12-2007

MORPHOLOGICAL CHARTS: A SYSTEMATIC EXPLORATION OF QUALITATIVE DESIGN SPACE

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MORPHOLOGICAL CHARTS:
A SYSTEMATIC EXPLORATION
OF QUALITATIVE DESIGN SPACE

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

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by
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December 2007

Accepted by:
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ABSTRACT

A morphological chart is a tool that represents a large qualitative design space. These charts list the functions identified for the design problem, and the means (solutions) that can perform each function. Combining one means for each function will produce a potential integrated conceptual design solution. Repeating this process with every possible combination contained in the morphological chart will generate a long list of conceptual design solutions. Not all of these solutions will be practical, or even physically possible.

As it is difficult to analyze a long list of design solutions and as at present, there are no systematic design tools to aid in such an analysis, a systematic study of morphological charts is explored in this thesis to build the foundation for developing future systematic exploration tools. Existing tools operate by eliminating possibilities at higher levels, such as with Axiomatic Design. Designers may sift through a morphological chart and create concepts based on what experience shows has worked in the past. Two experiments were conducted to determine relationships between morphological chart sizes and topologies with respect to the quality of design concepts generated from the charts. The findings from these experiments suggest that reducing the number of functions represented allowed designers to discover higher quality solutions. Based on these findings, recommendations are made to further filter morphological charts to sizes and shapes that are more easily explored by the designers.

ACKNOWLEDGEMENTS

Thank you, Dr. Summers for your assistance and guidance throughout this project.

Thank you, Dr. Fadel and Dr. Blouin for your time and assistance in reviewing this work.

Thank you to all the CREDO and AID members who assisted with and participated as judges in these experiments.

Thank you to all the ME202 undergraduate students who participated in these experiments.

DEDICATION

This dissertation is dedicated to my wife, Sarah. Thank you for your love, your help, and your encouragement.

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CHAPTER 1

MORPHOLOGICAL CHARTS: USE CONTEXT AND RESEARCH MOTIVATION

Use Context

The contemporary design process can be broken down into general phases: conceptual design, embodiment design, and detail design (Pahl and Beitz, 1996). In some works, embodiment design and detail design are combined into a single product development phase (Ullman, 2003). In the conceptual design phase, the principle solution is created. In the embodiment design phase, the physical layout of the solution is determined. During the detail design phase, the materials are specified and the production systems are finalized (Pahl and Beitz, 1996). This work, in dealing with morphological charts, examines the conceptual design phase.

The concept design phase is further broken down into the following steps. First, the specification is examined and the design problem is identified. Once the problem is understood, function decomposition begins. Solutions for each sub-function must be identified and combined to create a potential integrated conceptual design. Morphological charts may be used in this combination step. Multiple designs are evaluated, and a principle solution is selected. This principle solution will be further explored in the embodiment and detail design phases.

Description of Morphological Charts

A morphological chart in essence is a table of functions and solutions for each function. Normal convention is to list the functions in a column in the left hand side of the table, and list the solutions to each function to the right of the function. Various terms exist for these solutions. Dym and Little use the term *means* (Dym and Little, 2000). The English translation of Pahl and Beitz uses the term *working principle* (Pahl and Beitz, 1995). Suh (2001) uses the term *design parameters*. Throughout this paper, *means* will be used to define the solution to a specific function.

A generic morphological chart using this format is shown in Table 1.1. In this morphological chart, each function is represented with a term F_n. Each means is represented with a term $M_{n.m}$. For example, both means $M_{3.1}$ and $M_{3.2}$ are possible solutions to achieve function F_3.

Table 1.1: A Morphological Chart

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	$M_{n.1}$	$M_{n.2}$	$M_{n.3}$	…	$M_{n.m}$

Statement of the Problem

Idea generation tools are either intuitive or logical. Intuitive idea generation tools attempt to promote creativity (Shah, 1998). Logical idea generation tools have a process of steps to follow (Shah, 1998). Today, morphological charts are intuitive idea generation tools (Shah, 1998). A process for using them to generate high quality design concepts does not exist. This work seeks to support development of a process of steps that will enable morphological charts to be used as logical idea generation tools. In working towards that goal, this work examines the quality of integrated conceptual design solutions generated by undergraduate mechanical engineering students. This work will show that there is a statistically significant difference in the quality of concepts generated from different size morphological charts.

Hypothesis

This work proposes that in a fixed period of time, higher quality integrated conceptual design solutions can be created using morphological charts which contains fewer integrated conceptual design solutions. This claim is investigated through two experiments described in Chapter 3 and Chapter 4.

The following chapter discussed morphological charts as defined in the literature. Limitations to the use of morphological charts are extracted, specifically the randomness of exploring the design space. It is this limitation that forms the motivation for the experiments that are detailed in Chapter 3 and Chapter 4. Following the individual experiments, a comparison of the two approaches is found in Chapter 5. Finally, a summary, concluding remarks, and possible future extensions are discussed in the closing chapter.

Experimental Constraints

There are many aspects related to the use of morphological charts worthy of study. This work examines the impact of morphological chart size on the quality of integrated concepts generated. Other items which might impact the quality of integrated concepts include the amount of time permitted for a designer to consider the morphological chart, the experience of the designer, and the presence of known good or bad solutions in the charts. The process of generating a morphological chart also could be served by further study.

This work was limited to just the size and shape of morphological charts because these aspects are directly related to the number of functions and the number of means per function in the charts. The number of functions and the number of means per function directly influence the number of possible integrated concepts that the morphological chart may produce. Additional areas of impact, such as having the participants develop their own morphological chart, or using participants with a wide variation in experience were not investigated because those factors would introduce much more variation into the experiment, and make statistical analysis more difficult without increasing the number of participants.

Each experiment conducted for this work required a population of participants with similar backgrounds, but who had not already participated in this experiment. Using participants only once reduces any impact that a participant's familiarity with the experiment may have on the results. This limits the number of trials that may be run, because the pool of available participants is limited.

CHAPTER 2

MORPHOLOGICAL CHARTS: SOLUTION SPACE EXPANSION AND EXPLORATION TOOLS

A morphological chart is a tool that represents possible solutions to a design problem. It consists of a list of the decomposed sub-functions of a design and the means by which each sub-function may be realized. Typically, a morphological chart is shown in tabular form. The sub-functions are listed in the left-most column. The means are listed to the right of the sub-functions. To create a morphological chart, one must identify the primary function, decompose this function, and then generate ideas for how to achieve each sub-function. Once the chart is populated, the designer combines the possible means to form connected solutions. This chapter discusses the steps of creating morphological charts and evaluates their usage in design.

Function Identification

The first step in generating a morphological chart is identification of the primary function. When a need is identified, the search for a design solution can begin. Many works in design theory relate that the functions needed in the design solution must be identified (Pahl and Beitz, 1995; Otto and Wood, 2001; Ulrich and Eppinger, 1995; Dym and Little, 2000). Functions are the relationships between the inputs and outputs of a designed system. In basic form, they are a pair consisting of an action verb and a noun (Dym and Little, 2000; Suh, 2001; Otto and Wood, 2001; Stone and Wood, 1999; Hirtz et al., 2001). For most of this work, the examples will use two novel devices, a burrito folding machine, and an automatic pet food dispenser. In some cases, the more common kitchen refrigerator is used when familiarity with the device is desired. For the case of a refrigerator, several functions come to mind. A partial list includes *cool food*, *store food*, *preserve food*, *display food*, and *hold food*. However, the primary function of a refrigerator is to *preserve food*. Some devices which *preserve food* are shown below in Figure 2.1. The action, or verb, is *to preserve*; while the target of the action is the noun *food*. Once this primary function is identified, the designer may begin the search for means to achieve this function. Examples of additional primary functions are listed below in Table 2.1

Table 2.1: Example Primary Functions

Device	**Primary Function**
burrito folder	assemble burritos
automatic pet food dispenser	dispense food
Refrigerator	preserve food
Automobile	transport human
washing machine	clean clothes
Pencil	mark surface

refrigerator:	icebox:
	
http://www.kenmore.com/	http://www.museum.siu.edu/

can:	dehydrator:
	
http://www.samsclub.com/	http://www.bimart.com/

Figure 2.1: Some Artifacts Which Preserve Food

The top-level function should be defined in general terms to prevent influencing the design solution or restricting the region of design space considered (Ulrich and Eppinger, 1995; Dym and Little, 2000; Suh, 2001). Working from a function defined with non-general terms could place a restriction on the design process and possibly rule out promising search regions. In the refrigerator example above, if the primary function were stated as *cool food* rather than *preserve food*, other possible methods for preserving foods, such as the can, and the dehydrator shown in Figure 2.1, would not be identified as possible solutions. At present, there does not appear to be a systematic way to develop the function in a general way (Maier and Fadel, 2002). At best, the rule of thumb to "keep it general" (Dym and Little, 2000) provides a guide but no measure to evaluate success.

Function Decomposition

Once a high level primary function is identified, it may be decomposed into simpler sub-functions. It is generally agreed that decomposition of a complicated function is a good practice (Ulrich and Eppinger, 1995; Dym and Little, 2000; Pahl and Beitz, 1996). Systematic decomposition methods provide some assistance in doing this. Examples of such methods include function listing (Dym and Little, 2000; Otto and Wood, 2001), black box (Ulrich and Eppinger, 1995; Dym and Little, 2000; Suh, 2001; Hyman, 2003), axiomatic design (Suh, 2001), function-means tree (Dym and Little, 2000), reverse engineering (Dym and Little, 2000; Otto and Wood, 2001), and benchmarking (Dym and Little, 2000; Otto and Wood, 2001). A more detailed discussion of these methods follows below.

Sub-functions either support the higher-level function directly or deal with the byproducts of the means to achieve the higher-level function (Dym and Little, 2000; Pahl and Beitz, 1996). In the refrigerator example above, the higher-level function of *preserve food* is supported by the functions *cool food* and *hold food*. A byproduct of the standard kitchen refrigerator is waste heat, produced by the compressor motor. The compressor is a means employed to cool the food. A sub-function dealing with this byproduct could be *dissipate heat*. In contrast, an ice box would not require a sub-function to dissipate heat, because it does not generate heat while in operation.

In some cases, the order in which sub-functions occur and the relationships between them is important to the higher-level function (Ulrich and Eppinger, 1995; Pahl and Beitz, 1996). In an example morphological chart used in a user study, and described in greater detail in Chapter 3, an automatic burrito folding machine has functions which must occur in a specific order. The device must fold the burrito and then later dispense the burrito. If the order of these two functions is not respected in the design, the device will not function properly.

Further, there may not be just one single result for the decomposition of a particular function (Kurfman et al., 2000; Ulrich and Eppinger, 1995). The decomposition process requires decisions and evaluations that will rely on the personal experience of the designer. The anticipation of byproducts to include influences the sub-functions included. The tools used may also impact the functional decomposition produced. Starting with a different decomposition may result in a different integrated conceptual design solution. The following are existing methods for decomposing functions.

Function Listing

The task of listing sub-functions can provide a functional decomposition. To facilitate this process, Dym and Little (2000) suggest picturing the complete design solution and then taking away some aspect of the completed design. Otto and Wood (2001) suggest where possible to physically subtract components from an existing product. The designer would observe what happens as a result of removing this function. This process can illuminate necessary functions. For example, consider the function *prepare burrito*, which can be satisfied by a burrito folding machine. If the machine is unable to fold a tortilla, it will be unable to prepare a burrito. A necessary sub-function of *prepare burrito* is *fold tortilla.* A partial function listing for a burrito folding device is shown below in Figure 2.2. In general, listing functions can be difficult because there is no representation of how the sub-functions relate to each other. Otto and Wood (2001) propose constructing a function tree, which will be discussed below, with the functions observed in this process. This adds more structure to the list of functions.

- fold tortilla
- dispense filling
- dispense burrito
- collect raw materials
- …

Figure 2.2: Partial Function Listing for a Burrito Folder

Black Box

A common decomposition tool is to create a "black box" model of the system (Ulrich and Eppinger, 1995; Dym and Little, 2000; Suh, 2001; Hyman, 2003). First, the designer pictures the function as a black box with inputs and outputs. The term "black box" is used because at this stage, no attempt is made to describe what is inside the system (Ulrich and Eppinger, 1995; Dym and Little, 2000; Suh, 2001; Hyman, 2003). By directly addressing the inputs and outputs, this method closely matches the definition of function outlined above. The inputs and outputs to the system consist of material, energy, and signals. Convention is to use a heavy line for material, a light line for energy and a dashed line for signal as illustrated by the inputs to the black box in Figure 2.3. Dym and Little (2000) suggest that all inputs and outputs must be considered. This includes undesired outputs, such as byproducts or waste.

To consider what passes into and out of the system, one must define the system's boundary. The next step is to consider what is happening in the black box. Replace the single box with multiple boxes each with their own inputs, outputs, and boundaries contained within the initial black box. It is important to note how the outputs of sub-functions may be inputs to other sub-functions. Defining the appropriate boundary is essential for the use of this tool. An incorrect boundary will distort or even leave out the necessary inputs and outputs for the analysis. Dym and Little (2000) suggest consulting with the client or user to determine appropriate boundaries. Also, it is difficult to anticipate what byproducts will be produced when dealing purely with the functions. Byproducts will be the result of the means chosen to fulfill the functions. Figure 2.3 and Figure 2.4 illustrate one step in the process of black-box decomposition.

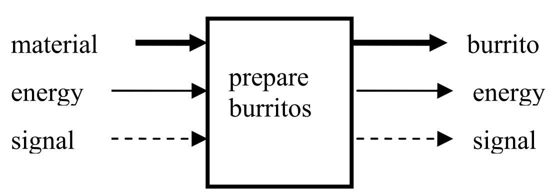


Figure 2.3: First "Black Box" for a Burrito Folder

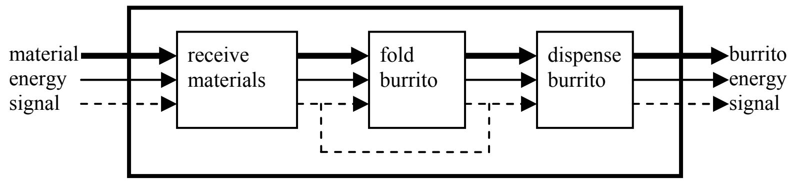


Figure 2.4: "Black-box" Components Identified

One possible way to capture information about byproducts is to consider what each means affords the system (Maier and Fadel, 2001). Byproducts are any negative, or undesirable affordances provided by a means. It is possible that byproducts can be compensated by the affordances of other means already in the system. If none exist to handle the byproduct, then another sub-function must be added specifically to address this byproduct. In contrast, Weber and Condoor suggest that designers should defer handling byproducts until later in the analysis and design process stating that it is sufficient to analyze only those inputs and outputs that are independent of the design solution (Weber and Condoor, 1999). This permits leaving out byproducts that are the result of a particular means.

Axiomatic Design

Axiomatic Design (Suh, 2001) provides another tool for decomposition. Suh's process captures both the functions and the means that can perform them. Again, one starts with a primary function in general terms. This primary function is set at the top of a tree that will grow to contain sub-functions. Next, one defines a primary means to obtain this function. The primary means is set at the top of a second tree. The decomposition process in axiomatic design is described as a "zig-zag" process where attention switches back and forth between the two trees. After a level in the function tree is defined, the corresponding level in the means tree is defined. Next, return to the function tree and decompose further any sub-functions that require it. Suh states that decomposition should continue "until the design is completed so that it can be implemented." For each of these functions, one must find a corresponding mean. At each step the preferred means should be chosen when there are multiple options. Suh proposes that the relationship between functions (Suh's term is "functional requirements" or "FR") and means (Suh's term is "design parameters" or "DP") can be expressed as a matrix operation shown here in Figure 2.5.

$$\begin{bmatrix} \vdots \\ FR_1 \\ FR_2 \\ \vdots \end{bmatrix} = \begin{bmatrix} \ddots & \cdots & \cdots & \iddots \\ \vdots & A_{11} & A_{21} & \vdots \\ \vdots & A_{12} & A_{22} & \vdots \\ \iddots & \cdots & \cdots & \ddots \end{bmatrix} \begin{bmatrix} \vdots \\ DP_1 \\ DP_2 \\ \vdots \end{bmatrix}$$

Figure 2.5: Axiomatic Design Equation Set

The matrix comprised of A_{11}, A_{21}, etc. is known as the design matrix. The preferred design is one where the design matrix is of the form where all values are zero except for the diagonal running from upper left to lower right. This is what Suh calls an "uncoupled" design. The functions are all independent of each other. If that is not possible, a satisficing option is for all values above and to the right of the diagonal to be zero. This is what Suh calls a “decoupled” design.

$$\begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \qquad \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & X & X \end{bmatrix}$$

uncoupled **decoupled**

Figure 2.6: Axiomatic Design: Design Matrices

Axiomatic design creates an early identification of possible means and requires an immediate choosing of the means. Dym and Little (2000) warn that choosing the means early can be a problem. This will bias further decomposition to fit with the means already chosen. The rationalization for doing this is that one chooses the best possible means at each step, so the design is not moving away from an optimal design solution. Axiomatic design does not capture multiple options. A tool which allows or generates multiple means will provide input into a morphological chart. Axiomatic design is a tool that sidesteps the generation of multiple means, so it would not work as well if one intends to work with a morphological chart.

