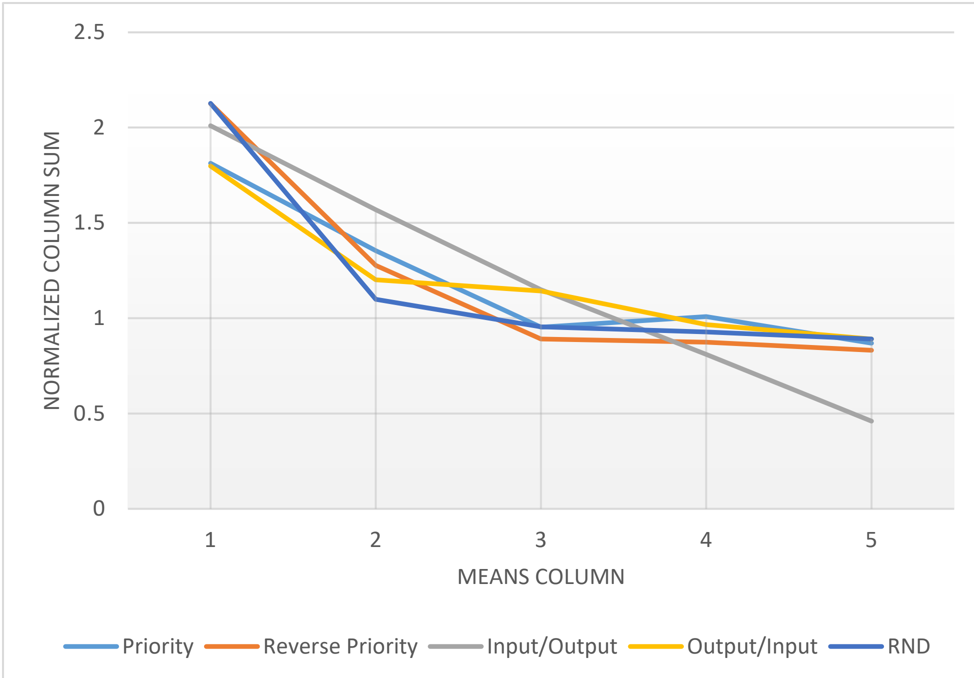



**Figure 9: Problem #1 Comparison of Means Column Selection Frequency**

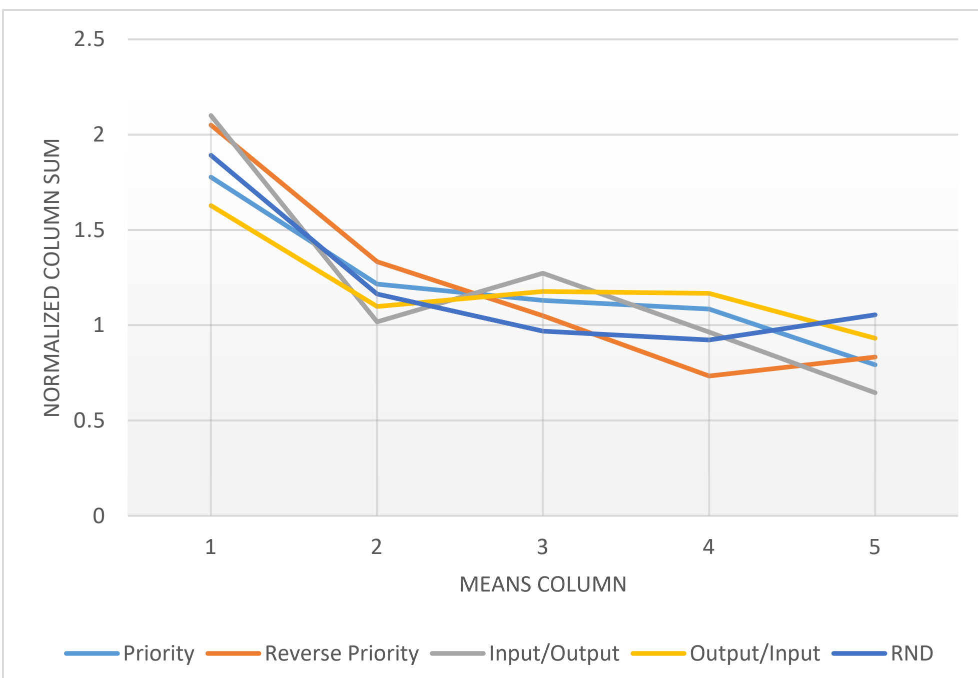



**Figure 10: Problem #2 Comparison of Means Column Selection Frequency**

In Figure 9, which contains the plotted results for problem one, all the lines are monotonically decreasing with the sole exception of priority functional arrangement. In the case of priority functional arrangement, a slight increase in selection frequency takes place when moving from Means Column 3 (0.95 value) to Means Column 4 (1.01 value). Figure 10 gives the plotted results for problem two, wherein only one line (priority functional arrangement) is monotonically decreasing. Similar to problem one, there exists an overall trend of decreasing selection frequency when moving from left (Means Column 1) to right (Means Column 5), however, the difference lies in the individual values shaping the trend. For problem two, the selection frequency decreases for every functional arrangement from Means Column 1 to Means Column 2. But starting Means Column 2, each functional arrangement appears to have a different trend, marked by slight increase and decrease in selection frequency at various intervals. A considerable increase in selection frequency is noticeable only for the I/O functional arrangement. Though the plots clearly indicate a downward trend, it appears that the type of problem also impacts the frequency of means selection. The difference in results may also arise from the fact that problem two came after problem one. For now, no conclusion with respect to problem type can be drawn and thus the effect of problem type and its significance remains unknown.

### 5.1.3 Effect of Functional Ordering

With the analysis of individual means selection and means column selection complete, the changes in functional arrangement can be investigated to quantify its impact. As mentioned in the previous chapter, to evaluate the effect of change in functional arrangement on means selection frequency, the row-wise cosine similarity between two

*frequency position matrices* is found for the ten combinations given in Table 18. Next, an average cosine-similarity is obtained out of the ten combinations. This represents the average similarity for each function between all the five different functional arrangements in problem one. The same process is repeated for problem two to obtain the average similarity.

The results for problem one and problem two are plotted in Figure 11 and Figure 12 respectively. For problem one, the similarity values are approximately in the range of 0.93 (93%) to 0.97 (97%) for each function. For problem two, the similarity values are approximately in the range of 0.88 (88%) to 0.98 (98%). For both the problems, the values for each function indicate high similarity, and consequently a lack of functional ordering effect. In addition, it can be observed that problem two has lower similarity values for functions 1,4, and 5, in comparison to problem one. Even though the similarity values are quite high and it is safe to conclude a lack of functional ordering effect, problem type is a variable that needs to be tested. More experiments need to be conducted to investigate the effect of problem type.