Function-Means Tree

A similar approach to Axiomatic Design decomposition is the function-means tree (Dym and Little, 2000). Like Axiomatic Design, this approach identifies both functions and means. The tree begins at the top with the primary function. The next level is a list of possible means that can perform that primary function. Supplemental sub-functions, both to achieve the function and to address and mitigate any byproducts of the means, are listed under each means. Means are listed under each new sub-function. The process continues, defining functions and means in alternating levels of the tree, as shown in Figure 2.7. Unlike Axiomatic Design, the function-means tree provides a way to display multiple options at once in the same diagram. Some editing of options can be imposed by the need to find a means to satisfy a function. If no means can be identified, or if the only options are impractical, then exploration along the branch may be terminated (Dym and Little, 2000). Again, this approach imposes an early selection of means, which Dym and Little (2000) state is undesirable.

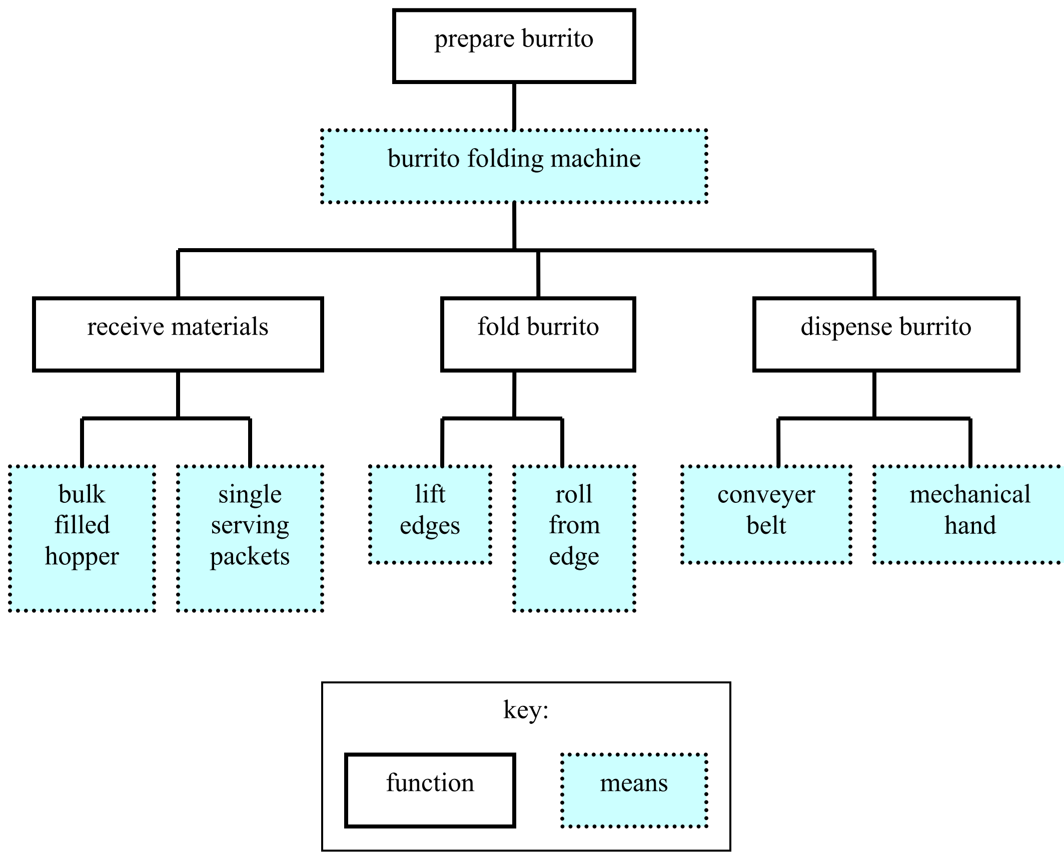


Figure 2.7: Function Means Tree

Reverse Engineering

Reverse engineering, or dissection, is another approach to decomposition. It employs a somewhat different process. Rather than imagining a design artifact that does not exist, one studies what already exists (Dym and Little, 2000; Otto and Wood, 2001). It does not require an exact match with what one is trying to design (Dym and Little, 2000; Fridley, et al., 1997). One must acquire this other object and examine it to determine what means are included with it. Dym and Little (2000) propose that the process begin by dissecting the object to identify the means. After the means are identified, the next step is to find the functions that these means satisfy. Next consider alternative means that could satisfy these functions, especially ones that could produce improvements over the old design artifacts. Otto and Wood (2001) argue that before dissection, it is important to understand the customer needs and have a functional model of the design problem. They suggest using a black box analysis to determine the function, but other decomposition methods outlined here would work as well. Problems with this approach include the expense of buying the object to reverse engineer, and a bias towards the original design goals of the product under examination (Dym and Little, 2000). This bias is significant because it is unlikely that the needs of one's customer will exactly match that of the customer of the previous design. The lack of alternative means can make it hard to make a large change from the product one is reverse engineering. There may be patent restrictions on the information one gains (Dym and Little, 2000).

Benchmarking

Benchmarking is a process similar to reverse engineering in that one is examining existing designs (Dym and Little, 2000; Otto and Wood, 2001). The difference is that one examines multiple designs, but in less detail. Complete designs may be benchmarked, or merely a specific function in a variety of designs. As the designs are analyzed, the characteristics and performance of each are rated. Compared with reverse engineering, this approach provides more variety of means to analyze. Benchmarking will provide information about general industry trends, however the knowledge gained shows where the competition is today, not where they will be tomorrow (Otto and Wood, 2001). Benchmarking shares the potential pitfall of patent restrictions with reverse engineering.

Function Decomposition Summary

All of these approaches outlined above and illustrated in Table 2.2 have a common unresolved problem: *How far should the design problem be decomposed?* At present, there are only guidelines and "rules of thumb" to answer this question. Stopping at too high a level can lead to means that are overly complicated. There may be fundamental problems in the underlying means that are not brought to light because the analysis is stopped too soon. Carrying out the analysis too far is a waste of time and effort. For any situation there will be a point where the returns from additional work are not justified by the effort necessary to achieve them. Ulrich and Eppinger (1995) propose that generating three to ten sub-functions is sufficient. Suh (2001) states that decomposition should continue "until the design is completed so that it can be implemented." The decomposition should be done until the point where the means are specific enough to permit an analysis. This works for axiomatic design and could also work for a function-means tree, where the means are identified as part of the functional decomposition.

Table 2.2: Summary of Decomposition Methods

Decomposition Method	Means Identified	Output	Required Expertise	References
Listing Functions	None explicitly	Generic function list	Low	Dym and Little, 2000
Black Box	None explicitly	Generic functional structure	Medium	Ulrich and Eppinger, 1995; Dym and Little, 2000; Suh, 2001; Hyman 2003
Axiomatic Design	One solution	A single solution	High	Suh, 2001
Function-Means Tree	Several solutions	Several possible solutions	Medium	Dym and Little, 2000
Reverse Engineering	Only existing ones	Existing solutions	Low	Dym and Little, 2000; Otto and Wood, 2001
Benchmarking	Only existing ones	Existing solutions	Low	Dym and Little, 2000; Otto and Wood, 2001

The next step after function decomposition is identifying and generating the means. Some approaches, such as Axiomatic Design, will generate means as part of the function analysis. Others, such as the black box approach, will not. For these approaches, means need to be identified for the functions. While it would be useful to have a way to prioritize the functions to determine which ones have the greatest potential for improving the design solution, and focus efforts on the means for those functions, this is out of scope for this research.

Means Generation

After the function has been decomposed, means must be generated for each function to fill out a morphological chart. Many existing idea generation tools can be used for this phase. Idea generation tools fall into two categories, logical and intuitive (Shah, 1998). Logical tools employ a regular process of sequential steps to generate ideas. Examples of logical tools include TRIZ, Axiomatic Design, and "German systematic idea generation methods" (Shah, 1998). Intuitive tools attempt to remove perceived barriers to creativity and increase chance for conditions thought to promote creativity. Examples of intuitive tools include brainstorming, 6-3-5 method, and C-sketch. Note that, if Axiomatic Design or Function-Means tree were used to decompose the functions, they also generated some means in the process. For this thesis, the actual generation of the different means to populate a morphological chart is considered out of scope of investigation.

Morphological Chart Detail

Morphological charts are tools for generating a listing of integrated conceptual design solutions for a design problem. Other terms used for morphological charts are concept combination tables (Ulrich and Eppinger, 1995), function-means tables (Dym and Little, 2000), morphological matrices (Weber and Condoor, 1998; Hutchensen et al, 2007; Bryant et al, 2007), and morphological overviews (Savanovic and Zeiler, 2007). A table is constructed by decomposing the design and listing all the functions in a column. These functions should all be at the same level of detail (Dym and Little, 2000; Tiwari et al, 2007). The possible means for each function are listed in rows to the side, as shown in Table 2.3. Combining one means for each function will produce a possible integrated conceptual design solution. Repeating this process with every possible combination contained in the morphological chart will generate an exhaustive list of conceptual design solutions. In this manner, morphological charts provide a sense of the size of the design space (Dym and Little, 2000). Morphological charts are used in situations where the design space is fairly open and when the designer wishes to use a systematic or methodical process to generate concepts.

Table 2.3: 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	

The size of the list can be calculated by multiplying the number of means for each function together (Pahl and Beitz, 1996; Dym and Little, 2000). In general, for a morphological chart with functions F_1, F_2, F_3 ... F_n, where each function has a number of means (M_1 for F_1, M_2 for F_2 ... M_n for F_n) the number of integrated conceptual design solutions can be determined by the equation:

Equation 2.1
$$\textit{number of solutions} = \prod_{i=1}^{n} M_i$$

For the special case of a rectangular morphological chart, with n functions where the number of means for each function is the same ($M_1 = M_2 = M_3 = \ldots = M_n = M$) Equation 2.1 reduces to the form:

Equation 2.2
$$\textit{number of solutions} = M^n$$

The solution list can be reduced in size by eliminating impractical concept means. This activity prunes the initial morphological chart. Combinations that are impractical can also be eliminated from consideration which reduces the number of resulting design solutions (Ulrich and Eppinger, 1995; Dym and Little, 2000; Pahl and Beitz, 1996; Aygün, 2000). Impractical combinations are those with interactions that imperil the rest of the design. One approach to prune the morphological chart, compatibility matrices, is proposed in (Pahl and Beitz, 1996). A compatibility matrix is offered in Table 2.4 which evaluates the suitability of combining concept means for two selected functions. The total number of compatibility matrices required is shown below in Equation 2.3, where *n* is the number of functions identified.

Equation 2.3

$$number\ of\ matrices = \frac{n(n-1)}{2}$$

Table 2.4: Compatibility Matrix for Two Functions

		Receive Tortilla		
		table	locating plate	work on top of a stack of tortillas
Fold Tortilla	lift edges with spatula	OK	OK	?
	Hinged work surface	OK	?	NO

key:

OK = means are compatible
? = means may be compatible
NO = means are not compatible

The compatibility matrix shown above in Table 2.4 has means that are compatible, means that are not compatible, and means that may be compatible. These three states are shown with the notes "OK", "NO", and "?". An example of a compatible combination is placing the tortilla on a table and folding it by lifting the edges with a spatula. This combination is compatible. By contrast, working on a stack of tortillas is not compatible with a hinged work surface that folds under the tortilla. In this case, with the stack of tortillas, the device would make a burrito with the tortilla on top, then remove the burrito and work on the next tortilla in the stack. Using a hinged work surface under the tortillas would not work because the hinged surface needs to be in direct contact with the tortilla you want to fold. If there is a whole stack of tortillas on top of the hinged work surface, the device will not function properly.

Advantages/Disadvantages

Based on the reviewed limited literature discussing morphological charts, some advantages of morphological charts include their ability to show unexpected pairings of features (Ulrich and Eppinger, 1995). In this way, they can lead to the creation of new concepts that may not have otherwise been thought of by the designer (Dym and Little, 2000). Further, they provide a perspective of the overall design space.

Generating all these new options is a disadvantage of morphological charts. With only a few functions and means, the number of integrated conceptual design solutions can grow quite extensive (Dym and Little, 2000). Some of the combinations generated will not be good solutions to the design problem (Dym and Little, 2000). Morphological charts provide a good method for generating a list of integrated conceptual design solutions, but do not have a useful way to choose the promising solutions for further evaluation.

Bohm, et al. (2005) discuss a tool that can automatically fill a morphological chart with means for each function, once properly identified. The procedure requires a certain formatting of the function requires a functional decomposition. The information is drawn from a repository of existing solutions. In this experiment, the morphological charts were generated manually by the author.

To continue the example of Table 2.3, there are three means for the function "receive tortilla", three means for the function "receive filling", two means for the function "combine filling" and two means for the function "fold tortilla". As shown by Equation 2.1, the total number of possible combination is the product of 3, 3, 2, and 2, which equals 36. This agrees with the number of integrated conceptual design solutions listed in Table 2.5.

Table 2.5: Exhaustive List of Combinations from Morphological Chart in Table 2.3

number	concepts	receive tortilla	receive filling	combine materials	fold tortilla
1	1-1-1-1	Table	hopper	dispense filling onto tortilla	Spatula
2	2-1-1-1	locating plate	hopper	dispense filling onto tortilla	Spatula
3	3-1-1-1	work on top of stack of tortillas	hopper	dispense filling onto tortilla	Spatula
4	1-2-1-1	Table	packets	dispense filling onto tortilla	Spatula
5	2-2-1-1	locating plate	packets	dispense filling onto tortilla	Spatula
6	3-2-1-1	work on top of stack of tortillas	packets	dispense filling onto tortilla	Spatula
7	1-3-1-1	Table	tube	dispense filling onto tortilla	Spatula
8	2-3-1-1	locating plate	tube	dispense filling onto tortilla	Spatula
9	3-3-1-1	work on top of stack of tortillas	tube	dispense filling onto tortilla	Spatula
10	1-1-2-1	Table	hopper	wrap tortilla around filling	Spatula
11	2-1-2-1	locating plate	hopper	wrap tortilla around filling	Spatula
12	3-1-2-1	work on top of stack of tortillas	hopper	wrap tortilla around filling	Spatula
13	1-2-2-1	Table	packets	wrap tortilla around filling	Spatula
14	2-2-2-1	locating plate	packets	wrap tortilla around filling	Spatula
15	3-2-2-1	work on top of stack of tortillas	packets	wrap tortilla around filling	Spatula
16	1-3-2-1	Table	tube	wrap tortilla around filling	Spatula
17	2-3-2-1	locating plate	tube	wrap tortilla around filling	Spatula
18	3-3-2-1	work on top of stack of tortillas	tube	wrap tortilla around filling	Spatula
19	1-1-1-2	Table	hopper	dispense filling onto tortilla	hinged work surface

number	concepts	receive tortilla	receive filling	combine materials	fold tortilla
20	2-1-1-2	locating plate	hopper	dispense filling onto tortilla	hinged work surface
21	3-1-1-2	work on top of stack of tortillas	hopper	dispense filling onto tortilla	hinged work surface
22	1-2-1-2	Table	packets	dispense filling onto tortilla	hinged work surface
23	2-2-1-2	locating plate	packets	dispense filling onto tortilla	hinged work surface
24	3-2-1-2	work on top of stack of tortillas	packets	dispense filling onto tortilla	hinged work surface
25	1-3-1-2	Table	tube	dispense filling onto tortilla	hinged work surface
26	2-3-1-2	locating plate	tube	dispense filling onto tortilla	hinged work surface
27	3-3-1-2	work on top of stack of tortillas	tube	dispense filling onto tortilla	hinged work surface
28	1-1-2-2	Table	hopper	wrap tortilla around filling	hinged work surface
29	2-1-2-2	locating plate	hopper	wrap tortilla around filling	hinged work surface
30	3-1-2-2	work on top of stack of tortillas	hopper	wrap tortilla around filling	hinged work surface
31	1-2-2-2	Table	packets	wrap tortilla around filling	hinged work surface
32	2-2-2-2	locating plate	packets	wrap tortilla around filling	hinged work surface
33	3-2-2-2	work on top of stack of tortillas	packets	wrap tortilla around filling	hinged work surface
34	1-3-2-2	Table	tube	wrap tortilla around filling	hinged work surface
35	2-3-2-2	locating plate	tube	wrap tortilla around filling	hinged work surface
36	3-3-2-2	work on top of stack of tortillas	tube	wrap tortilla around filling	hinged work surface

As is illustrated here, the list of possible combinations can quickly grow quite large (Dym and Little, 2000). Adding another function to a morphological chart will multiply the number of design solutions by the number of means added with that function. For example, adding another function with two means to the morphological chart shown in Table 2.3 would double the number of integrated conceptual design solutions from 36 to 72 (Π(means per function) = 3*3*2*2*2 = 72). Adding means to existing functions in a morphological chart will also increase the number of solutions. Adding two additional means to the "receive filling" function would increase the number of solutions to 60 (Π(means per function) = 3*5*2*2 = 60). These alternatives are illustrated in Table 2.6.