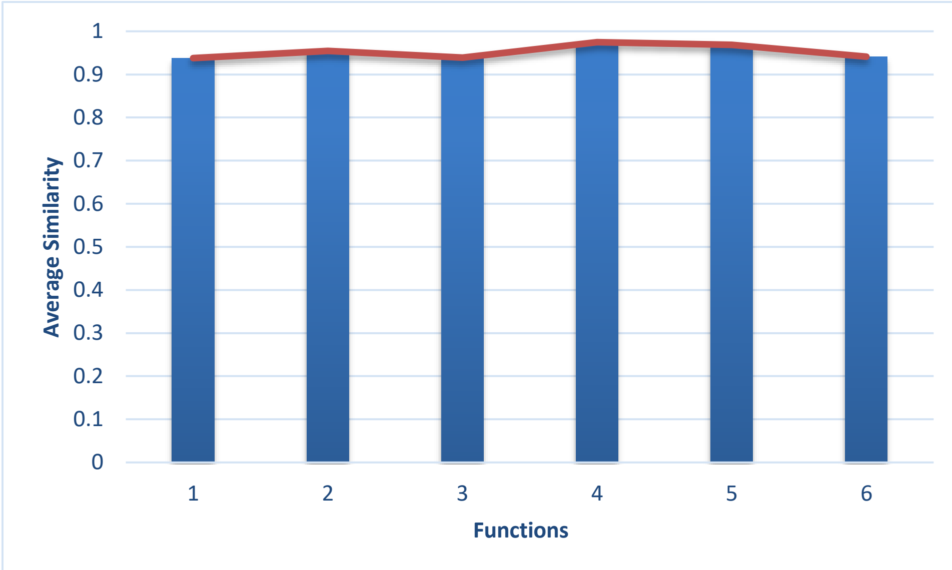



**Figure 11: Problem #1 Effect of Functional Ordering**

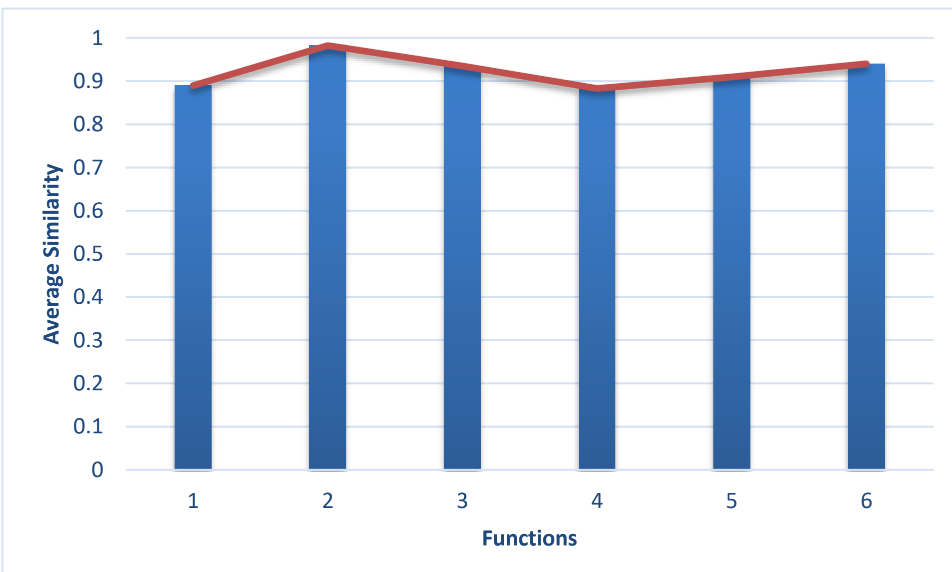



**Figure 12: Problem #2 Effect of Functional Ordering**

### 5.2 Morph Chart Coverage

Table 34 gives the coverage value for each participant, sorted by functional arrangement and problem type. The bottom four rows give the mean coverage value

(rounded to closest integer), standard deviation (SD), and maximum and minimum coverage value for each functional arrangement. An important observation is that the standard deviation values for problem two are considerably larger than that of problem one. To plot the results, four ranges were set from minimum chart coverage value (eleven) to maximum chart coverage value (thirty). The participant values for morph chart coverage were then grouped in these ranges.

Figure 13 and Figure 14 display the percentage distribution of coverage values as per functional arrangement. The numbers on the bottom indicate range of coverage values and the percentage values signify how many participants fall within the specific coverage range out of the total number of participants for that functional arrangement. For the purpose of analyzing the results, high coverage is indicated by the ranges of 21 to 25 (color yellow) and 26 to 30 (color grey), and low coverage is indicated by the ranges of 11 to 15 (color green) and 16 to 20 (color blue). Such a classification of high and low coverage is based on the author's viewpoint. It seems reasonable that at least two-third of the morph chart should be explored before it can be classified as high coverage.

**Table 34: Coverage Value per Participant**

| | Problem 1 | | | | | Problem 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Priority | Reverse Priority | I/O | O/I | RND | Priority | Reverse Priority | I/O | O/I | RND |
| | 28 | 15 | 25 | 28 | 26 | 30 | 28 | 23 | 24 | 27 |
| | 27 | 27 | 21 | 24 | 28 | 26 | 16 | 14 | 13 | 26 |
| | 23 | 27 | 24 | 30 | 29 | 29 | 29 | 30 | 15 | 11 |
| | 18 | 26 | 13 | 18 | 30 | 15 | 28 | 20 | 18 | 29 |
| | 24 | 23 | 28 | 24 | 15 | 24 | 28 | 19 | 18 | 17 |
| | 25 | 23 | 18 | 28 | 30 | 20 | 25 | 29 | 24 | 27 |
| | 29 | 25 | 15 | 22 | 27 | 28 | | 28 | 29 | 28 |
| | 25 | 26 | 16 | 18 | 25 | 24 | | 13 | 27 | 25 |
| | 24 | 12 | 27 | 12 | 23 | 27 | | 11 | 30 | 13 |
| | 15 | 27 | 16 | 25 | 16 | 15 | | 27 | 27 | 11 |
| | 23 | 25 | | 19 | 23 | 23 | | 15 | 16 | 28 |
| | | 17 | | 25 | | 15 | | | | 30 |
| | | | | | | 22 | | | | 23 |
| **Mean** | **24** | **23** | **20** | **23** | **25** | **23** | **26** | **21** | **22** | **23** |
| **SD** | **4.13** | **5.17** | **5.42** | **5.19** | **5.18** | **5.31** | **4.93** | **6.98** | **6.07** | **7.09** |
| **Max** | **29** | **27** | **28** | **30** | **30** | **30** | **29** | **30** | **30** | **30** |
| **Min** | **15** | **12** | **13** | **12** | **15** | **15** | **16** | **11** | **13** | **11** |

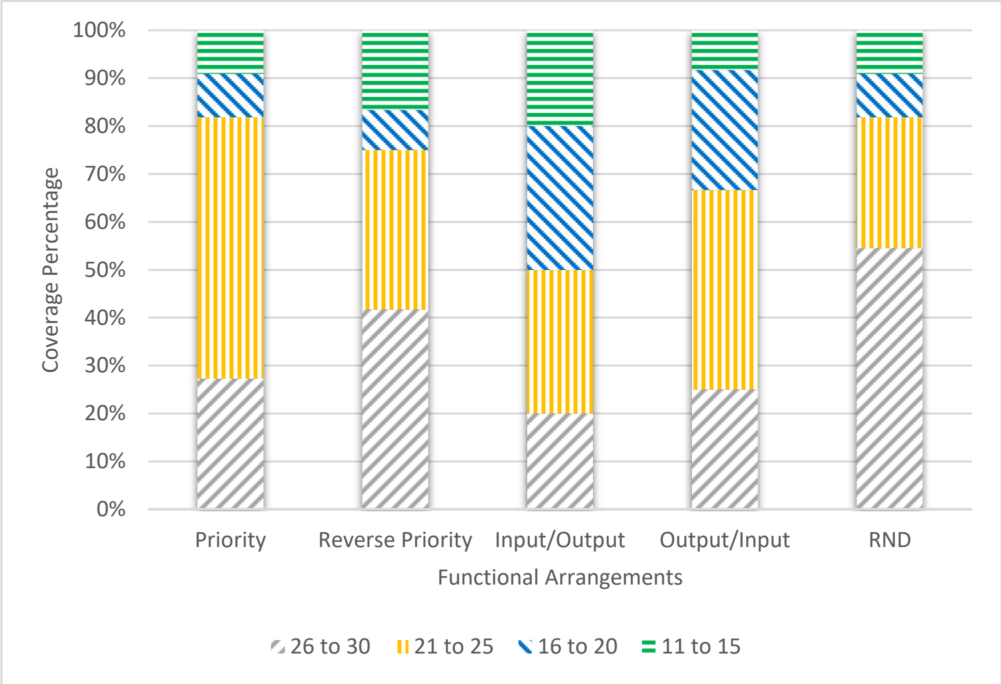



**Figure 13: Problem #1 Morph Chart Coverage**

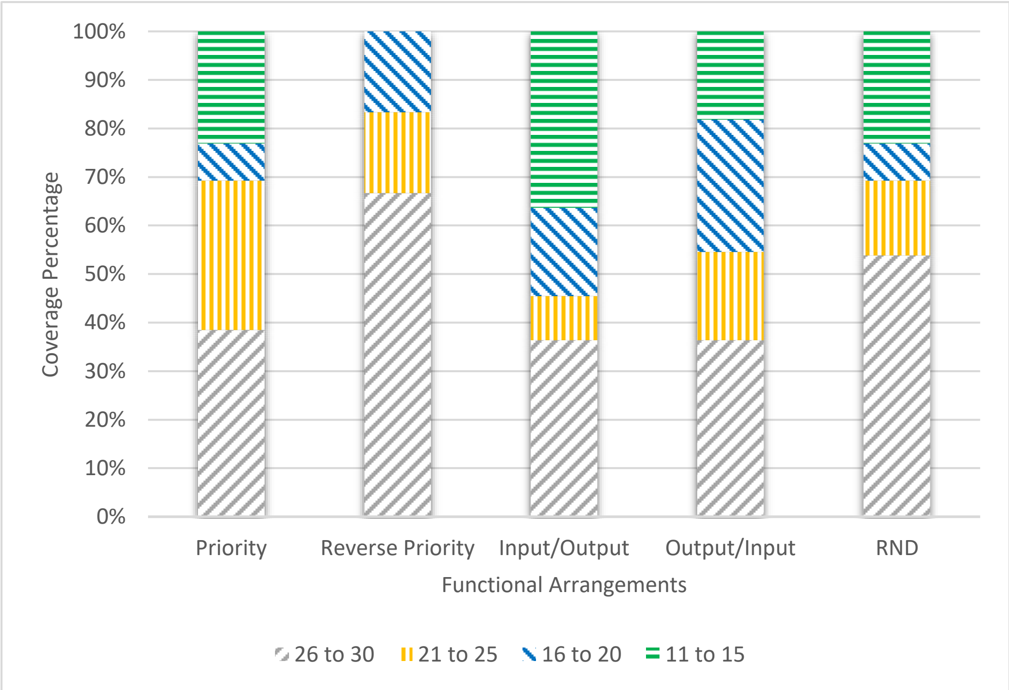



**Figure 14: Problem #2 Morph Chart Coverage**

For problem one, the ranking from high coverage percentage to low coverage percentage is Priority and RND, Reverse Priority, Output/Input, Input/Output respectively. For problem two, the ranking from high coverage percentage to low coverage percentage is Reverse Priority, Priority and RND, Output/Input, Input/Output respectively. It is evident that the Input/Output and Output/Input functional arrangements are not well suited for exploring the design space, in comparison to the other arrangements. The Priority, Reverse Priority and RND arrangements perform similarly and showcase high coverage chances. Also, an important observation is the similarity between coverage charts for Priority and RND, with same high coverage values for both problems.