Table 2.6: Number of Integrated Conceptual Design Solutions in Three Different Size Morphological Charts

	Number of means for each function	Number of possible solutions
Chart shown in Table 2.3	3, 3, 2, and 2	36
Adding 1 new function with 2 means	3, 3, 2, 2, and 2	72
Adding 2 means to an existing function	3, 5, 2, and 2	60

A morphological chart is a tool which can represent a large number of integrated conceptual design solutions in a concise manner. As the number of means and sub-functions grow, the number of potential solutions can grow quite large. It may be impossible or at least very time consuming to try and evaluate every potential solution, so a designer must choose those that look promising for further analysis. It would be useful to know if the number of sub-functions, the number of means per sub-function, or the number of potential integrated conceptual design solutions contained in a morphological chart has an impact on the ability of a designer to find the promising design solutions contained in a morphological chart. The experimental studies detailed in subsequent chapters of this document seek to study these effects.

CHAPTER 3

EXPERIMENTAL STUDY WITH TWO MORPHOLOGICAL CHARTS

If one is to use a morphological chart to generate integrated conceptual design solutions, it would be useful to know if the structure of the morphological chart impacts how easily one can find promising design solutions contained in the morphological chart. To develop understanding of this, the author conducted an experiment to determine the effects of morphological chart shape on the quality of design solutions chosen from the morphological chart. Two morphological charts were created, one with five functions, and one with three functions. Both charts contained the same number of means, or sub solutions. These charts were then used by participants to form different concepts with an emphasis on identifying high quality concepts. These concepts were then evaluated by a panel of judges to determine which configuration of morphological charts yielded the higher quality concepts. The following sections detail this experimental exercise.

Experimental Method

For this study, the author prepared rectangular morphological charts for the burrito folder design problem discussed above. For the first chart, the design problem was decomposed into three separate functions. For the second, the problem was decomposed into five separate functions. The process of generating means for each function was deliberately fixed such to prepare a certain number of means for each function, as shown in Table 3.1. The chart with three functions had five means for each function, and the chart with five functions had three means for each. This produced two morphological charts, each with a total of fifteen means, but representing different quantities of potential design solutions. The two morphological charts are shown below in Table 3.2 and Table 3.3. No means were included in either chart that were intentionally poor choices.

Table 3.1: Morphological Chart Sizes

	Morphological Chart #1	Morphological Chart #2
Number of functions	3	5
Number of means per function	5	3
Total number of means in chart	15	15
Total number of design solutions	53 = 125	35 = 243

Table 3.2: Morphological Chart #1 (3 x 5)

Function	Means				
store and dispense filling	extrude through tube from sack	pour from hopper	transfer with spoon from bucket	unwrap individual serving size and drop	sprinkle in powder form then rehydrate
fold burrito	plate under tortilla is hinged and folds	spatula lifts the edges of the tortilla	flexible work surface rolls up	work-surface edges lift up and slide towards center	tortilla punched through hole in work surface
dispense burrito	slide on conveyor belt	slide down chute	push off to side	drop from elevated area	grab with mechanical hand

Table 3.3: Morphological Chart #2 (5 x 3)

Function	Means		
store filling	multi-serving package	bulk filled hopper	single serving package
position tortilla	physical stop	visual marker	work on top of a stack of tortillas
fill tortilla	extrude filling through tube	pour filling onto tortilla	spoon filling onto tortilla
fold burrito	spatula lifts edges	roll into tube	punch through opening in table
dispense burrito	gravity	conveyor belt	mechanical hand

Participants

The participants employed in this experiment possessed a similar educational background. They were all students enrolled in a required sophomore level mechanical engineering design and kinematics class at Clemson University. The students had exposure to morphological charts in the class through both lectures and in class exercises. However, not all the students had used morphological charts in their semester long design projects. Some students may have possessed outside experience with morphological charts. The extent of outside knowledge was not captured in this experiment.

Two different groups participated in this study; students from two different class sections. The two sections were taught by different instructors. The inclusion of two sections was done to increase the number of participants. Differences between the groups were minimized by both being from the same course and both meeting in their usual classrooms and at the usual class time on the same day. Analysis was done to verify if the different sections were significant in this research. Participants were randomly assigned either Morphological Chart #1 or Chart #2. The chart assignments were done such that the same number of participants worked with each morphological chart in each class period. In the event that the number of participants was not exactly divisible by the number of groups, the difference between group sizes did not exceed one. There was some risk in this method as if a significant number of students elected not to participate after accepting a chart assignment; it could skew the group sizes. As can be seen below in Table 3.8, there was some disruption in this manner, but the total number of participants is nearly equal for the two charts.

Design Problem

The design problem chosen for this study was to create a burrito folding device. This was a project from the same sophomore mechanical engineering course these participants were taking, but from an earlier semester. The burrito folding device was chosen to ensure that the design problem was of a similar scope to the project these participants were currently studying in class, but to have a design problem they were not likely to have preconceived thoughts about in advance of the experiment. If some participants knew more about the design problem than others, that would introduce an additional variable into the study.

The author reviewed several final reports from the burrito folding device class. These reports included functional decompositions and morphological charts. Although the author prepared new morphological charts, the review of the old reports was useful. By reading these reports, effectively, the input of several designers went into the creation of the morphological charts for this study. The assumption was made that this input reduced the likelihood that critical functions were left out of the morphological charts.

In this study, transforming from one morphological chart to the other required changes both to the means and the functions. To reduce the number of functions, one pair of functions was merged (*store filling* and *fill tortilla* were replaced by *store and dispense filling*), and a third function was omitted (*position tortilla*). To add means, the level of detail was increased. These transformations do not guarantee the exact same solution set for the two morphological charts. The goal of this work was to study the effect of morphological chart size on the quality of integrated concepts generated from the chart. The method chosen to change the chart size was to change the number of functions and the number of means per function. Changing these will change the number of possible integrated concepts, which presents a different set of solutions to the designer.

Procedure

During the semester, the students had an overview of functional decomposition, means generation, and morphological charts as part of their regular lectures. On the day of the study, the author provided a reminder of the details of morphological charts.

The participants were given a packet of information containing a morphological chart and an answer form. The form contains room for the participant to list eight integrated conceptual design solutions and rate them against criteria provided by the author. These criteria are shown in Table 3.4. The participants were instructed to use a 9-3-1 scale in their ratings, as shown in Table 3.5. Participants who used values other than those provided were not excluded from the results. The nonstandard values were accepted as they were, and were not mapped to the standard 9-3-1 values. The participant ratings and criteria weightings were used in a decision matrix to determine a final score for each solution generated. The participants were randomly assigned either a chart with three functions, as shown in Table 3.2, or one with five functions, as shown in Table 3.3.

Table 3.4: Solution Evaluation Criteria

Criteria	Weight
low cost	9
easy to clean	3
number of parts	1

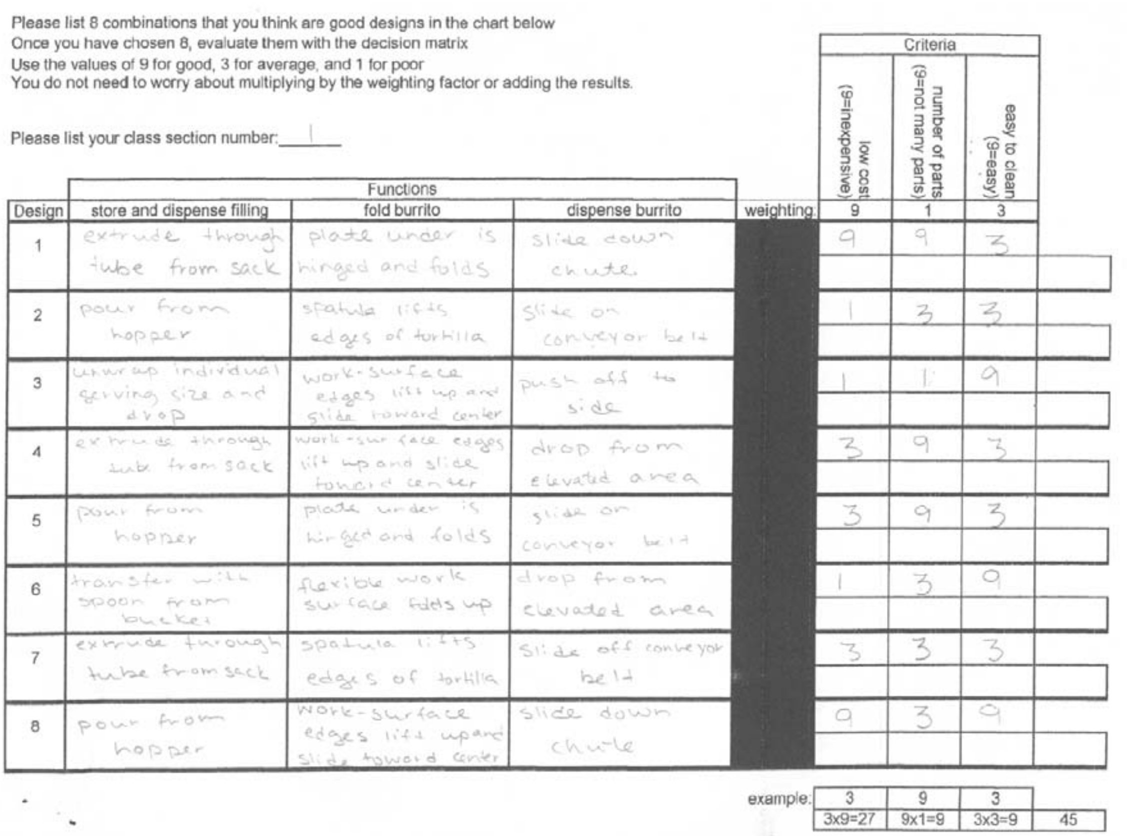
Table 3.5: Solution Evaluation Weights

Level	value
Good	9
Fair	3
Poor	1

The participants were given instructions about the testing procedure. They were told how to record and score their chosen integrated conceptual design solutions. After the introduction, they were allowed 30 minutes to develop and evaluate their design solutions for the exercise. The participants were explicitly instructed to try and form the highest quality conceptual combinations that they could. The time limit for the concept generation phase was fixed by the need to conduct the experiment without exceeding the time scheduled for the class. To choose the number of concepts required, the author worked through the concept generation activity and was able to generate and evaluate eight concepts in less than 30 minutes.

Data Collection

At the end of the exercise, all handouts were collected. A sample datasheet is shown below in Figure 3.1. The three highest rated design solutions from each participant were combined into a list of design solutions to be evaluated. In cases where there was not a clear group of three, such as if a tie existed for third place, the extra design solutions were added to the compilation. The list was purged of any exact duplicate solutions. The participants generated integrated conceptual design solutions covering 29% to 44% of the overall design space, as shown in Table 3.6. This list of the three highest rated concepts included approximately half of the concepts generated for each morphological chart.



Please list 8 combinations that you think are good designs in the chart below
Once you have chosen 8, evaluate them with the decision matrix
Use the values of 9 for good, 3 for average, and 1 for poor
You do not need to worry about multiplying by the weighting factor or adding the results.

Please list your class section number: 1

	Functions				Criteria			
					low cost (9=inexpensive)	number of parts (9=not many parts)	easy to clean (9=easy)	
Design	store and dispense filling	fold burrito	dispense burrito	weighting	9	1	3	
1	extrude through tube from sack	plate under is hinged and folds	slide down chute		9	9	3	
2	pour from hopper	spatula lifts edges of tortilla	slide on conveyor belt		1	3	3	
3	unwrap individual serving size and drop	work-surface edges lift up and slide toward center	push off to side		1	1	9	
4	extrude through tube from sack	work-surface edges lift up and slide toward center	drop from elevated area		3	9	3	
5	pour from hopper	plate under is hinged and folds	slide on conveyor belt		3	9	3	
6	transfer with spoon from bucket	flexible work surface folds up	drop from elevated area		1	3	9	
7	extrude through tube from sack	spatula lifts edges of tortilla	slide off conveyor belt		3	3	3	
8	pour from hopper	work-surface edges lift up and slide toward center	slide down chute		9	3	9	
				example:	3	9	3	
					3x9=27	9x1=9	3x3=9	45

Figure 3.1: Sample Solution Combination with the Student's Evaluation of the Solutions from Morphological Chart #1 (Table 3.2)

Table 3.6: Amount of Design Space Evaluated by Participants

Morphological Chart		Table 3.2 (3-function)	Table 3.3 (5-function)
Number of Participants		12	13
Number of possible concept combinations		125	243
Number of Unique Concept Combinations Generated by Participants	quantity	55	70
	% of possible concepts	44%	29%
Number of Unique Concept Combinations in Set of "Top 3"	quantity	31	33
	% of possible concepts	25%	14%
	% of generated concepts	56%	47%

The list was evaluated by a jury of five graduate students in the Clemson University mechanical engineering department. Due to the size of the list, the design solutions were distributed among the jury, such that each solution was evaluated by three different people. The basic assignment pattern for the first ten design solutions to the evaluation jurists is shown in Table 3.7. This pattern was repeated through the entire list of design solutions. Using this distribution, each jury member only had to evaluate 60% of the concept list. The jury members were assigned the same proportion of solutions from the two different morphological charts. The jury members rated each design solution against the same criteria as the study participants. The jury members also used the 9-3-1 scale.

Table 3.7: Sample Jury Member Assignments

	Jury Members					Evaluations per concept
	1	2	3	4	5	
Concept 1	X	-	X	-	X	3
Concept 2	X	-	-	X	X	3
Concept 3	-	X	X	X	-	3
Concept 4	-	X	X	-	X	3
Concept 5	-	X	-	X	X	3
Concept 6	-	-	X	X	X	3
Concept 7	X	X	X	-	-	3
Concept 8	X	X	-	X	-	3
Concept 9	X	X	-	-	X	3
Concept 10	X	-	X	X	-	3

A final score was assigned to each concept by averaging the three scores provided by the jury. These scores were used to evaluate integrated conceptual design solutions generated by each participant. Each participant was assigned the score from the average of the top three design solutions identified. In the case where there was not a clearly identified third place, the scores for the group that were in third place were averaged to create a composite third score. This composite score was averaged with the scores for first and second place, as shown in Equation 3.1.

Equation 3.1
$$score = \frac{solution_1 + solution_2 + \frac{solution_{3a} + solution_{3b}}{2}}{3}$$

The choice of evaluation criteria and their respective weights influenced the integrated concepts created by the participants in this study. Participants were required to score concepts against these criteria rather than pick what they personally felt were the best concepts. This was necessary to ensure that all participants were working towards an identical goal. This experiment intended to only study the process of generating integrated concepts, and not the process of evaluating them. Creating a consistent set of criteria for the participants and judges minimizes the variation between what participants would identify as the best integrated concepts without these specific criteria.

Data Analysis

In order to involve more participants, two separate class sessions were involved in this experiment. To determine if this mixing of class sections had an impact on the analysis, the variation between classes will be examined with the ANOVA statistical tool. ANOVA can compare the means of two different samples to determine if they are equal or not. Common practice is to test at a 90% confidence level, or $\alpha = (100\% - 90\%) = 0.10$. The ANOVA tool calculates several parameters, but for this analysis, the useful one is the "p-value". When the p-value is found to be larger than α, the means of the analyzed groups are likely the same. When the p-value is less than α, the means are not the same (Daniel and Terrell, 1995). In these experiments, consideration was given at an 80% confidence level, or $\alpha = 0.20$. When a p-value is found to be 0.10 or less, there is a statistically significant relation. When a p-value is greater than 0.10, but less than or equal to 0.20, there is likely a relation (Wetmore and Summers, 2004).

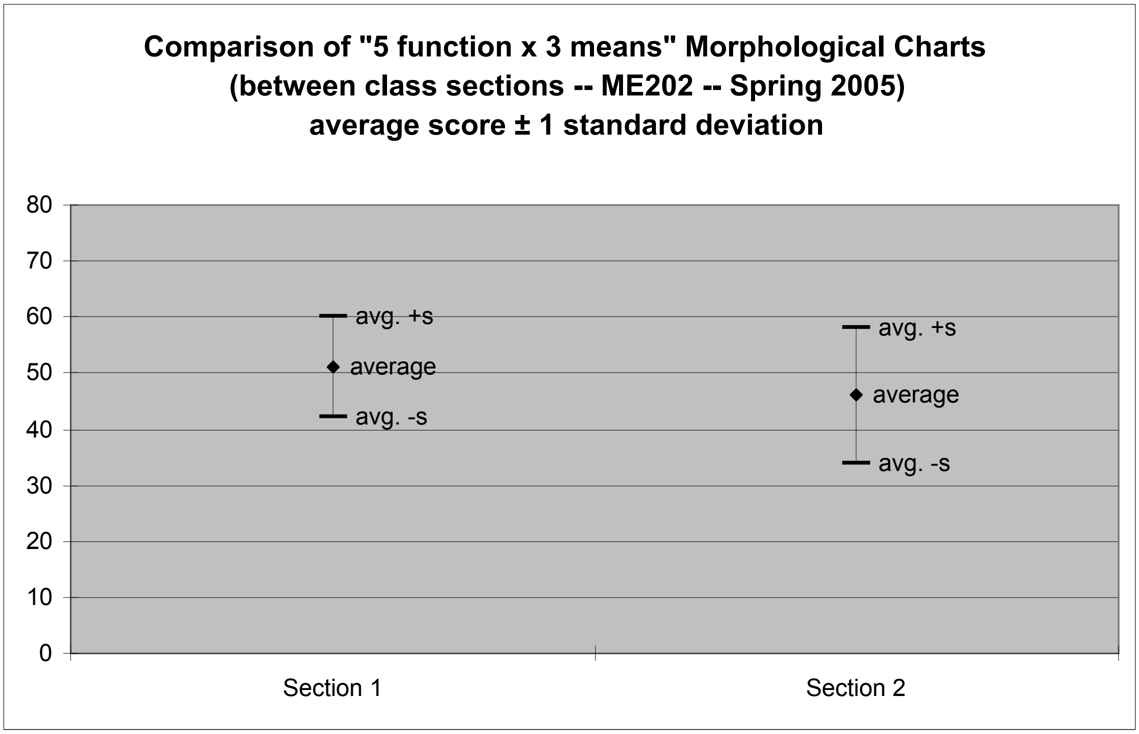


Figure 3.2: Comparison of "5 Function x 3 Means" Morphological Charts Between ME202 Spring 2005 Class Sections (Average Score ±1 Standard Deviation)

The p-value for this group was calculated as 0.44. Since the p-value for this pair is greater than α, the means of the two groups are the same. Therefore, they may be pooled together for further analysis.

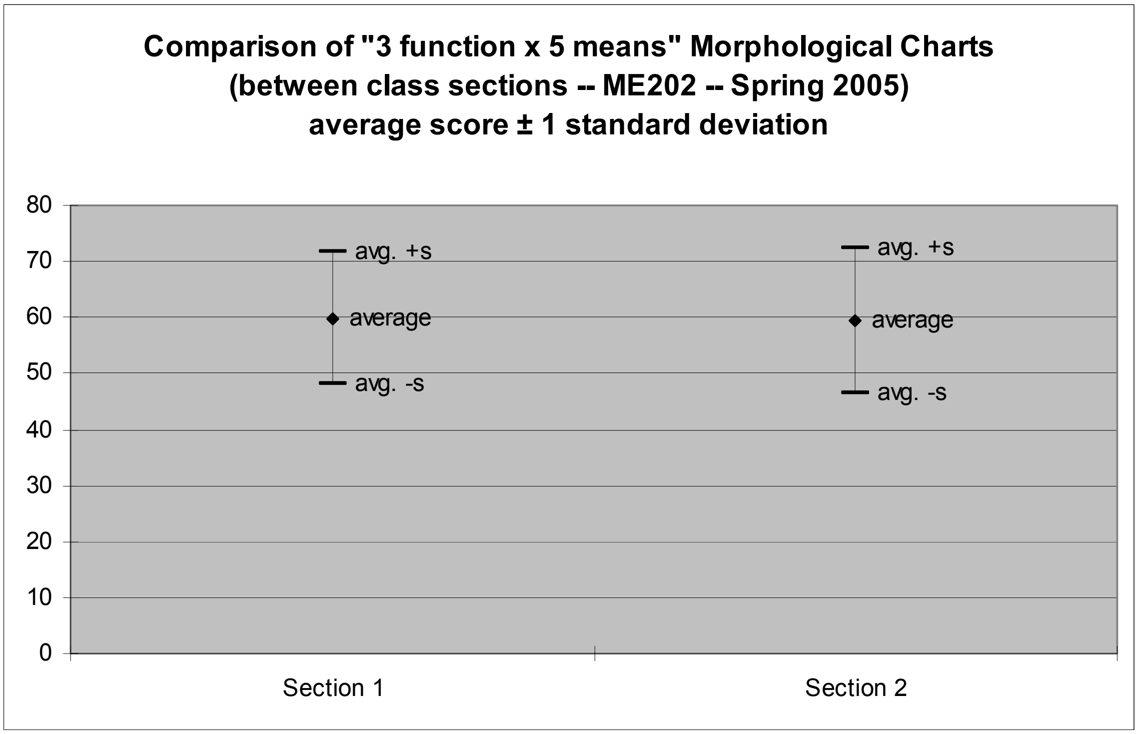


Figure 3.3: Comparison of "3 Function x 5 Means" Morphological Charts Between ME202 Spring 2005 Class Sections (Average Score ±1 Standard Deviation)

The p-value for this group was calculated as 0.94. Since the p-value for this pair is greater than α, the means of the two groups are the same. Therefore, they may be pooled together for further analysis.

Since both class sections showed comparable means, they will be combined and treated as one group.

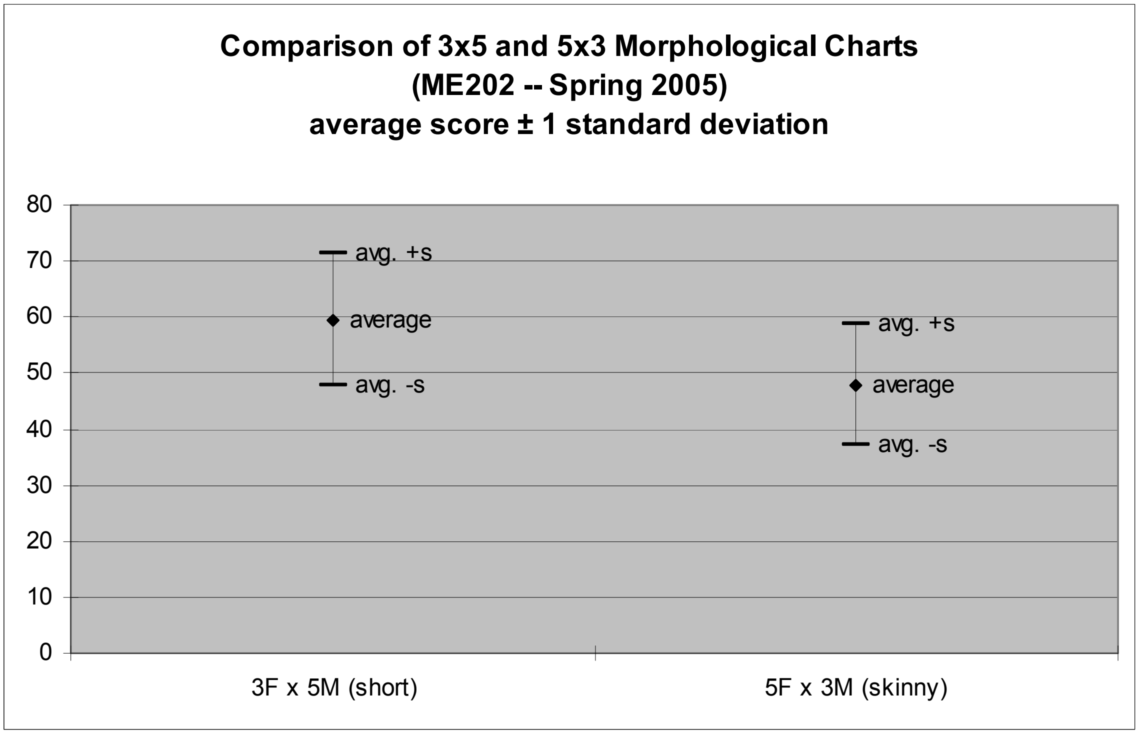


Figure 3.4: Comparison of "3 Function x 5 Means" and “5 Function x 3 Means” Morphological Charts for Both ME202 Spring 2005 Class Sections (Average Score ±1 Standard Deviation)

Since the p-value for this pair is less than α, the means of the two groups are different. Therefore, the results from a "short" morph chart (3 function x 5 means) produced higher quality concepts than a "skinny" morph chart (5 function x 3 means).

<u>User Study Results</u>

There were thirty participants in this exercise. Upon examination of the answer sheets, four participants appeared to misunderstand the directions. They chose to create their own means for each function, rather than choosing from the provided morphological chart. These participants were excluded from the analysis. Additionally, one participant did not completely rank all of their integrated conceptual design solutions, so this participant was excluded as well. The fact that only one participant did not complete the task shows that sufficient time was provided for the study and that the scope of the design problem provided to the students was acceptable. The ranked averages of the combined solutions for each participant are listed in Table 3.8. A summary of the ANOVA tests outlined above are listed below in Table 3.9

Table 3.8: Participant Scores

morphological chart	#1	#2
section 1 scores	81.8	60.6
	61.7	57.0
	59.2	52.9
	55.3	47.4
	52.3	37.5
	48.8	
section 2 scores	79.2	61.4
	70.8	59.7
	54.8	54.1
	53.5	48.1
	52.6	44.3
	44.8	39.4
		31.9
		29.0
number of participants	12	13
section 1 mean	59.9	51.1
section 2 mean	59.3	46.0
combined mean	59.6	47.9
standard deviation of combined group	11.8	10.9

Table 3.9: Summary of ANOVA Results

Groups		p-value	Evaluation
Chart #1	Chart #2	0.018	Means are not equal
Section 1	Section 2	0.42	Means are equal
Chart #1 for Section 1 only	Chart #1 for Section 2 only	0.93	Means are equal
Chart #2 for Section 1 only	Chart #2 for Section 2 only	0.44	Means are equal

Discussion

This study investigated the quality of integrated conceptual design solutions created by designers evaluating two different morphological charts. These morphological charts were prepared for the same design problem. The morphological charts were both rectangular, but were of opposite dimensions. Chart #2 contained nearly twice as many possible design solutions as chart #1.

The results of this study indicate a statistically significant difference between the perceived quality of the solutions generated from the two charts. Morphological chart #1, with fewer functions but more means per function than chart #2 produced higher quality design solutions. It may be that by providing a smaller set of solutions, chart #1 allows a more thorough analysis by the designer, who is presented with fewer options.

One artifact of the scoring system was that there was no possible overlap in scores between a concept where highest weighted criteria, *low cost*, were given the highest evaluation, and where it was assigned a lower evaluation. For an example, see Table 3.10 below. Concept #1 received a top rate for the criteria *low cost*, but bottom rates for the other two criteria. Concept #2 received a mid rate for *low cost*, and top rates for the other two criteria. The criteria *low cost* when given a top level rate was the dominant effect in the overall concept score.

Table 3.10: Scoring Scenarios

Concept	Low cost	Number of parts	Easy to clean	Score
Weight	9	1	3	
#1	9	1	1	85
#2	3	9	9	63

Assumptions are made in this experiment that may have influenced the results. The functional decompositions used to create morphological chart #1 and chart #2 are not the same. This could influence the concepts generated by them. The intent was to match the two morphological charts with each other so that they would contain similar design solutions. It is possible that the statistical difference between the two groups reflects the influences of the two different functional decompositions.

The jury system used to evaluate the concepts may have disrupted the analysis. There is a potential for differences in the evaluations provided by each jurist for the same concept. In fact, differences were observed in the data from the jury. The discrepancies were reduced by averaging three evaluations to create a combined score. Given the strong results of the ANOVA comparing the two different charts, it is probable that the judges did detect a significant difference between the two groups.

The perceived higher quality of solutions from chart #1 suggests a possible way in which morphological charts may be structured to promote successful evaluation of the design solutions contained within them. Structuring charts with fewer functions appears to aid in the analysis of the integrated conceptual design solutions contained in them.

CHAPTER 4

EXPERIMENTAL STUDY WITH FOUR MORPHOLOGICAL CHARTS

The previous chapter detailed an experiment with two different sized morphological charts. A second experiment was performed to build upon what was discovered in the first and to improve on limitations observed. This second experiment separated the effects of morphological chart size and morphological chart shape. The impact of changing just the number of functions, or just the number of means per function was explored. Larger morphological charts, up to eight functions and seven means, were used to provide a larger design space. Lastly, the concept selection criteria weighting and decision systems were changed to reduce the impact of the weighting criteria. As was discussed in Chapter 3, there was no possible overlap in scores between a concept where highest weighted criteria, *low cost*, was given the highest evaluation, and where it was assigned a lower evaluation. This correction was achieved by adjusting the relative weightings of the criteria and by using a 9-6-3-1 scale in place of a 9-3-1 scale for the allowable evaluations. As in the previous experiment, these morphological charts were used by participants to form different concepts, which were evaluated by a panel of judges to determine which configuration of morphological charts yielded the highest quality concepts. The following sections detail this experimental exercise.

Experimental Method

Rectangular morphological charts were prepared for an automatic pet feeding machine. The design problem for the device was as follows:

"Design a device to feed a dog or cat. The device should allow the pet owners the flexibility of filling a reservoir at the beginning of a week without the worry of monitoring the status of the food in the bowl. Specifically, the device should regulate the food dependant upon the type of animal (dog, cat), size of the animal (small, medium, large), and the dietary needs (normal, fat). Generally, the device should be able to detect when the new food is required in the bowl and detect when the reservoir is getting low and notify the pet owner. Further, the device should remain stationary."

Four different morphological sizes were generated, as outlined in Table 4.1. The individual morphological charts are shown in Table 4.2 through Table 4.5. The morphological charts have either four or eight functions. They have either five or seven means per function. In this experiment, for a given number of functions, the morphological chart with seven means has all the means listed in the chart with five means. The additional means are scattered throughout the morphological chart, not just added to the right hand side. Therefore, all the concepts which can be generated from Table 4.2 are a subset of those which can be generated from Table 4.3. All concepts which can be generated from Table 4.4 are a subset of those which can be generated from Table 4.5. No means were incorporated into the charts that were intentionally bad choices.

Table 4.1: Morphological Chart Sizes

	Pet Feeder Morphological Chart #1	Pet Feeder Morphological Chart #2	Pet Feeder Morphological Chart #3	Pet Feeder Morphological Chart #4
Number of functions	4	4	8	8
Number of means per function	5	7	5	7
Total number of means in chart	20	28	40	56
Total number of design solutions	$5^4 = 625$	$7^4 = 2{,}401$	$5^8 = 390{,}625$	$7^8 = 5{,}764{,}801$

Table 4.2: 4 x 5 Morphological Chart (Pet Feeder)

	Means				
Function	1	2	3	4	5
fill bowl	screw	rotary pocket	conveyor belt	solenoid	piston
regulate food	weight	windup – spring	fixed volume container	fluid displacement	trip laser
signal (to fill bowl/ inform owner)	weight	lever in bowl	camera/ image processing	proximity sensor	radar
power source	battery	gravity	air pressure – compressed air	windup – spring	engine

Table 4.3: 4 x 7 Morphological Chart (Pet Feeder)

	Means						
Function	1	2	3	4	5	6	7
fill bowl	screw	rotary pocket	conveyor belt	solenoid	piston	blower	robotic arm
regulate food	weight	windup – spring	cam	fixed volume container	fluid displacement	plunger	trip laser
signal (to fill bowl/ inform owner)	switch	weight	lever in bowl	camera/ image processing	proximity sensor	radar	pressure sensor
power source	battery	gravity	air pressure – compressed air	plug - AC	windup – spring	flywheel	engine

Table 4.4: 8 x 5 Morphological Chart (Pet Feeder)

	Means				
Function	1	2	3	4	5
fill bowl	screw	rotary pocket	conveyor belt	solenoid	piston
quantity of food	weight	butterfly valve	fixed volume container	wheel – fixed volume	trip laser
regulate time	cam	pendulum	windup – spring	reversible chemical reaction	fluid displacement
record keeping	analog – dial	graduation etched on transparent container	dial on dispenser (moves if dispenser moves!)	measure and display weight	rotary counter
signal owner to fill the reservoir	buzzer (electronic)	light	SMS/ email	emit odor	play recorded message
signal itself to fill bowl	weight	lever in bowl	camera/ image processing	proximity sensor	radar
error check	capacitance	laser	LVDT	electric contact – bowl and dispenser	weight
power source	battery	gravity	air pressure – compressed air	windup – spring	engine

Table 4.5: 8 x 7 Morphological Chart (Pet Feeder)

	Means						
Function	1	2	3	4	5	6	7
fill bowl	screw	rotary pocket	conveyor belt	solenoid	piston	blower	robotic arm
quantity of food	weight	butterfly valve	cam	fixed volume container	wheel – fixed volume	plunger	trip laser
regulate time	timer – microprocessor	cam	pendulum	bimetal – heater	windup – spring	reversible chemical reaction	fluid displacement
record keeping	analog – dial	graduation etched on transparent container	barometer	gauge stick	dial on dispenser (moves if dispenser moves!)	measure and display weight	rotary counter
signal owner to fill the reservoir	buzzer (electronic)	light	vibrate	SMS/ email	emit odor	ring bell (mechanical)	play recorded message
signal itself to fill bowl	switch	weight	lever in bowl	camera/ image processing	proximity sensor	radar	pressure sensor
error check	hall effect	capacitance	laser	LVDT	electric contact – bowl and dispenser	Weight	photo detector
power source	battery	gravity	air pressure – compressed air	plug – AC	windup – spring	flywheel	engine

Participants

The participants employed in this experiment possessed a similar educational background to each other and to the group used in Chapter 3. They were all students enrolled in a required sophomore level mechanical engineering design and kinematics class at Clemson University. The students had exposure to morphological charts in the class through a lecture two days before the experiment. Unlike in the previous experiment, all of the participants were from the same class section, so they all received the same lecture at the same time. Some students may have possessed outside experience with morphological charts in addition to what was gained through this lecture, however the extent of outside knowledge was not captured in this experiment. The participants in this experiment were taking the same course as those in the experiment in Chapter 3, but one year later. It is unlikely that any of these students participated in the morphological chart study with the burrito folder, although they were not directly asked.