### 5.3 Exploration Sequence

As stated in the analysis, the exploration sequence was analyzed along functions and along means. Along functions, most of the participants did not alter the provided functional arrangement. Majority of the participants followed the provided function arrangement, with the F1-F2-F3-F4-F5-F6 pattern appearing on their data recording sheets for all ten integrated design concept solutions. Table 35 gives the number of participants which altered the provided functional arrangement. For both the problems, only the I/O functional arrangement did not undergo high number of alterations. Figure 15 shows function-wise exploration graphs for two of the altered functional arrangements. For the first function-wise exploration graph, an F6-F5-F1-F2-F4-F3 pattern was present for all ten integrated design concepts. For the second function-wise exploration graph, an F1-F2-F3-F4-F5-F6 pattern was present for eight out of ten integrated design concepts, and the

patterns for other two integrated design concepts were F6-F4-F3-F1-F2-F5 and F3-F4-F1-F5-F2-F6.

**Table 35: Distribution of Altered Functional Arrangements**

| Problem 1 | | Problem 2 | |
|---|---|---|---|
| **Order** | **Participant Alterations** | **Order** | **Participant Alterations** |
| Priority | 0 | Priority | 6 |
| Reverse Priority | 1 | Reverse Priority | 5 |
| Input/Output | 1 | Input/Output | 0 |
| Output/Input | 7 | Output/Input | 1 |
| RND | 5 | RND | 1 |

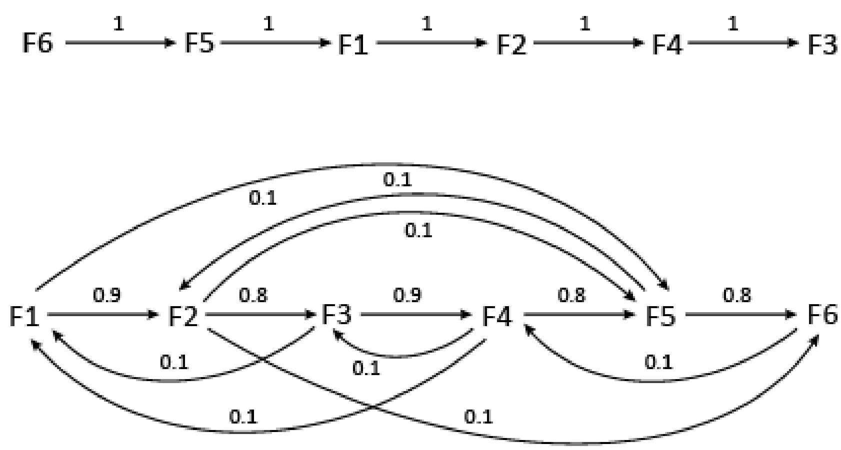



**Figure 15: Function-wise Exploration Graphs**

To analyze the exploration sequence along means, means-column wise exploration graphs are created. To create the exploration graphs, a convention was followed to ensure the graphs are as similar as possible. First, the normalized *exploration matrix* was analyzed along rows from top to bottom for values greater than 0.2 (ideal). The location of identified means conveys the sequence of exploration. If the navigation takes from a lower means

column number to higher means column number (e.g. M1 to M2), the green arrow is used. If the navigation takes from a higher means column number to lower means column number (e.g. M3 to M2), the blue arrow is used. Navigation to the same means column is indicated by black circular arrow. The location of means columns (M1 to M5) remains the same for all graphs. Figure 16, Figure 17, Figure 18, Figure 19, Figure 20 provide the means column-wise exploration graphs for problem one. Figure 21, Figure 22, Figure 23, Figure 24, Figure 25 give the means column-wise exploration graphs for problem two. Observations below each figure include the top two means columns who have the largest number of inbounds (incoming arrows), and the maximum inbound value.

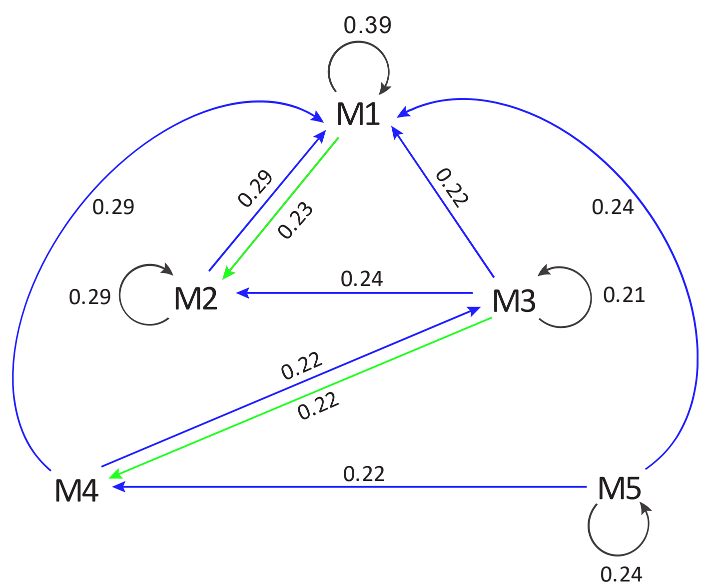



**Figure 16: Problem #1 Priority Column-wise Exploration Graph**

In Figure 16, M1 has five inbounds followed by three inbounds on M2. The maximum value of inbound is 0.39, for navigation from M1 to M1 itself.

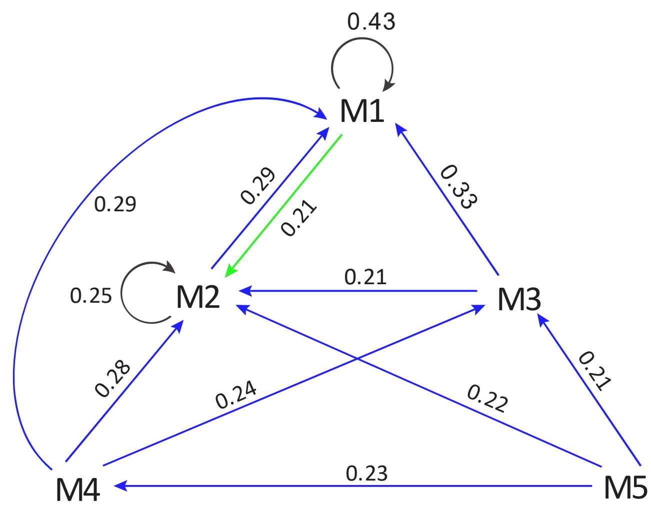



**Figure 17: Problem #1 Reverse Priority Column-wise Exploration Graph**

In Figure 17, M2 has five inbounds followed by four inbounds on M1. The maximum value of inbound is 0.43, for navigation from M1 to M1 itself.

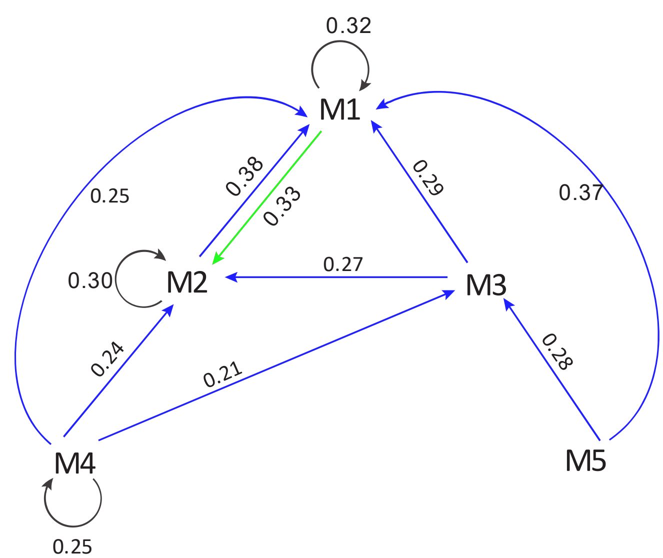



**Figure 18: Problem #1 Input/Output Column-wise Exploration Graph**

In Figure 18, M1 has five inbounds followed by four inbounds on M2. The maximum value of inbound is 0.38, for navigation from M2 to M1.