Design Problem

The design problem chosen for this study was to create an automatic pet feeder, as was mentioned above. Unlike in the previous study, this was not a project previously used for the sophomore mechanical engineering course. It was believed to be of a similar scope to what the participants were currently working with in their class. It was also believed to be a new problem for the participants so that they would all be equally familiar with the design problem.

As this design problem was not previously studied by a design class, the functional decompositions and morphological charts were new. A team of ten graduate students in the Mechanical Engineering department considered the design problem and prepared the morphological charts. In this way, the input of several designers was solicited for the creation of the morphological charts. The assumption was made that this input reduced the likelihood that critical functions were left out of the morphological charts.

This study presented changes in the number of functions and means per function separately and together. The four morphological charts represent all the possible combinations of two levels of numbers of functions, and two levels of the number of means per function. For a given number of functions in a chart, individual means were added to the chart to make the transition from five means per function to seven means per function. The new means were added at various places in row for each function, not just at the end of the row.

For the transition from eight functions to four functions, some functions were merged (the functions *quantity of food* and *regulate time* were merged into a new function *regulate food*, and the functions *signal owner to fill the reservoir* and *signal itself to fill bowl* were merged into a new function *signal (to fill bowl / inform owner)*). As was the case in the previous study, these changes to the morphological charts do not guarantee the same solution sets. Changing the number of functions or means per function will change the number of possible integrated concepts, which presents a different set of solutions to the designer.

Procedure

During the semester, the participants had an overview of functional decomposition and means generation in their class. The participants received a lecture on morphological charts two days before this experiment. On the day of the study, the participants received a brief reminder of how to use a morphological chart. Participants were given a morphological chart and an answer form. The answer form contained room for the participant to list ten integrated conceptual design solutions and rate them against criteria provided. The criteria and relative weights are shown in Table 4.6. The participants were instructed to use the rating scale shown in Table 4.7. Many, but not all, participants followed this instruction. Participants who used values other than those listed in Table 4.7 were not excluded from the results. Participants were assigned to work with one of the morphological chart sizes. As can be seen from the number of participants listed for each morphological chart below in Table 4.8, the experiment had between six and eight participants for each chart size.

Table 4.6: Solution Evaluation Criteria

criteria	weight
cost	7
not many parts	1
easy to clean	9

Table 4.7: Solution Evaluation Weights

level	value
very good	9
good	6
Ok	3
poor	1

The participants were given instructions about the testing procedure. They were told how to record and score their chosen integrated conceptual design solutions. After the introduction, they were allowed 30 minutes to develop and evaluate their design solutions for the exercise. The participants were explicitly instructed to try and form the highest quality conceptual combinations that they could. The time limit for the concept generation phase was fixed by the need to conduct the experiment without exceeding the time scheduled for the class. This time limit is consistent with the procedure developed for the burrito folder experiment, although the number of concepts increased in this experiment.

<u>Data Collection</u>

At the end of the exercise, the morphological charts and answer sheets were collected. A sample participant's datasheet is shown below in Figure 4.1. This participant generated concepts from the morphological chart shown in Table 4.4. Participants could note their concepts by writing the number for the column containing the desired means. For example, the first concept listed in Figure 4.1 is "1-1-1-1-2-1-1-1". This corresponds to the following function-means pairings:

- *fill bowl*: screw (1)
- *quantity of food*: weight (1)

- *regulate time*: cam (1)
- *record keeping*: analog – dial (1)
- *signal owner to fill the reservoir*: light (2)
- *signal itself to fill bowl*: weight (1)
- *error check*: capacitance (1)
- *power source*: battery (1)

The three highest rated concepts for each participant were collected for evaluation. In cases where there was not a clear group of top three, such as if a tie existed for third place, a set of three concepts were chosen to represent the participant. This set included the highest rated concepts for the participant. The concepts identified by the participants as their "top three" integrated conceptual design solutions covered at most 1.3% of the overall design space, depending on the morphological chart. Details for all of the morphological charts are listed below in Table 4.8.

Table 4.8: Amount of Design Space Evaluated by Participants

Morphological Chart		Table 4.2 (4x5)	Table 4.3 (4x7)	Table 4.4 (8x5)	Table 4.5 (8x7)	all 4-function	all 8-function
Number of Participants		8	7	8	6	15	14
Number of possible concept combinations		625	2401	390625	5764801	2401	5764801
Number of Unique Concept Combinations in Set of "Top 3"	quantity	19	21	24	18	38	42
	% of generated concepts	1.3%	0.29%	0.0020%	0.00010%	0.62%	0.00024%

	Solution	Criteria (scale is 9=very good; 6=good; 3=ok; 1=poor)			Score
		Cost	Not Many Parts	Easy to Clean	
		Importance = 7	Importance = 1	Importance = 9	
1	1-1-1-1-2-1-1-1	9	9	3	99
2	2-3-3-2-2-2-4-1	9	9	6	126
3	5-4-5-4-5-4-1-1	6	6	6	102
4	3-2-2-3-1-1-4-4	6	6	9	129
5	2-2-3-2-2-2-4-5	1	1	3	35
6	4-4-3-3-1-4-1-4	6	6	3	75
7	5-1-1-3-3-3-2-2	1	6	6	67
8	5-5-5-5-4-5-1-1	3	6	3	54
9	3-2-4-4-2-4-4-3	1	6	9	94
10	1-2-3-4-5-4-2-1	1	3	3	37

Figure 4.1: Sample Solution Combination with the Student's Evaluation of the Solutions from 8x5 Morphological Chart (Table 4.4)

Two judge panels evaluated the concepts. Each panel consisted of three graduate students in the Mechanical Engineering department at Clemson University. Half of the participants were evaluated by one judge panel, while the remaining participants were evaluated by the second panel. Each judge individually evaluated the allotted set of concepts using the same 9-6-3-1 scale as the participants. The participant's score was an average of nine scores, three from each judge for each of three concepts. The specific scores are detailed and discussed in the following sections.

Data Analysis

Since analysis was performed by separate judge panels, it is necessary to check if the results from judge panel #1 were the same as judge panel #2 for cases where they evaluated members of the same population. For the pet feeder group, there was sufficient overlap between the judge panels for three of the morphological charts, the 4x5, 4x7, and 8x5 sizes. Judge panel #1 only evaluated one case at the 8x7 morphological chart size, so there was not enough information to compare the single result with the multiple results from judge panel #2.

The following graph, Figure 4.2, shows the average scores for all evaluations performed by the judge panels for all four morphological chart sizes combined. As in the previous chapter, ANOVA tests were used to compare the two groups, using the same decision criteria.

The p-value was calculated as 0.49 for the complete group of morphological chart sizes. Since the p-value for this pair is greater than α, the means of the two groups are the same. However, as will be shown below, the subgroups were found to be unequal. The result of this comparison may or may not show that the judge panels were scoring the same. The judge panels did not score equal quantities of each group which could also skew this result.

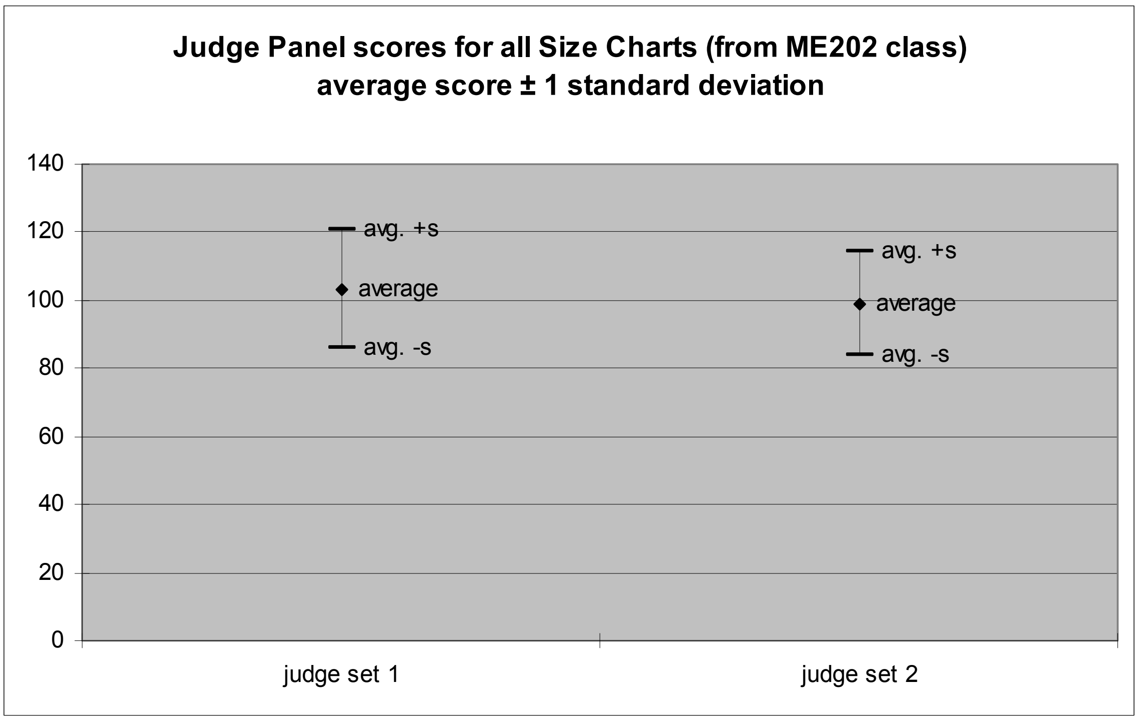


Figure 4.2: Comparison of Judge Panel Scores for All Size Morphological Charts (Average Score ±1 Standard Deviation)

Next, this comparison of judge panels is repeated for the three chart sizes where each judge panel reviewed more than one participant. Figure 4.3 through Figure 4.5 show the averages for each chart size. The results are summarized below in Table 4.9.

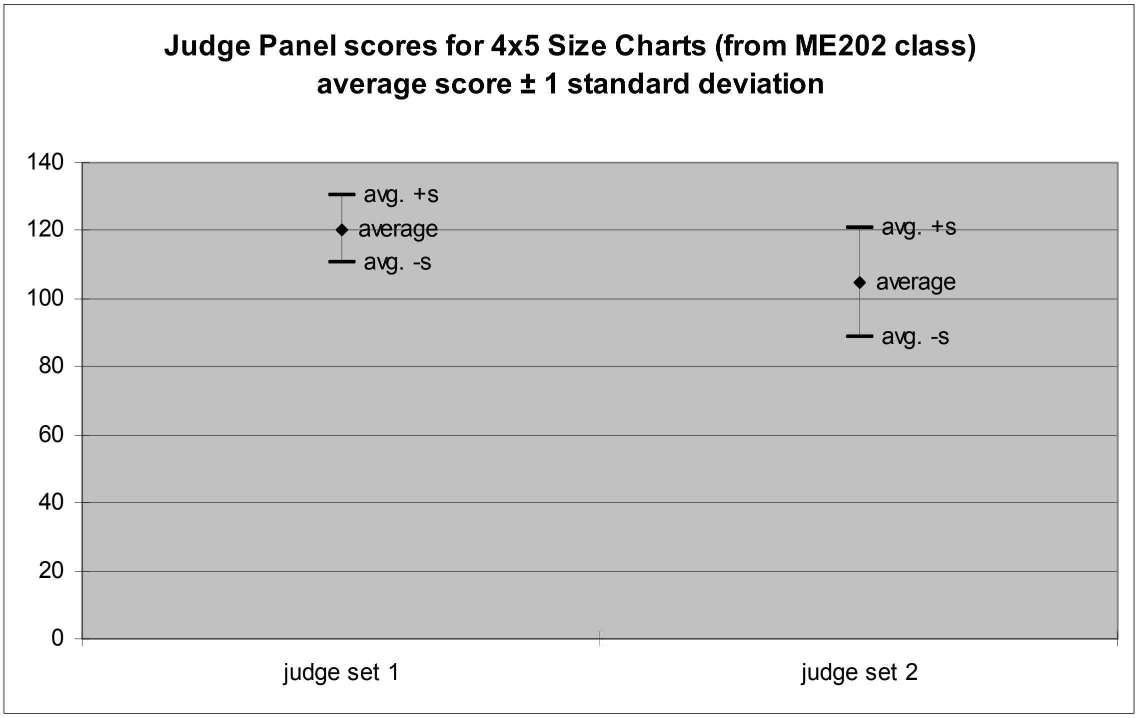


Figure 4.3: Comparison of Judge Panel Scores for 4x5 Size Morphological Chart (Average Score ±1 Standard Deviation)

Figure 4.3 shows the average scores for the 4x5 chart size. For this group, the p-value was calculated as 0.15. Since the p-value for this pair is less than α, the means of the two groups are different. The two judge panels did not score this group consistently.

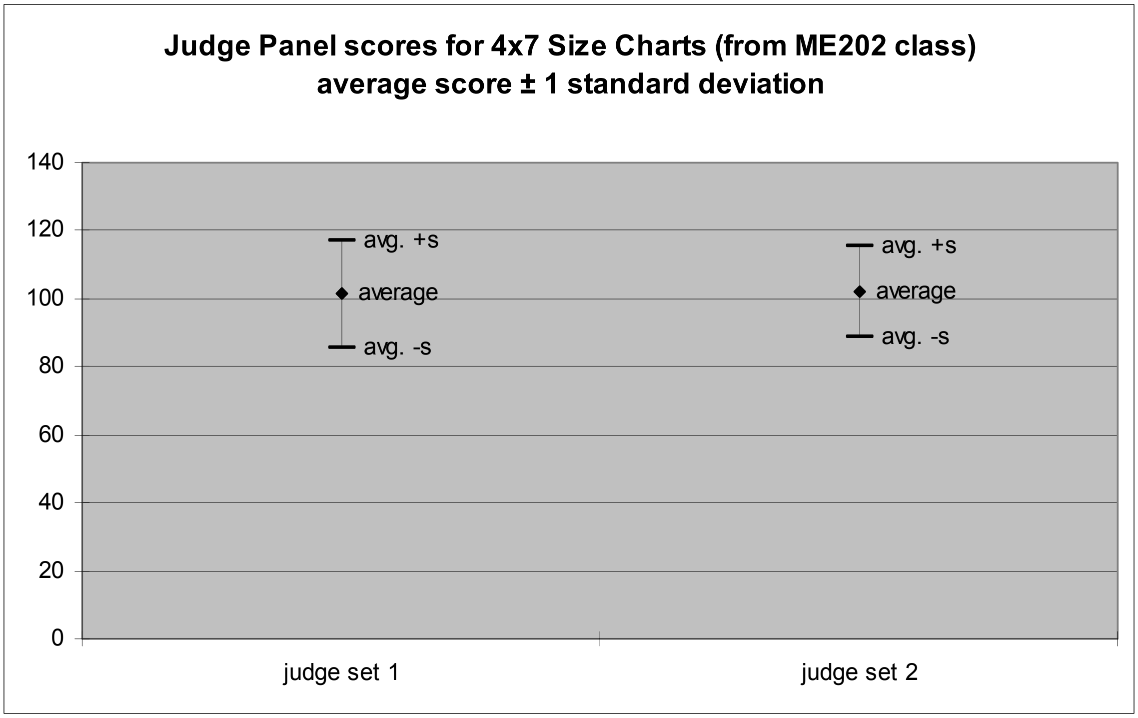


Figure 4.4: Comparison of Judge Panel Scores for 4x7 Size Morphological Chart (Average Score ±1 Standard Deviation)

The average scores for the 4x7 charts are shown in Figure 4.4. The p-value for this group was calculated as 0.96. Since the p-value for this pair is greater than α, the means of the two groups are the same. Therefore the judge panels scored this group consistently.

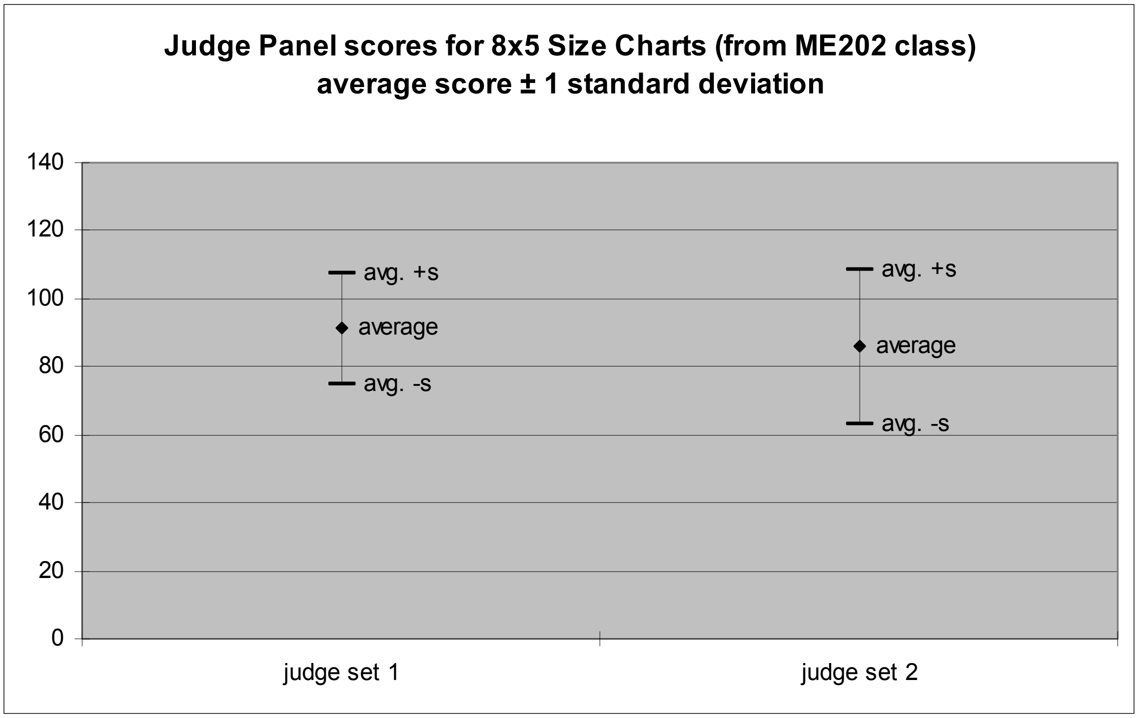


Figure 4.5: Comparison of Judge Panel Scores for 8x5 Size Morphological Chart (Average Score ±1 Standard Deviation)

Figure 4.5 shows the average scores for the 8x5 chart size. The p-value for this group was calculated as 0.71. Since the p-value for this pair is greater than α, the means of the two groups are the same. Therefore the two judge panels scored this group consistently.