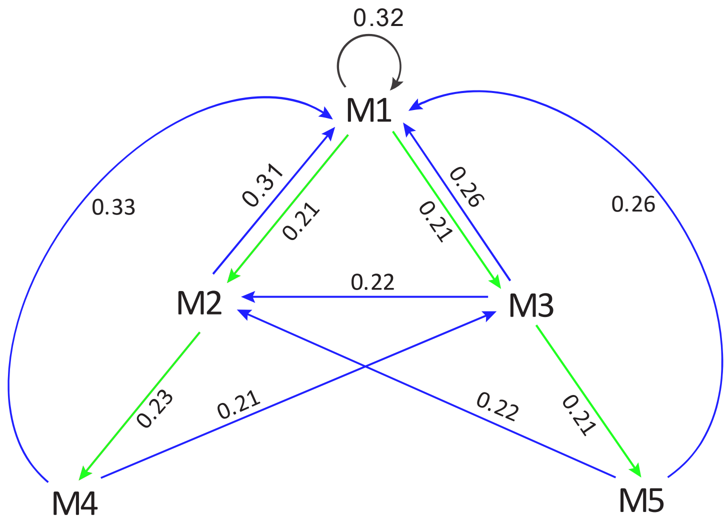



**Figure 19: Problem #1 Output/Input Column-wise Exploration Graph**

In Figure 19, M1 has five inbounds followed by three inbounds on M2. The maximum value of inbound is 0.33, for navigation from M4 to M1.

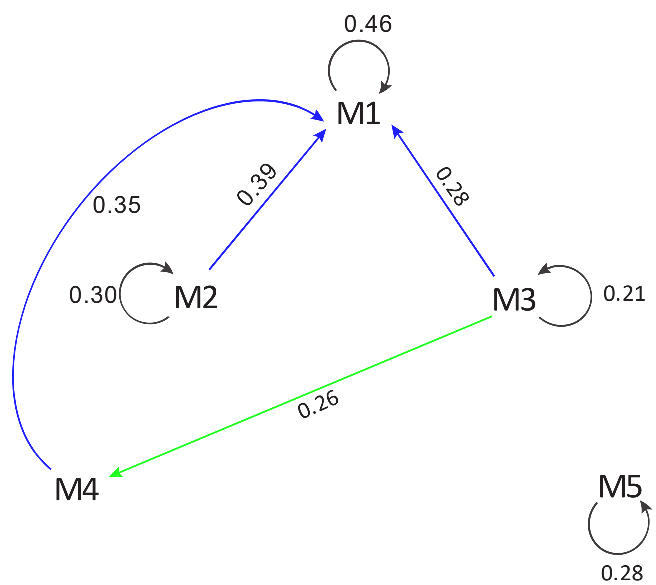



**Figure 20: Problem #1 RND Column-wise Exploration Graph**

In Figure 20, M1 has four inbounds, and the rest have one inbound each. The maximum value of inbound is 0.46, for navigation from M1 to M1 itself.

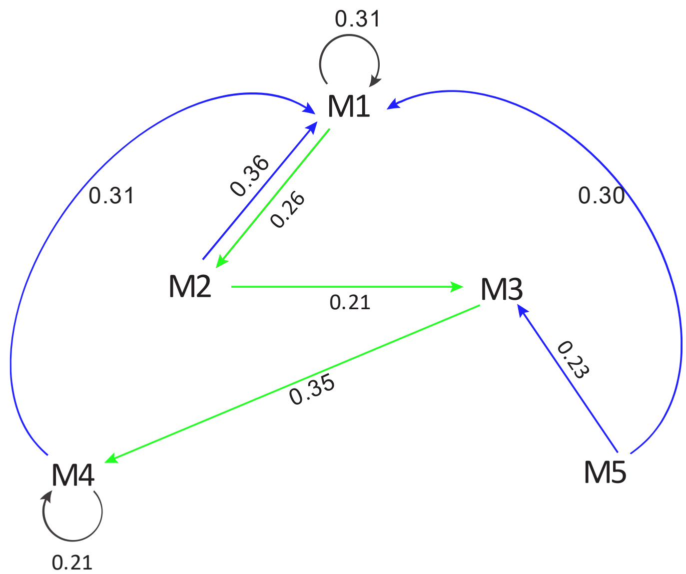



**Figure 21: Problem #2 Priority Column-wise Exploration Graph**

In Figure 21, M1 has five inbounds followed by two inbounds on M2, M3 and M4. The maximum value of inbound is 0.36, for navigation from M2 to M1.

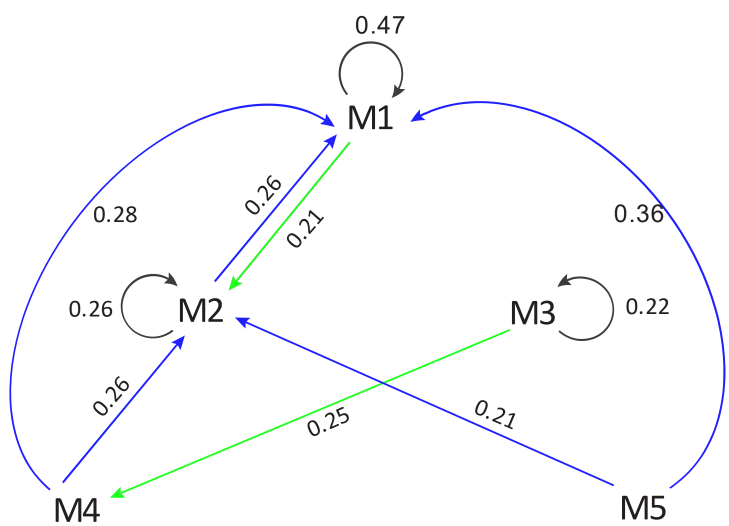



**Figure 22: Problem #2 Reverse Priority Column-wise Exploration Graph**

In Figure 22, M1 and M2 both have four inbounds. The maximum value of inbound is 0.47, for navigation from M1 to M1 itself.

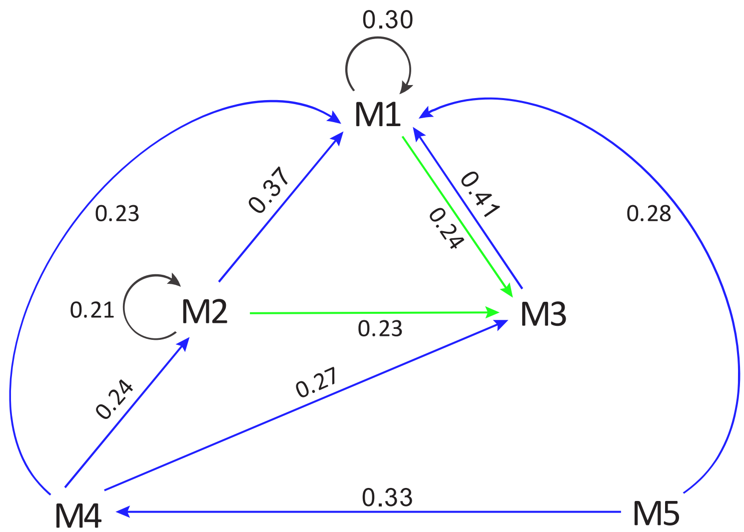



**Figure 23: Problem #2 Input/Output Column-wise Exploration Graph**

In Figure 23, M1 has five inbounds followed by three inbounds on M3. The maximum value of inbound is 0.41, for navigation from M3 to M1.

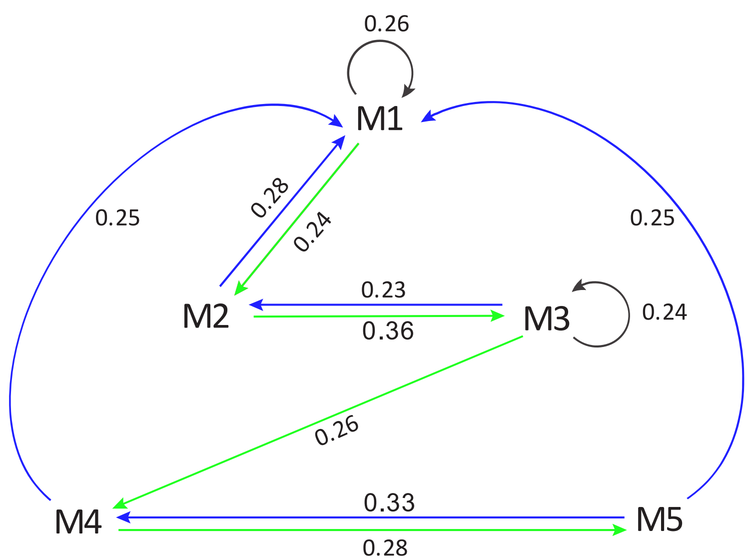



**Figure 24: Problem #2 Output/Input Column-wise Exploration Graph**

In Figure 24, M1 has four inbounds followed by two inbounds on M2, M3 and M4. The maximum value of inbound is 0.36, for navigation from M2 to M3.