Table 4.9: Evaluation of Judge Panel Scoring with ANOVA

Chart	p-value	evaluation
4x5	0.15	groups means are not equal
4x7	0.96	groups means are equal
8x5	0.71	groups means are equal
8x7	N/A	not evaluated due to lack of overlap between judge panels

Now the analysis shifts to looking for trends in the data between pairs of chart sizes. As mentioned above, the results for the 4x5 chart were the only group that may not be consistent between the judge panels. In cases where this chart is compared against other sizes, it will be done as a whole and then separately as just the set from judge panel #1 and then just the set from judge panel #2. Figure 4.6 through Figure 4.16 show the averages for each pair of charts. The results are summarized below in Table 4.11.

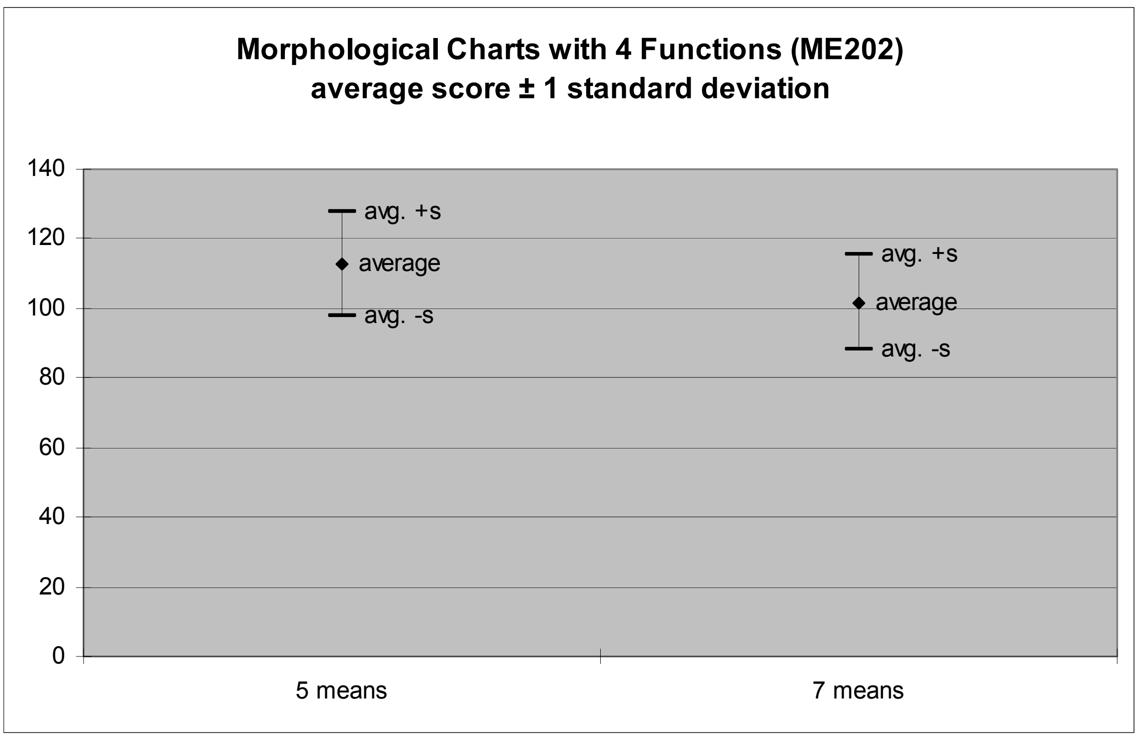


Figure 4.6: Comparison of Judge Panel Scores for Morphological Charts with Four Functions (Average Score ±1 Standard Deviation)

Figure 4.6 shows the averages for each size chart that had four functions. The p-value for this group was calculated as 0.16. Since the p-value for this pair is less than α, the means of the two groups are different. Therefore, for the morphological charts with four functions, the quality of generated solutions decreased as the number of means per function increased from five to seven. However, there were some inconsistencies between the judge panel evaluations of the 4x5 chart. This examination is repeated below using only the results from judge panel #1, and then again for only panel #2.

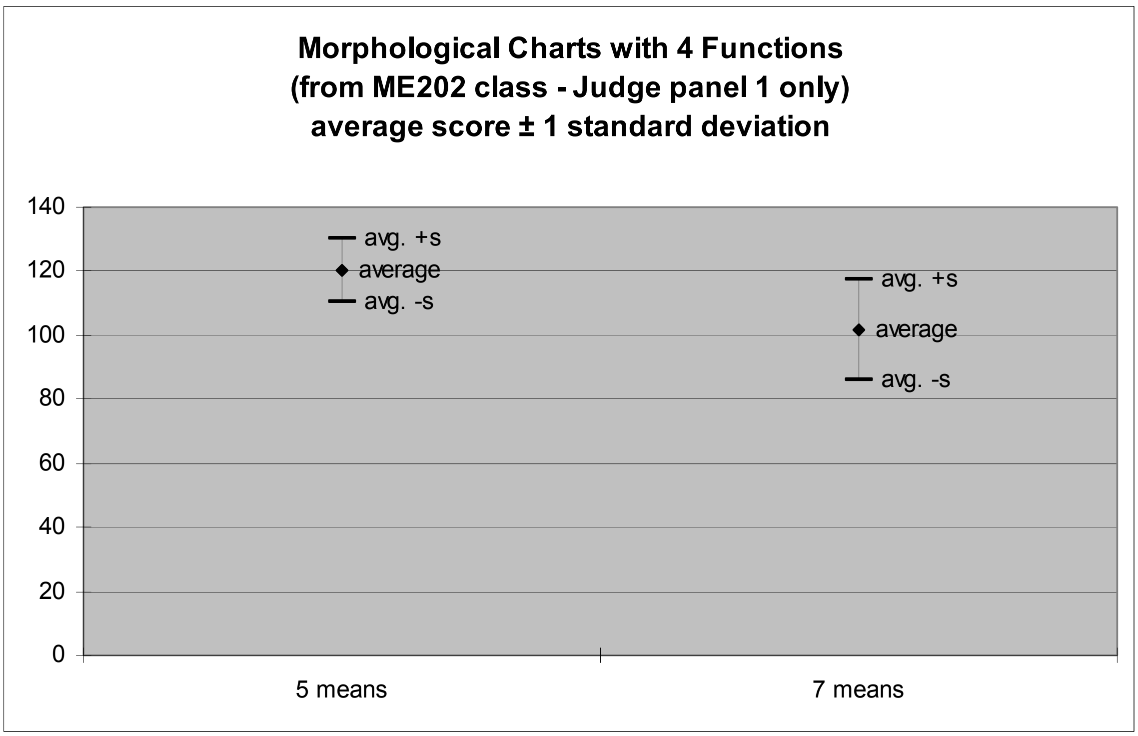


Figure 4.7: Comparison of Scores from Judge Panel #1 for Morphological Charts with Four Functions (Average Score ±1 Standard Deviation)

The averages for charts with four functions evaluated by judge panel #1 are shown above in Figure 4.7. For this group, the p-value was calculated as 0.09. Since the p-value for this pair is less than α, the means of the two groups are different. Therefore, for the morphological charts with four functions, the quality of generated solutions decreased as the number of means per function increased from five to seven, as judged by panel #1.

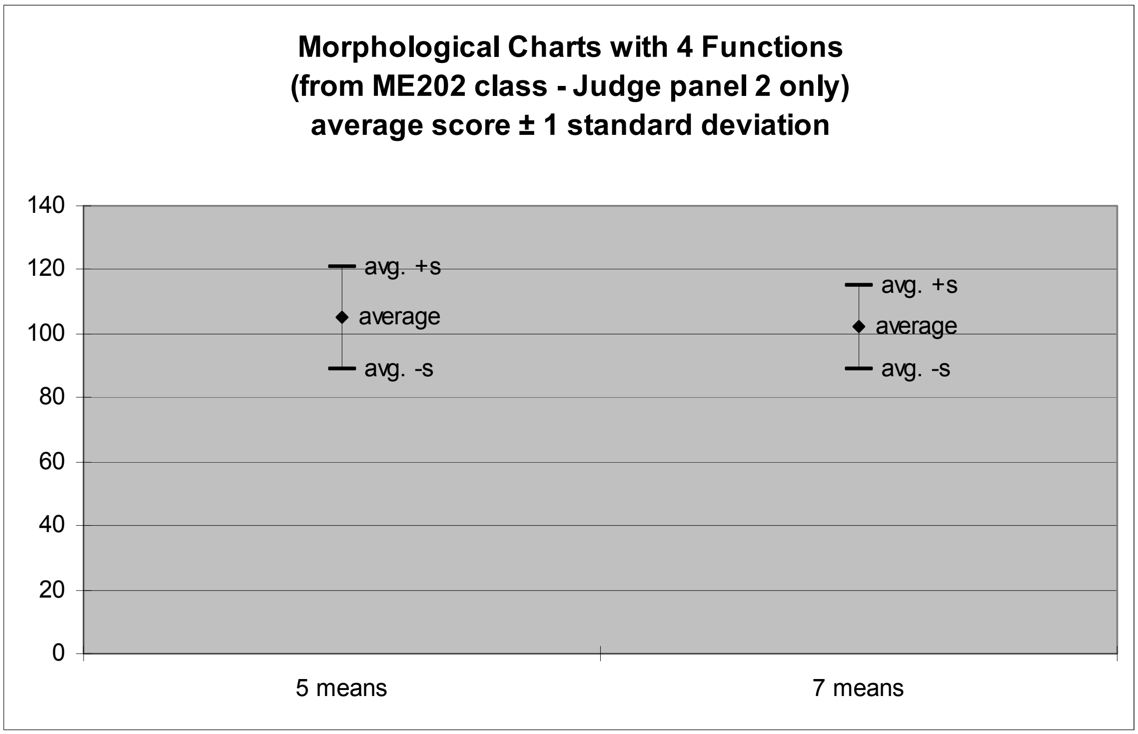


Figure 4.8: Comparison of Scores from Judge Panel #2 for Morphological Charts with Four Functions (Average Score ±1 Standard Deviation)

The averages for charts with four functions evaluated by judge panel #2 are shown above in Figure 4.8. The p-value for this group was calculated as 0.81. Since the p-value for this pair is greater than α, the means of the two groups are the same. Therefore, for the morphological charts with four functions, the quality of generated solutions remained constant as the number of means per function increased from five to seven, as judged by panel #2. The general trend matches that shown for judge panel #1, with a slight decrease in the average score from five means to seven means.

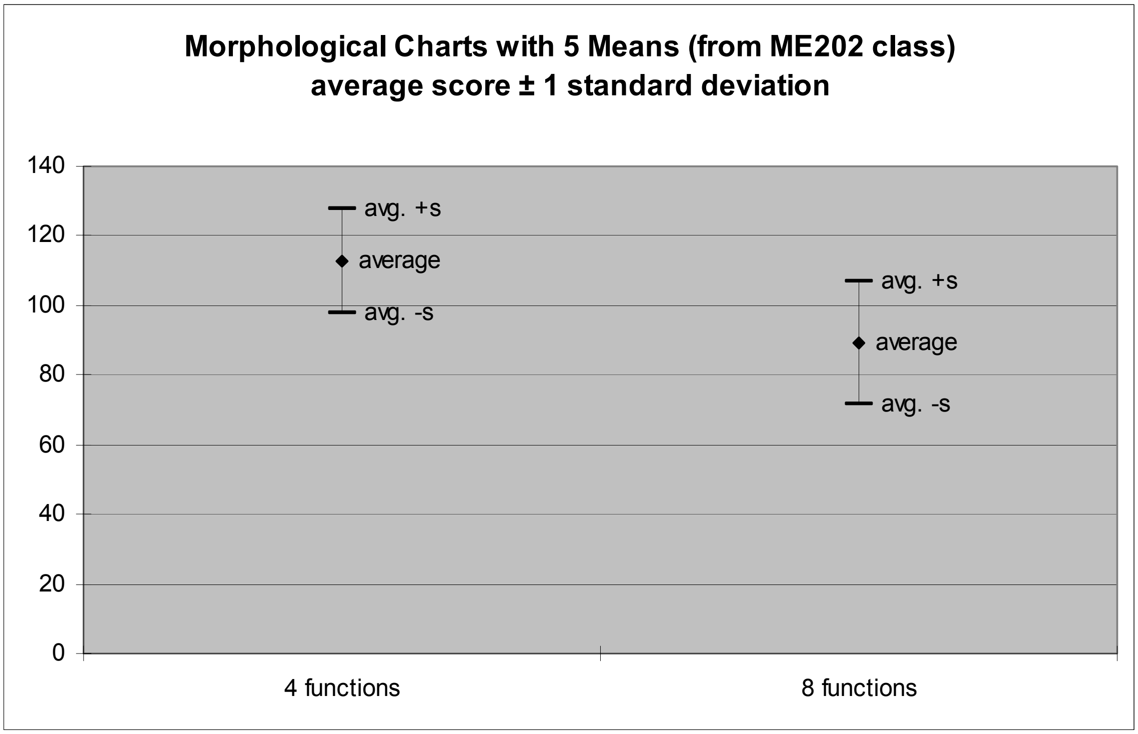


Figure 4.9: Comparison of Judge Panel Scores for Morphological Charts with Five Means (Average Score ±1 Standard Deviation)

Figure 4.9 shows the averages from both judge panels for each chart with five means. The p-value was calculated as 0.01. Since the p-value for this pair is less than α, the means of the two groups are different. Therefore, for the morphological charts with five means, the quality of generated solutions decreased as the number of functions increased from four to eight. Again, as mentioned above, this analysis is repeated separately for judge panel #1 and judge panel #2 because of the inconsistencies in scoring the 4x5 size chart.

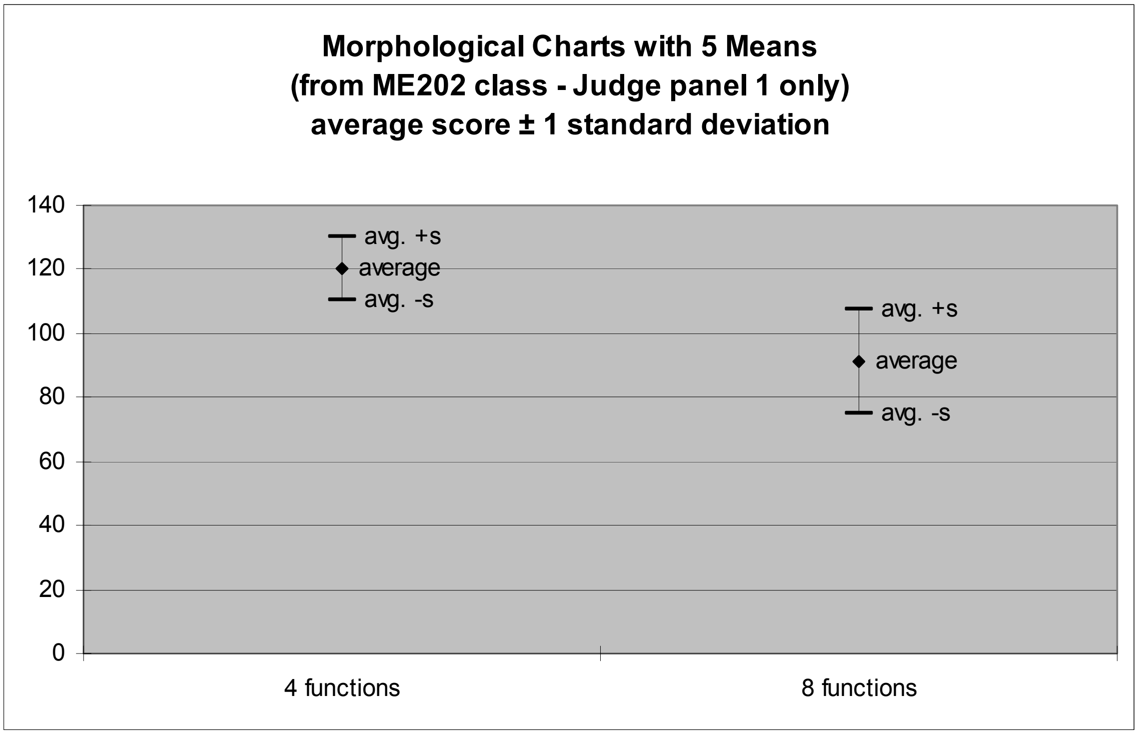


Figure 4.10: Comparison of Judge Panel #1 Scores for Morphological Charts with Five Means (Average Score ±1 Standard Deviation)

For judge panel #1 only, the averages are shown in Figure 4.10. The p-value was calculated as 0.02. Since the p-value for this pair is less than α, the means of the two groups are different. Therefore, for this subset of morphological charts with five means, the quality of generated solutions decreased as the number of functions increased from four to eight.