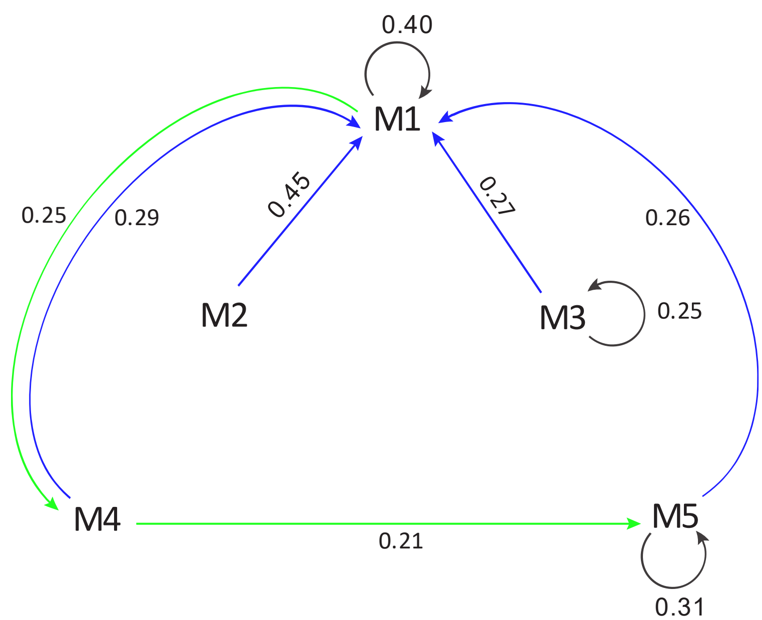



**Figure 25: Problem #2 RND Column-wise Exploration Graph**

In Figure 25, M1 has five inbounds followed by two inbounds on M5. The maximum value of inbound is 0.45, for navigation from M2 to M1.

Examining each functional arrangement graph leads to the following conclusions:

- High inbound on means column one followed by means column two. Presence of high inbound values on means column one.
- High uniformity in exploration pattern of Priority and Output/Input functional arrangements. This is also evident from the fact that the exploration graphs of these functional arrangements are spread along their width rather than height.
- The exploration graph for every functional arrangement is different, and hence, the exploration sequence along rows is not truly random.

# Chapter Six
# CONCLUSIONS

In this thesis research, the objective was to detail the experiment conducted to study morph chart exploration. Chapters 1 and 2 present background information on morph charts, and outline the significance of morph charts in engineering design research. In Chapter 3, a research question and hypothesis is formulated, followed by specifics on experiment design and execution. The subsequent chapters describe the process of analyzing the results, and discuss the results to draw inferences. Conclusions given in this chapter summarize findings of the experimental study, provide guidelines on using morph charts for exploration, and discuss the experimental limitations.

The experimental study conducted in this thesis aimed to evaluate the impact of functional arrangement on concept exploration using morph charts. The motive was to answer the research question: *How does the location of a function in a morph chart affect the selection of means associated with that function?* The hypothesis was: *Designers tend to focus relatively more on initial columns of the morph chart, irrespective of functional order*. The study consisted of two design problems, each with five different functional arrangements. The five functional arrangements in investigation were Priority, Reverse Priority, Input/Output, Output/Input and Random. Sixty-seven junior mechanical engineering students participated in the experiment. Participants were provided with a prepopulated morph chart of a particular functional arrangement, and asked to develop integrated design concept solutions. The generated results were analyzed for location (frequency and coverage) and sequence of means selection.

## 6.1 Summary of Experimental Results

Based on the results obtained, the following conclusions can be drawn:

- **Designers tend to focus relatively more on initial columns of the morph chart, irrespective of functional order.**

This result is a re-statement of the research hypothesis. The frequency analysis of individual means (shaded normalized *frequency position matrices*) and means column clearly show decreasing means selection frequency when moving from left-to-right on the morph chart of any functional arrangement. The selection frequency of individual means does not remain the same when changing the functional arrangement of the morph chart. Nevertheless, the variation is insignificant and there exists a high similarity when the means for a given function are analyzed collectively. The means column selection pattern (the cumulative effect of means selection along columns) also does not alter significantly from one functional arrangement to the other.

The overall decreasing trend is not linear i.e. the slope of the line from F1 to F2 is not always equal to the slope of the line from F2 to F3 and so forth. The type of the design problem also influences the individual selection pattern. However, based on the obtained results the effect of problem type is inconsequential when taking the overall decreasing trend into consideration.

- **The Priority and Output-to-Input functional arrangements result in higher exploration uniformity.**

For every functional arrangement, the selection frequency for each individual means was found. Ideally, the selection frequency for every means should be 20% (0.2 value), but the actual results vary. These variations are highlighted using a color gradient corresponding to selection frequency.

Out of the five functional arrangements considered, there are lesser variations present in the Priority and Output-to-Input functional arrangements, for both problem statements. The exploration pattern is more uniform or close to ideal in the case of Priority and Output-to-Input functional arrangements. The exploration patterns for both the problems are not completely similar, but the differences between them are negligible.

- **The Priority, Reverse Priority and Random functional arrangement increase the chances of high design space exploration.**

Chart coverage was one of the aspects analyzed to study the exploration pattern. It signifies the amount of design space covered by the participant while generating concepts. The minimum and maximum coverage values for the provided 6x5 morph chart are ten and thirty. Coverage values of participants above 21 were labelled as high coverage, whereas coverage values below 21 were labelled as low coverage.

For problem one, the priority functional order had 82% participants with high coverage, the reverse priority functional order had 75% participants with high coverage, the input/output functional order had 50% participants with high coverage, the output/input functional order had 67% participants with high coverage and finally the random functional order had 82% participants with high coverage. For problem two, the priority functional

order had 70% participants with high coverage, the reverse priority functional order had 83% participants with high coverage, the input/output functional order had 46% participants with high coverage, the output/input functional order had 55% participants with high coverage and finally the random functional order had 70% participants with high coverage. To conclude, higher percentage of participants ended up with high coverage values in the case of priority, reverse priority and random functional arrangements. Thus, the chances of high design space exploration increase with these functional arrangements.

In a nutshell, though functional re-ordering does not alter the overarching designer tendency to focus more on first few columns of the morph chart, the priority and output-to-input arrangements can reduce the effect leading to more uniform exploration, and probability of better design space exploration can increase with priority, reverse priority, or random arrangement.

## 6.2 Recommendations

The insights obtained from conducting the experimental study and analyzing the results has led to guidelines and recommendations. Following are the guidelines and recommendations that can help designers explore the morph chart effectively:

1. Designers should order the functions in a morphological chart from Most Important (top) function to Least Important (bottom) function, or Output (top) function to Input (bottom) function, in order to explore the morph chart uniformly.

2. Designers should order the functions in a morphological chart from Most Important (top) function to Least Important (bottom) function, or Least Important (bottom) function to Most Important (top) function, or randomly, in order to increase design space exploration.

3. Algorithms used in design automation should exploit the results by giving the concept generator output in the form of a morphological chart, and by placing those means columns first where designer's focus is needed. The question of where designer's focus is needed depends on whether the computational concept generator intends to complement or mimic human behavior.

In summary, ordering the morph chart functions in priority (most important to least important) functional arrangement gives uniform exploration and high design space exploration. Designer tendency to focus on initial morph chart columns should be employed in algorithms used for automatic design space exploration. The above stated recommendations rely on the assumption that the priority functional arrangement is obtained by counting the number of input-output flows in the function structure, with weights assigned to flows. It should be emphasized that the experiment was conducted with students, and thus the recommendations are valid only for students and novice designers.

### 6.3 Future Work

As identified in Chapter 1 and 2, morph charts lack guidelines on representation and exploration. The experiment conducted in this study has helped in identifying new research directions. Following is a list of research questions to explore.

1. How does the order of listing means for any given function in a morphological chart influence concept exploration? The posited question supplements the experiment conducted in this thesis. In this thesis, the effect of function re-ordering was evaluated, whereas this research question aims to evaluate the effect of means re-ordering.

2. How does the type of design problem influence concept exploration using morphological charts? This research question directly follows from the observation that problem type has an effect on means generation frequency.

3. How does the representation of means in a morphological chart – textual, graphical or hybrid, impact the generated concepts? The engineering design literature does not contain guidelines on means representation. Past studies have concluded a lack of effect of function representation in morphological charts, however the representation of means was not investigated.

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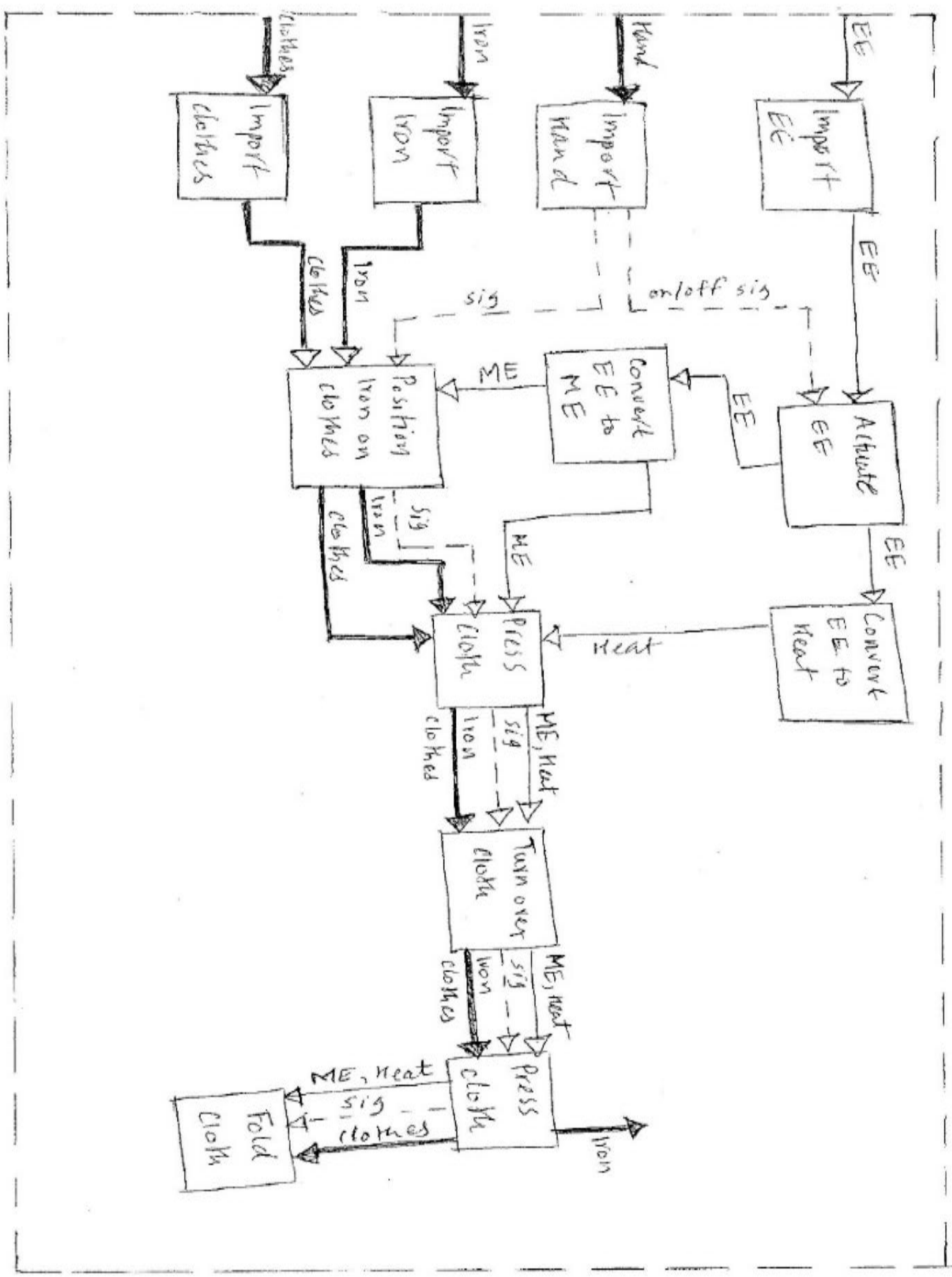
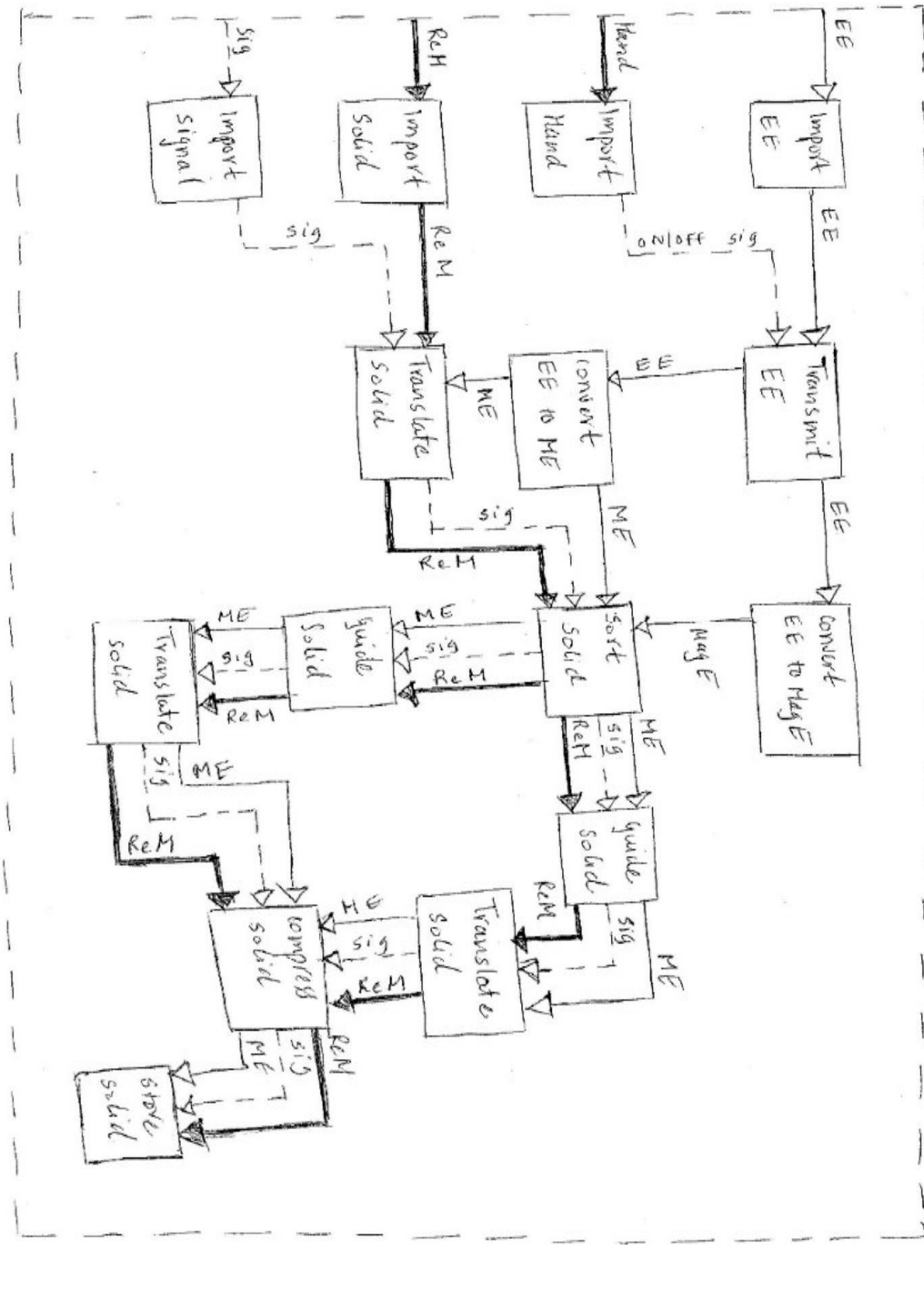
APPENDICES

## Appendix A

## Function Structures




Import signal
Import Solid
Import Hand
Import EE
Translate Solid
Convert EE to ME
Transmit EE
Convert EE to MagE
Sort Solid
Guide Solid
Translate Solid
Guide Solid
Translate Solid
Compress Solid
Store Solid
sig
ReM
Hand
EE
ON/OFF sig
ME
MagE

Appendix B

Procedure for determining Function Ranking

## Problem 1 - Automatic Clothes Ironing Device

- **Method 1 - Requirements-Function Mapping**

| Functions / Requirmnts | EE to Heat | EE to ME | Position | Press | Fold | Turn | **Weight** |
|---|---|---|---|---|---|---|---|
| Usage Cost | 9 | 9 | 0 | 9 | 0 | 0 | **9** |
| Ease of Use | 0 | 0 | 9 | 9 | 0 | 0 | **9** |
| Reliable | 3 | 3 | 3 | 3 | 3 | 3 | **3** |
| Safe Operation | 3 | 3 | 0 | 0 | 3 | 3 | **3** |
| Quick | 1 | 0 | 0 | 1 | 0 | 0 | **3** |
| Easy to Maintain | 1 | 1 | 1 | 1 | 1 | 1 | **1** |
| **Weighted Sum** | **17** | **16** | **13** | **23** | **7** | **7** | |

- **Method 2 – Counting the number of Input & Output Flows**

EE to Heat: 1+1 = **2**
EE to ME: 1+2 = **3**
Position: 4+3 = **7**
Press: 5+3 = **8**
Fold: 3+0 = **3**
Turn: 3+3 = **6**

- **Method 3 – Counting the number of Input & Output Flows (with Weights)**
  Assigning weights to flows (Energy – 9, Material – 3, Signal – 1)

  EE to Heat = **18**
  EE to ME = **27**
  Position = **21**
  Press = **38**
  Fold = **13**
  Turn = **26**

- **Results Comparison Chart**

| **Requirements** | **I/O** | **I/O (Weights)** |
|---|---|---|
| Press Cloth | Press Cloth | Press cloth |
| Convert EE to Heat | Positioning | Convert EE to ME |
| Convert EE to ME | Turn Cloth | Turn Cloth |
| Positioning | Convert EE to ME | Positioning |
| Fold Cloth | Fold Cloth | Convert EE to Heat |
| Turn Cloth | Convert EE to Heat | Fold Cloth |

**<u>Problem 2 - Automatic Recycling Sorter</u>**

- **Method 1 - Requirements-Function Mapping**

| Functions / Requirmnts | Sort Solid | EE to ME | EE to MagE | Translate | Guide | Compress | **Weight** |
|---|---|---|---|---|---|---|---|
| Usage Cost | 9 | 9 | 9 | 0 | 0 | 9 | **9** |
| Ease of Use | 9 | 0 | 0 | 0 | 0 | 0 | **9** |
| Reliable | 3 | 3 | 3 | 3 | 3 | 3 | **3** |
| Safe Operation | 0 | 3 | 0 | 0 | 0 | 0 | **3** |
| Quick | 1 | 0 | 1 | 1 | 1 | 0 | **1** |
| Easy to Maintain | 1 | 1 | 1 | 1 | 1 | 1 | **1** |
| **Weighted Sum** | **23** | **16** | **14** | **5** | **5** | **13** | |