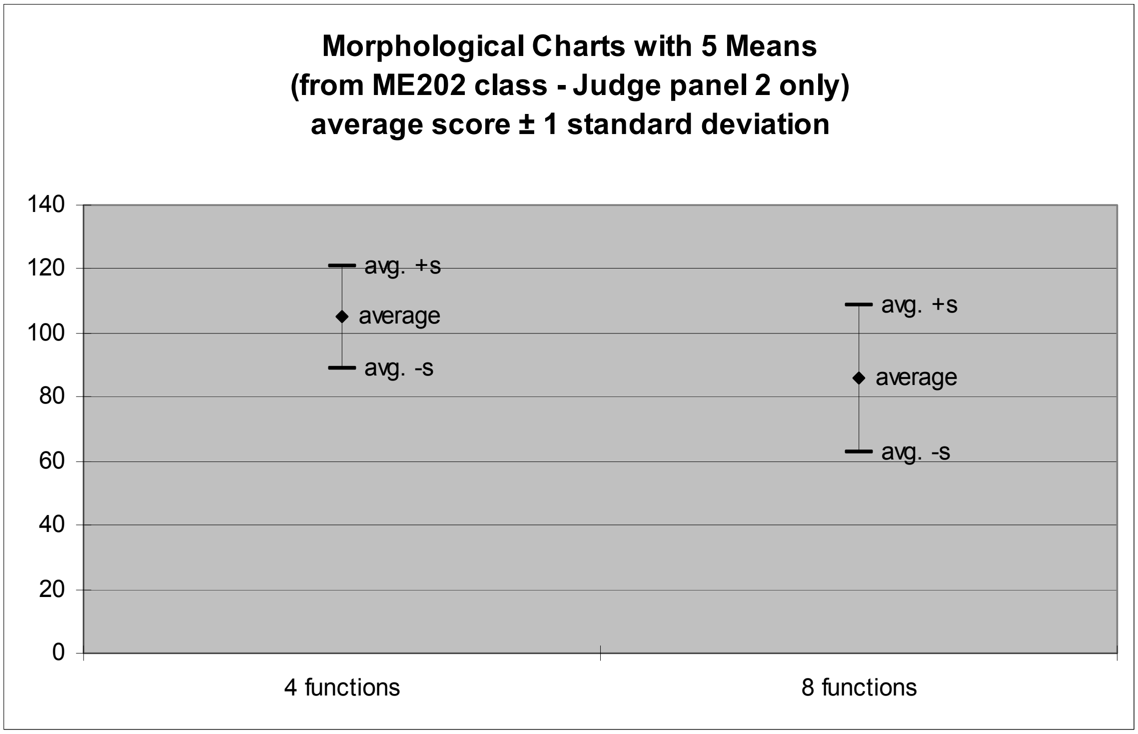


Figure 4.11: Comparison of Judge Panel #2 Scores for Morphological Charts with Five Means (Average Score ±1 Standard Deviation)

The averages for charts with five means that were evaluated by judge panel #2 only are shown in Figure 4.11. The p-value was calculated as 0.25. Since the p-value for this pair is greater than α, the means of the two groups are not different. Therefore, for this subset of morphological charts with five means, the quality of generated solutions did not change as the number of functions increased from four to eight. However, the general trend in the averages appears to mirror the results of the other group.

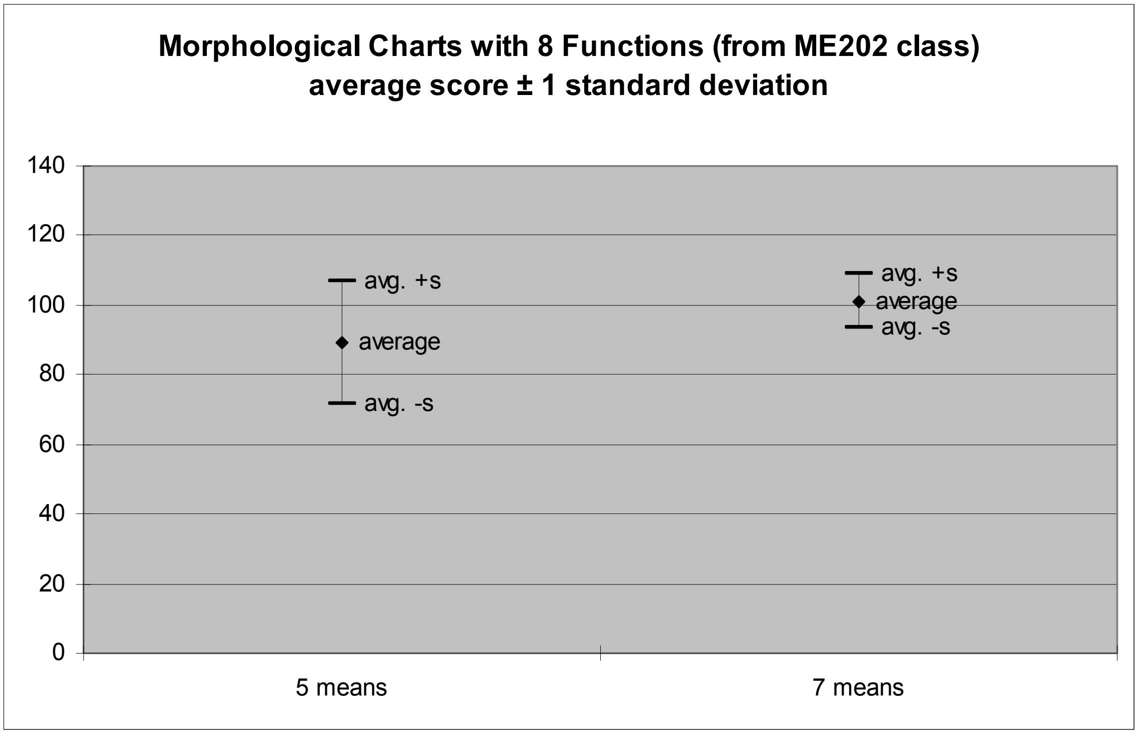


Figure 4.12: Comparison of Judge Panel Scores for Morphological Charts with Eight Functions (Average Score ±1 Standard Deviation)

Figure 4.12 shows the averages for charts with eight functions. For this group, the p-value was calculated as 0.14. Since the p-value for this pair is less than α, the means of the two groups are different. Therefore, for the morphological charts with eight functions, the quality of generated solutions increased as the number of means per function increased from five to seven.

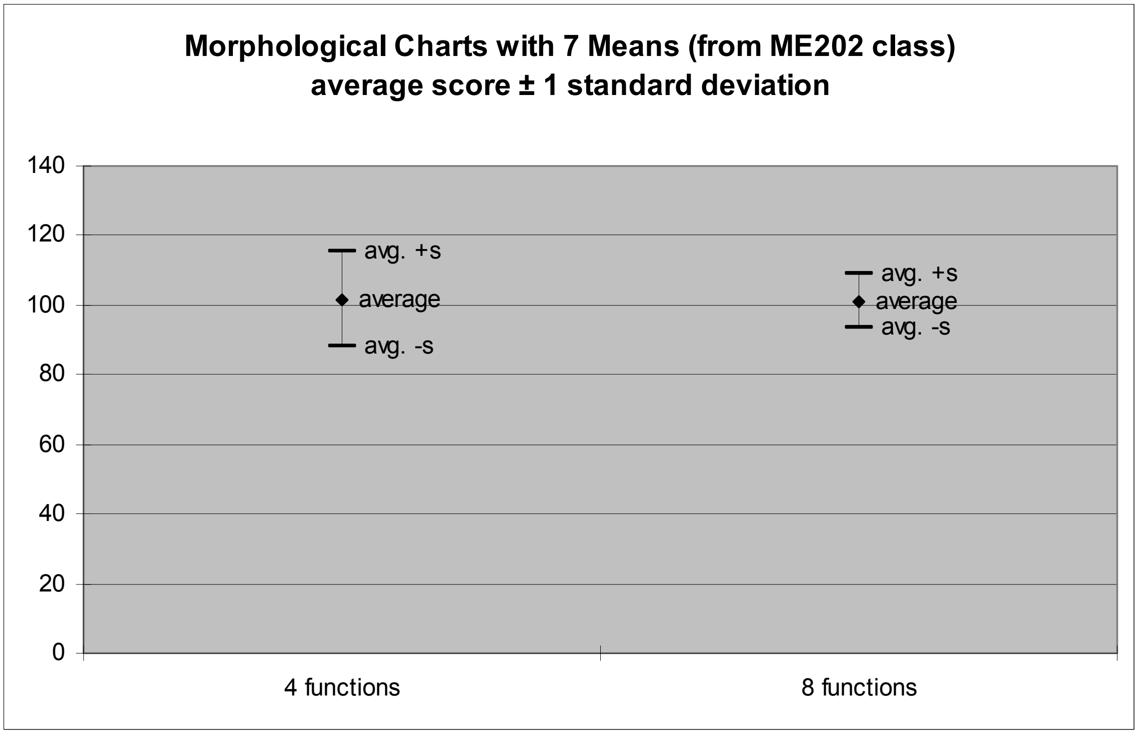


Figure 4.13: Comparison of Judge Panel Scores for Morphological Charts with Seven Means (Average Score ±1 Standard Deviation)

The averages for charts with seven means are shown in Figure 4.13. For this group the p-value was calculated as 0.93. Since the p-value for this pair is greater than α, the means of the two groups are the same. Therefore, for the morphological charts with seven means, the quality of generated solutions did not change as the number of functions increased from four to eight.

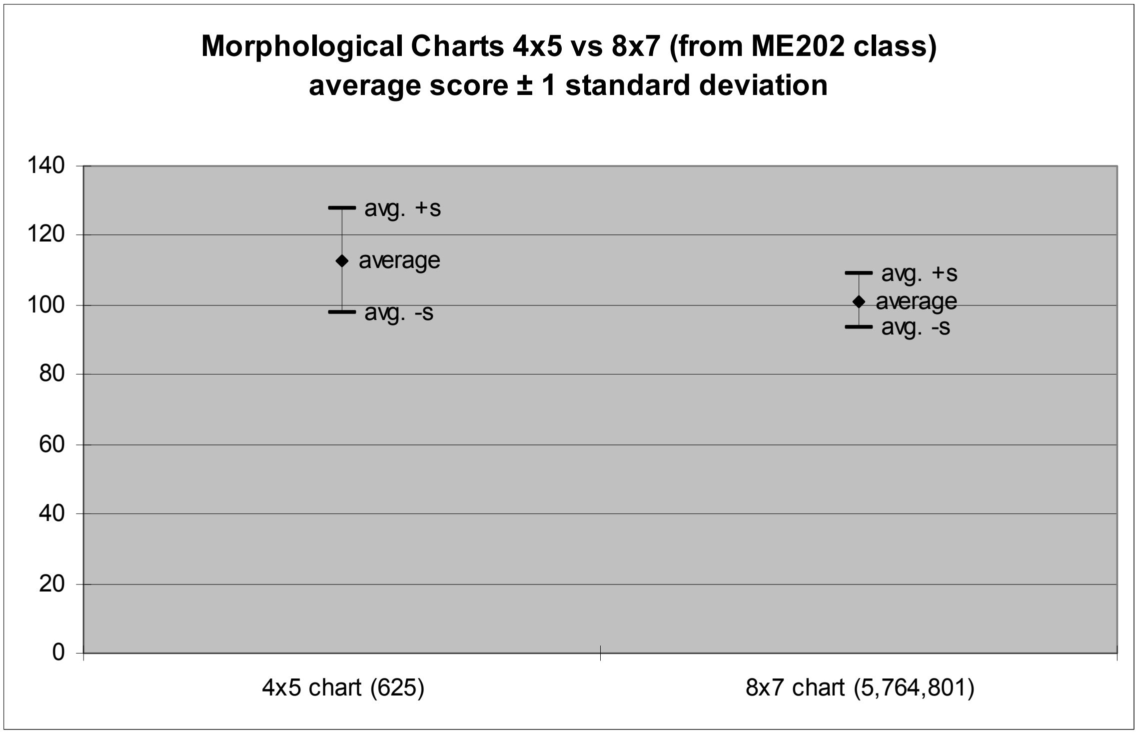


Figure 4.14: Comparison of Judge Panel Scores for "Nearly Square" Morphological Charts (Average Score ±1 Standard Deviation)

The averages for this group are shown in Figure 4.14. For this group the p-value was calculated as 0.11. Since the p-value for this pair is less than α, the means of the two groups are different. Therefore changing the morphological chart size from 4x5 to 8x7 decreased the quality of solutions generated. However, there were some inconsistencies between the judge panel evaluations of the 4x5 chart. This examination is repeated below using only the results from judge panel #2. As mentioned previously, judge panel #1 only evaluated a single participant with the 8x7 chart size, and that is not enough data for an ANOVA comparison.

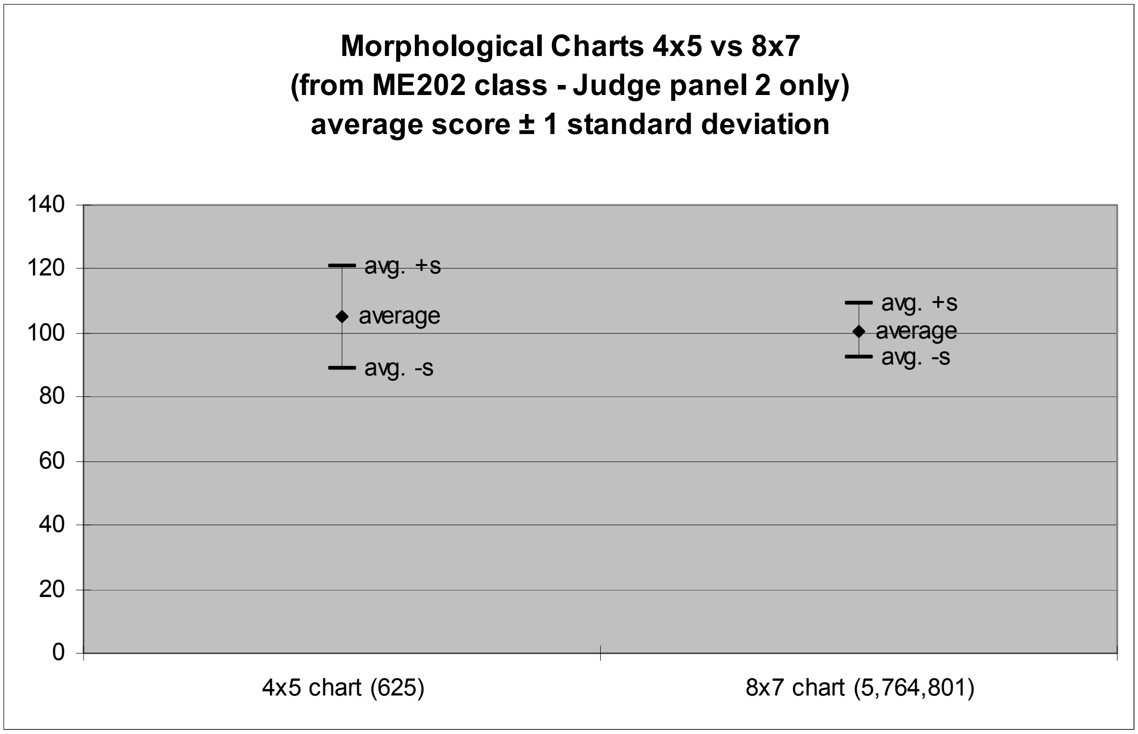


Figure 4.15: Comparison of Judge Panel #2 Scores for "Nearly Square" Morphological Charts (Average Score ±1 Standard Deviation)

Figure 4.15 shows the averages for the 4x5 and 8x7 size charts as evaluated by judge panel #2. For this group the p-value was calculated as 0.62. Since the p-value for this pair is greater than α, the means of the two groups are not different. Therefore changing the morphological chart size from 4x5 to 8x7 did not change the quality of solutions generated, as evaluated by judge panel #2.