- **Method 2 – Counting the number of Input & Output Flows**

Sort Solid: 4+6 = **10**
EE to ME: 1+2 = **3**
EE to MagE: 1+1 = **2**
Translate: 3+3 = **6**
Guide: 3+3 = **6**
Compress: 6+3 = **9**

- **Method 3 – Counting the number of Input & Output Flows (with Weights)**
  Assigning weights to flows (Energy – 9, Material – 3, Signal – 1)

  Sort Solid = **48**
  EE to ME: 1+2 = **27**
  EE to MagE: 1+1 = **18**
  Translate = **26**
  Guide = **26**
  Compress = **39**

- **Results Comparison Chart**

| **Requirements** | **I/O** | **I/O (Weights)** |
|---|---|---|
| Sort Solid | Sort Solid | Sort Solid |
| Convert EE to ME | Compress Solid | Compress Solid |
| Convert EE to MagE | Translate | Convert EE to ME |
| Compress Solid | Guide | Translate |
| Translate | Convert EE to ME | Guide |
| Guide | Convert EE to MagE | Convert EE to MagE |

Appendix C

Experimental Material

- **Participant Handouts**

## Morphological Chart Tutorial:

A morphological matrix is a design tool typically used in the conceptual phase to systematically explore the design space and select meaningful concepts for further development. Conceptual Design can be viewed as consisting of four stages as shown below: decomposition, concept generation, concept selection and concept evaluation. Decomposition is the process of breaking down the main design task into a function structure consisting of various lower-level sub-functions. Concept generation is mainly identifying different means of achieving the sub-functions with the help of idea generation methods such as brainstorming, 6-3-5 method, biological inspiration, etc. Concept selection involves combining the identified means for each sub-function to form integrated design concept solutions, keeping in mind the compatibility between selected means. Evaluation is pruning the integrated design concept solutions to a smaller set on the basis of design requirements and perceived performance. The morphological matrix is used as a concept selection tool organized in a table by listing the functions in a column in the left side of the matrix and solution means to the right of each function. A sample morphological chart for four functions of a burrito-folding device is shown (Table 1) per this convention. Selecting one means from every row forms an integrated design concept solution.

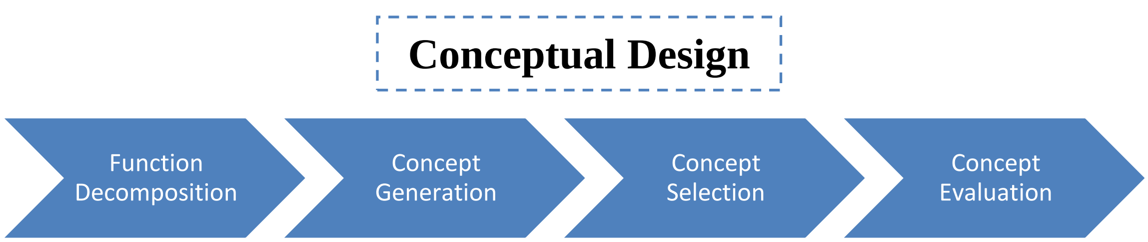


**Table 1 – Sample Morphological Chart**

| Function | Means | | |
|---|---|---|---|
| Receive Tortilla | Table | Locating Plate | Work on top of a stack of tortillas |
| Receive Filling | Hopper | Packets | Tube |
| Combine Materials | Dispense filling onto tortilla | Wrap tortilla around filling | |
| Fold Tortilla | Spatula | Hinged work surface | |

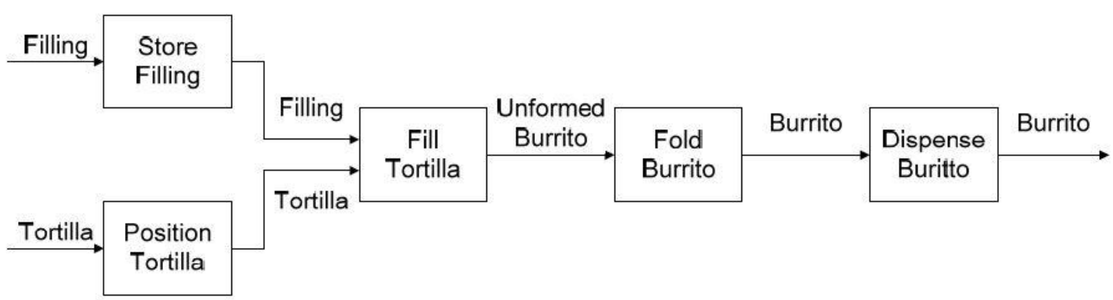
## Morph Chart Training (5-10 mins):

<u>Design Problem Statement</u>

*In general, the food service industry has a great need for speed, efficiency, and cleanliness as preparing large amounts of food quickly is their main goal. As a result, a local restaurant has identified the need for a machine to fold their burritos. Each burrito is made up of a ten-inch tortilla shell and 2 ounces of filling.*

*Design a burrito-folding machine which satisfies the following five functions and can be easily manufactured and installed locally.*

<u>Function Structure</u>



Morphological Chart

| Function | Means | | |
|---|---|---|---|
| 1. Store Filling | 1. Multi-serving package | 2. Bulk filled hopper | 3. Single serving package |
| 2. Position Tortilla | 1. Physical Stop | 2. Visual Marker | 3. Work on top of a stack of tortillas |
| 3. Fill Tortilla | 1. Pour filling onto tortilla | 2. Spoon filling onto tortilla | 3. Extrude filling through tube |
| 4. Fold Burrito | 1. Spatula lifts edges | 2. Roll into tube | 3. Punch through opening in table |
| 5. Dispense Burrito | 1. Gravity | 2. Conveyor belt | 3. Mechanical hand |

Selected Concepts

| | | | | |
|---|---|---|---|---|
| **F1M2** | **F2M2** | **F3M1** | **F4M1** | **F5M2** |
| **F1M3** | **F2M1** | **F3M2** | **F4M1** | **F5M3** |

- **Pre-sketching Prompts**

Prompt 1 – Sketch your dream home in Alaska
Prompt 2 – Sketch a personal yacht at the U.S. Virgin Islands

- **Instructor Reference Sheet**

## USER EXPERIMENT STUDY

## <u>Title</u> – Effect of Function Ordering within Morphological Charts

- <u>Introduction</u> (5 mins)
  Good morning everyone. My name is Anant Chawla, and this is Doug and Hallie. We all are graduate students under Dr. Summers. This activity is part of a research study being conducted at CEDAR Lab to study how designers use morphological charts. Before we begin the research activity, we will introduce to you guys the basics of Engineering Design and explain what are morphological charts. Next we will start the experimental study with some interspersed sketching activities for relaxation. If you guys have any questions or are interested in our research, feel free to contact us any time after class.

- <u>Morphological Chart Tutorial</u> (5 mins)
  - Distribute the tutorial sheet (Page 1) to students
  - Give a brief introduction to what are morphological charts and how are they used.

- <u>Morphological Chart Training</u> (10 mins)
  - Distribute the training sheet (Page 2) to students
  - Go through the design problem statement, function structure and morphological chart
  - Illustrate the selection of two integrated concept design solutions

- <u>Pre-Sketching</u> (5 mins)
  - Distribute the pre-sketching sheet 1 (Page 3) to students

- <u>Experiment 1 – Automatic Clothes Ironing Device</u> (20 mins)
  - Distribute the five sets of Experiment 1 sheets to students
  - Emphasize on time limit and evaluation criteria

- <u>Pre-Sketching</u> (5 mins)
  - Distribute the pre-sketching sheet 2 to students

- <u>Experiment 2 – Automatic Recycling Sorter</u> (20 mins)
  - Distribute the five sets of Experiment 2 sheets to students
  - Emphasize on time limit and evaluation criteria

**<u>Total Time</u> – 70 mins**

- **Data Recording Sheet**

**Concept 1:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 2:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 3:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 4:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 5:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 6:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 7:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 8:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 9:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 10:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 11:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 12:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 13:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 14:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 15:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 16:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 17:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 18:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 19:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

**Concept 20:**

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

- **Morph Chart Presentation**

## EXPERIMENT STUDY - MORPHOLOGICAL CHART

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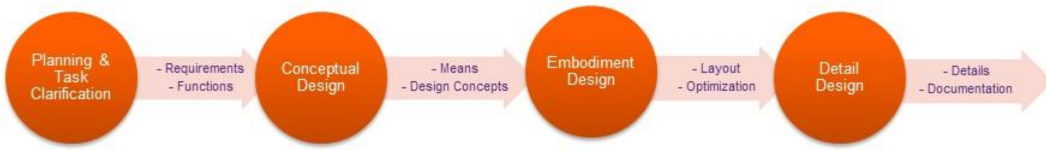
CEDAR
Clemson Engineering Design Applications and Research

CLEMSON UNIVERSITY

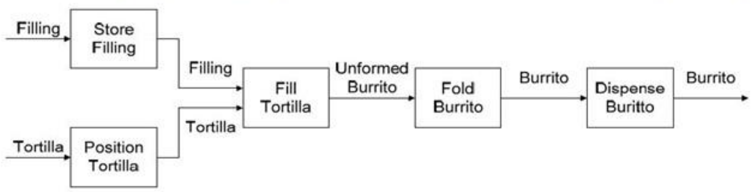
## Engineering Design

- Systematic process to develop functional products and processes
- Stages guide from abstract problem statement to detailed final product/process




## Functions & Function Structure

- Every engineering device performs a function (purpose/transformative action)
- Function structure graphically represents the functions and input-output flows

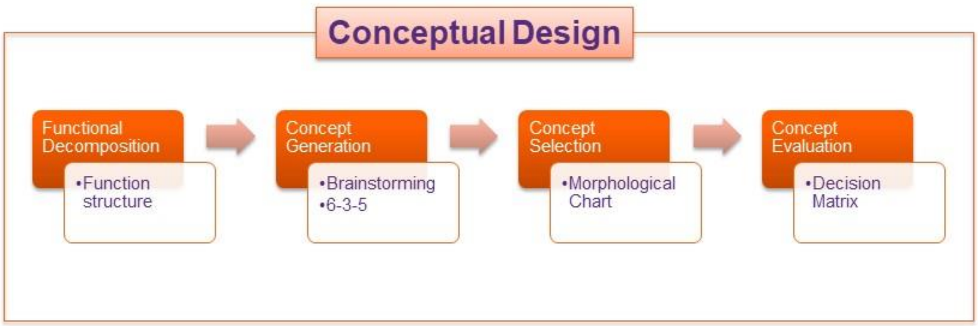


# Morphological Chart



## What is a Morphological Chart?

- Concept selection tool to systematically explore the design solution space
- Used in Conceptual Phase to select concepts for further detailed evaluation
- Functions in one column and solution means to the right of each function

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# Morphological Chart – Training

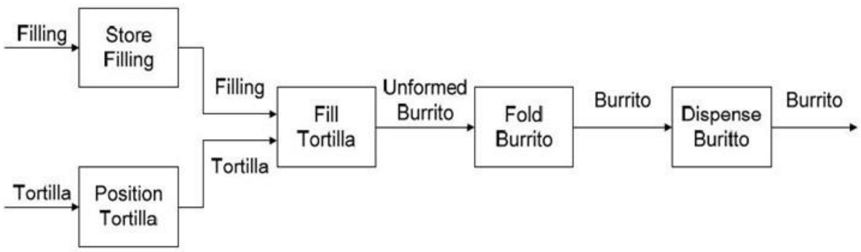


## Design Problem Statement:

*In general, the food service industry has a great need for speed, efficiency, and cleanliness as preparing large amounts of food quickly is their main goal. As a result, a local restaurant has identified the need for a machine to fold their burritos. Each burrito is made up of a ten-inch tortilla shell and 2 ounces of filling.*

*Design a burrito-folding machine which satisfies the following five functions and can be easily manufactured and installed locally.*

## Function Structure:



# Morphological Chart – Training



## Morphological Chart:

| Function | Means | | |
|---|---|---|---|
| 1. Store Filling | 1. Multi-serving package | 2. Bulk filled hopper | 3. Single serving package |
| 2. Position Tortilla | 1. Physical Stop | 2. Visual Marker | 3. Work on top of a stack of tortillas |
| 3. Fill Tortilla | 1. Pour filling onto tortilla | 2. Spoon filling onto tortilla | 3. Extrude filling through tube |
| 4. Fold Burrito | 1. Spatula lifts edges | 2. Roll into tube | 3. Punch through opening in table |
| 5. Dispense Burrito | 1. Gravity | 2. Conveyor belt | 3. Mechanical hand |

## Selected Concepts:

| | | | | |
|---|---|---|---|---|
| **F1M2** | **F2M2** | **F3M1** | **F4M1** | **F5M2** |
| **F1M3** | **F2M1** | **F3M2** | **F4M1** | **F5M3** |

# Appendix D

## MATLAB Analysis Script

```
function [MC, F_Exp1, F_Exp2, M1, M2] = final_analysis (A)

%Input matrix A for all 10 morph charts (MCs). Contains all numerical values and 0's

for ii = 1:10                                   % 10 is the number of MCs
    jj = 1:9:82;
    MC(ii).values = A(1:end, jj(ii):jj(ii)+5); %temporary MC including excess size and
gaps of zeros
    while true
        if isequal(MC(ii).values(end-10:end, :), zeros(11,6))
            MC(ii).values = MC(ii).values(1:end-11,:);        %temporary MC including
gaps of zeros
        else
            break
        end
    end

    MC(ii).samplesize = (1 + size(MC(ii).values,1))/11;        %sample size for every MC
    MC(ii).freq_sum = zeros(6,5);
    MC(ii).exp_sum = zeros(5,5);

    for mm = 1:MC(ii).samplesize
        nn = (mm - 1)*10 + mm;
        MC(ii).student(mm).IDC = MC(ii).values(nn:nn+9, :);        %separating data for
every student
        MC(ii).student(mm).freq = zeros(6,5);
        MC(ii).student(mm).exp = zeros(5,5);
        for xx = 1:10
            for yy = 1:6
                temp = MC(ii).student(mm).IDC(xx, yy);
                if temp > 0 && temp < 6
                    MC(ii).student(mm).freq(yy, temp) = MC(ii).student(mm).freq(yy, temp)
+ 1;
                    if yy < 6
                        TEMP = MC(ii).student(mm).IDC(xx, yy+1);
                        if TEMP > 0 && TEMP < 6
                            MC(ii).student(mm).exp(temp, TEMP) =
MC(ii).student(mm).exp(temp, TEMP) + 1;
                        end
                    end
                end
            end
        end
```

```
        MC(ii).student(mm).coverage = sum(sum(MC(ii).student(mm).freq > 0));
        MC(ii).freq_sum = MC(ii).freq_sum + MC(ii).student(mm).freq;
        MC(ii).exp_sum = MC(ii).exp_sum + MC(ii).student(mm).exp;
        MC(ii).exp_sum_unnorm = MC(ii).exp_sum;
        MC(ii).freq_sum_unnorm = MC(ii).freq_sum;
        MC(ii).row_sum = sum(MC(ii).freq_sum);
    end
    MC(ii).freq_sum = MC(ii).freq_sum/sum(MC(ii).freq_sum(1,:));
%normalizing
    for kk = 1:5
        MC(ii).exp_sum(kk,:) = MC(ii).exp_sum(kk,:)/sum(MC(ii).exp_sum(kk,:));
%normalizing
    end
end

%Alignment - Switching & Flipping
%Experiment 1
MC(2).freq_sum = flipud(MC(2).freq_sum);
MC(3).freq_sum([1 2 3 4 5 6],:) = MC(3).freq_sum([4 1 5 2 3 6],:);
MC(4).freq_sum([1 2 3 4 5 6],:) = MC(4).freq_sum([3 6 2 5 4 1],:);
MC(5).freq_sum([1 2 3 4 5 6],:) = MC(5).freq_sum([2 4 5 1 6 3],:);
%Experiment 2
MC(7).freq_sum = flipud(MC(7).freq_sum);
MC(8).freq_sum([1 2 3 4 5 6],:) = MC(8).freq_sum([4 6 1 2 5 3],:);
MC(9).freq_sum([1 2 3 4 5 6],:) = MC(9).freq_sum([3 1 6 5 2 4],:);
MC(10).freq_sum([1 2 3 4 5 6],:) = MC(10).freq_sum([5 3 2 1 6 4],:);

%Dot Products
%Experiment 1
xx = 1; yy = 2; zz = 1;
F_Exp1 = zeros(6,10); F_Exp2 = F_Exp1;
%preallocation
while zz < 11
    while xx < 5
        if yy == 6
            yy = xx + 1;
        end
        while yy < 6
            den1 = sqrt(diag(MC(xx).freq_sum*MC(xx).freq_sum')).*...
                sqrt(diag(MC(yy).freq_sum*MC(yy).freq_sum'));
            F_Exp1(:,zz) = dot(MC(xx).freq_sum, MC(yy).freq_sum, 2)./den1;
            yy = yy + 1;
            zz = zz + 1;
        end
        xx = xx + 1;
    end
end
%Experiment 2
xx = 6; yy = 7; zz = 1;
while zz < 11
    while xx < 10
```

```
        if yy == 11
            yy = xx + 1;
        end
        while yy < 11
            den2 = sqrt(diag(MC(xx).freq_sum*MC(xx).freq_sum')).*...
                sqrt(diag(MC(yy).freq_sum*MC(yy).freq_sum'));
            F_Exp2(:,zz) = dot(MC(xx).freq_sum, MC(yy).freq_sum, 2)./den2;
            yy = yy + 1;
            zz = zz + 1;
        end
        xx = xx + 1;
    end
end
M1 = mean(F_Exp1,2); M2 = mean(F_Exp2,2);
```