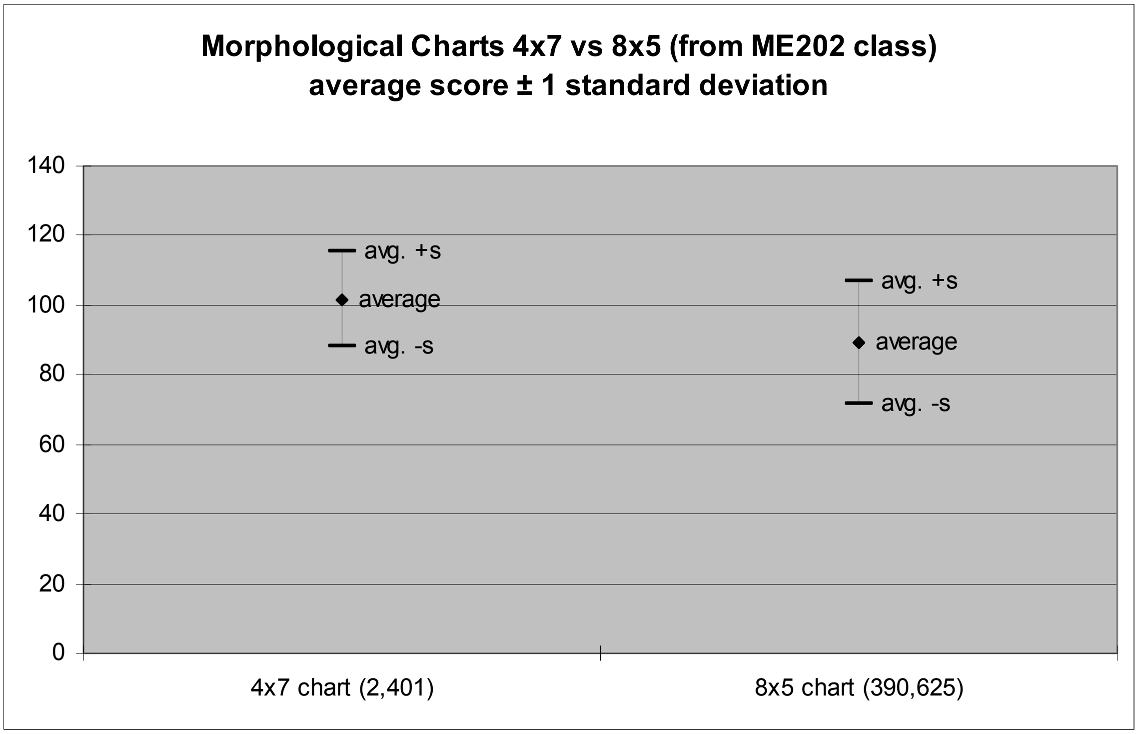


Figure 4.16: Comparison of Judge Panel Scores for "Rectangular" Morphological Chart (Average Score ±1 Standard Deviation)

Lastly, the averages for the 4x7 and 8x5 charts are shown in Figure 4.16. For this group the p-value was calculated as 0.15. Since the p-value for this pair is less than α, the means of the two groups are different. Therefore changing the morphological chart size from 4x7 to 8x5 decreased the quality of solutions generated.

<u>User Study Results</u>

Of the four morphological chart sizes, only two evaluate as having equal means. Among the six pair of comparisons between chart sizes, only one can show statistical significance on the basis of combined judge panels. The remaining comparisons still provide some insight into the relationships between groups. The individual participant scores are shown in Table 4.10. The comparisons between groups are shown in Table 4.11. First, the morphological charts were compared with combined judge panels. Then, for the cases where one or both judge panels did not have a p-value greater than α, the scores for just judge panel #1 and just judge panel #2 were compared. For those cases which relied on the 8x7 size morphological chart, no test was done with judge panel #1 by itself, because of there only being one participant evaluated by judge panel #1 at this size.

Table 4.10: Participant Scores

morphological chart	4x5	4x7	8x5	8x7
judge panel 1 scores	129.8	115.0	119.7	104.3
	127.7	114.8	86.8	
	114.8	91.6	85.4	
	109.3	84.6	84.4	
			79.2	
judge panel 2 scores	121.8	112.1	104.6	113.1
	112.3	106.9	92.7	103.8
	101.3	87.1	60.3	100.3
	84.3			93.3
				92.4
number of participants	8	7	8	6
judge panel 1 mean	120.4	101.5	91.1	104.3
judge panel 2 mean	104.9	102.0	85.9	100.6
combined mean	112.7	101.7	89.1	101.2
standard deviation of combined group	14.9	13.5	17.5	7.7

Table 4.11: Evaluation of Morphological Chart Size Relationships with ANOVA

		Combined Judges	Judge Panel #1	Judge Panel #2
4 function	p-value	0.16	0.09	0.81
	evaluation	means are not equal	means are not equal	means are equal
5 means	p-value	0.01	0.02	0.25
	evaluation	means are not equal	means are not equal	means are equal
8 function	p-value	0.14	(a)	0.22
	evaluation	means are not equal	(a)	means are equal
7 means	p-value	0.93	(a)	0.85
	evaluation	means are equal	(a)	means are equal
4x5 / 8x7	p-value	0.11	(a)	0.61
	evaluation	means are not equal	(a)	means are equal
4x7 / 8x5	p-value	0.15	(b)	(b)
	evaluation	means are not equal	(b)	(b)

(a) There was not enough data for the 8x7 size to evaluate Judge Panel #1.
(b) It was unnecessary to evaluate individual judge panel relationships for this case. Judge Panels were consistent for both sizes. (see above)
color key:

$p \leq 0.10$	$0.10 < p \leq 0.20$	$0.20 < p$

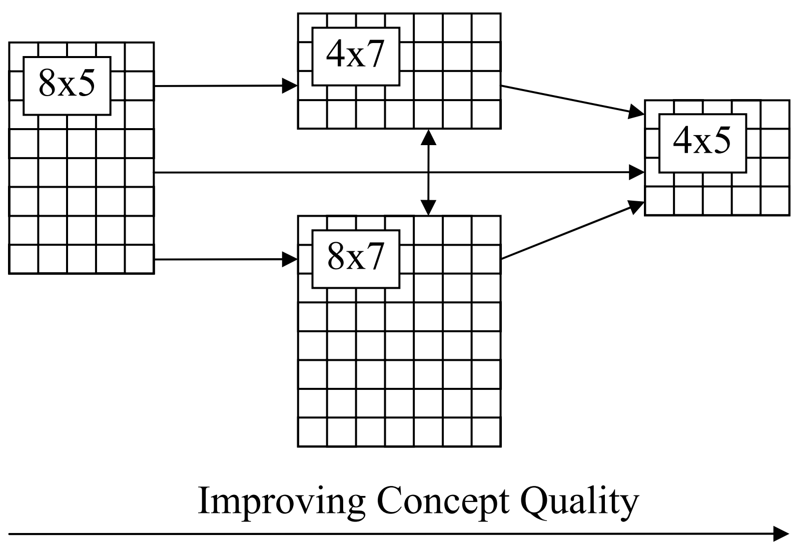


Figure 4.17: Morphological Charts Arranged By Participant Scores

In examining the individual chart scores, the following relationships emerge for the relative concept quality generated from each morphological chart. In Figure 4.17 through Figure 4.23, the charts are placed in relative position, with an axis of improving integrated conceptual design quality from left to right. Vertical position in these figures is not significant. Each chart is represented by a grouping of squares, showing the number of functions as the height and the number of means as the width. For example, the 4x7 morphological chart is four squares tall and seven squares wide in these figures. Figure 4.17 shows the complete set of relationships between the four morphological charts.

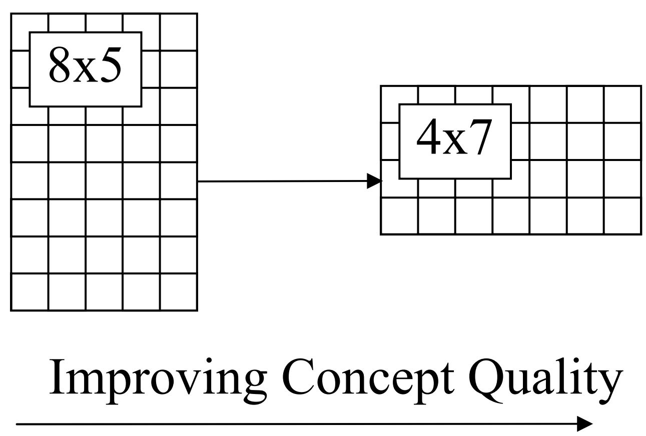


Figure 4.18: 8x5 and 4x7 "Rectangular" Morphological Charts

In the following paragraphs, the relationship between each pair of morphological charts is explored. The change between the 8x5 and 4x7 size morphological charts was to both reduce the number of means and increase the number of functions, as shown in

Figure 4.18. The 8x5 chart has more functions than means, while the 4x7 chart has more means than functions. Both charts are rectangular in form, but one is oriented vertically, while the other his oriented horizontally. This is similar to the morphological charts used in Chapter 3. Both of these charts were scored consistently by the two judge panels, as shown in Table 4.9. Since both sizes were scored consistently, the two chart sizes may be compared on the basis of their combined judge panel scores. The ANOVA comparison between the two sizes showed that the means of the two groups were not the same, as shown in Table 4.11. By comparing the average judged scores for each chart size, in Table 4.10, one can see that the 4x7 size chart was judged to produce higher scores than the 8x5 morphological chart size. This is a statistically significant difference between the two sizes. For this pair, reducing the number of functions and increasing the number of means produced higher quality concepts.

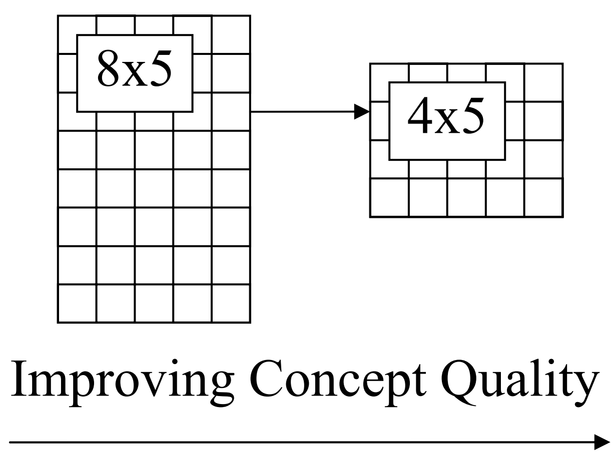


Figure 4.19: Morphological Chart with Five Means

The change between the two morphological charts with five means was to change the number of functions while holding the number of means constant, as shown in Figure 4.19. Only the 8x5 size morphological chart was scored consistently by the two judge panels, as shown in Table 4.9. Therefore, a statistically significant ANOVA comparison between the two sizes cannot be made only on the basis of the combined judge panel scores (Daniel and Terrell, 1995). The ANOVA test for the combined groups showed that the means were not the same, as is shown in Table 4.11. For judge panel #1, the means were also not found to be the same, however for judge panel #2, there was no difference found between the two chart sizes. A statistically significant comparison cannot be made between these two sizes. Based on the average scores alone, shown in Table 4.10, there does appear to be an improvement between the two sizes. Reducing the number of functions at a low level of means may improve the quality of concepts generated with morphological charts.

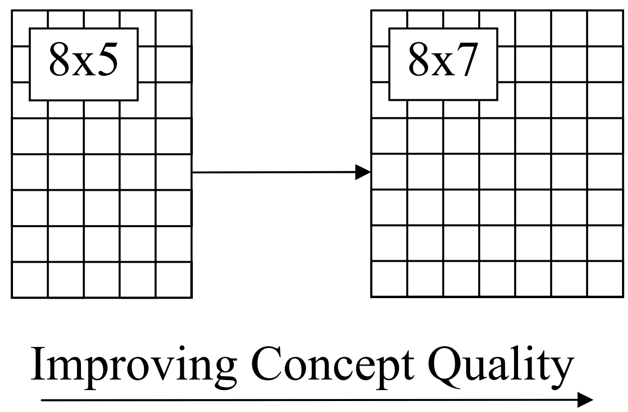


Figure 4.20: Morphological Charts with Eight Functions

The change between the two morphological charts with eight functions was to change the number of means while holding the number of functions constant, as shown in Figure 4.20. As was mentioned in Table 4.9, only the 8x5 size morphological chart was scored consistently by the two judge panels. The 8x7 size morphological chart had only a single participant evaluated by judge panel #1, so it was not possible to determine if the two judge panels evaluated this group consistently. A statistically significant ANOVA comparison between the two sizes cannot be made only on the basis of the combined judge panel scores (Daniel and Terrell, 1995). The ANOVA test for the combined groups showed that the means were not the same, as is shown in Table 4.11. For judge panel #2, however, no difference was found between the two chart sizes. A statistically significant comparison cannot be made between these two sizes. Based on the average scores alone, shown in Table 4.10, there does appear to be an improvement between the two sizes.

Adding means at a high level of functions may improve the quality of concepts generated with morphological charts.

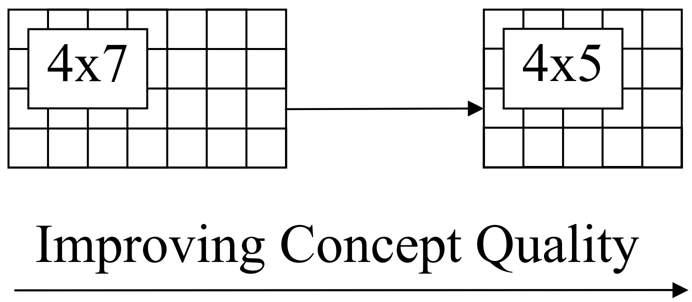


Figure 4.21: Morphological Charts with Four Functions

The change between the two morphological charts with four functions was to change the number of means while holding the number of functions constant, as illustrated by Figure 4.21. As was mentioned in Table 4.9, only the 4x7 size morphological chart was scored consistently by the two judge panels, so it was not possible to determine if the two judge panels evaluated this group consistently. A statistically significant ANOVA comparison between the two sizes cannot be made on the basis of the combined judge panel scores. The ANOVA test for the combined groups showed that the means were not the same, as is shown in Table 4.11. For judge panel #1, the means were also not found to be the same, however for judge panel #2, there was no difference found between the two chart sizes. A statistically significant comparison cannot be made between these two sizes. Based on the average scores alone, shown in

Table 4.10, there does appear to be an improvement between the two sizes. Removing means at a low level of functions may improve the quality of concepts generated with morphological charts.

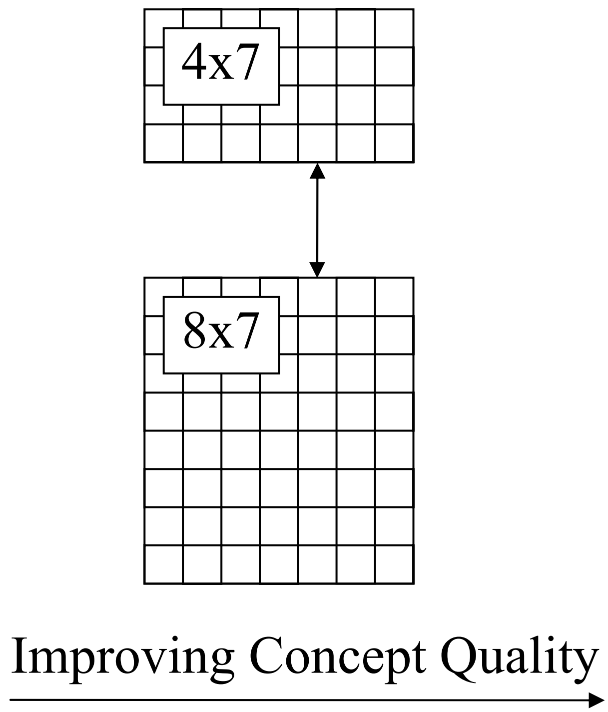


Figure 4.22: Morphological Charts with Seven Means

The change between the two morphological charts with seven means was to change the number of means while holding the number of functions constant, as shown in Figure 4.22. As was mentioned in Table 4.9, only the 4x7 size morphological chart was scored consistently by the two judge panels. The 8x7 size morphological chart had only a single participant evaluated by judge panel #1, so it was not possible to determine if the two judge panels evaluated this group consistently. The ANOVA test for the combined groups showed that the means were the same, as is shown in Table 4.11. This also held for judge panel #2. In this case, both the combined and the individual judge panel evaluations match. There does not appear to be a change between the two sizes. Adding functions at a high level of means does not appear to change the quality of concepts generated with morphological charts.

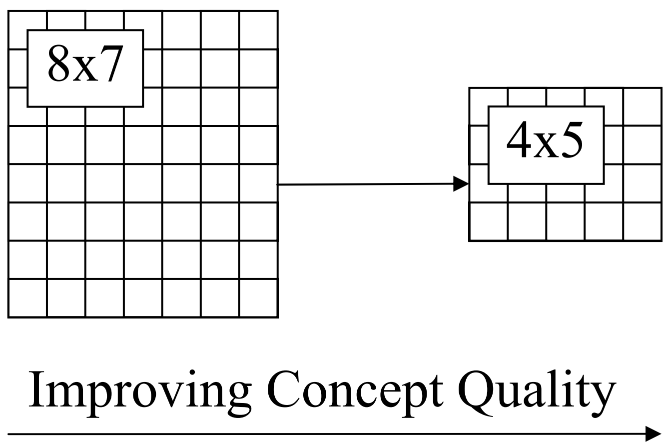


Figure 4.23: 8x7 and 4x5 "Nearly-Square" Morphological Charts

The change between the 8x7 and 4x5 size morphological charts was to reduce the number of means and functions at the same time. As can be seen in Figure 4.23, both charts are nearly square in form, with the change being one of size. As was mentioned in Table 4.9, the 4x5 size morphological chart was not scored consistently by the two judge panels. The 8x7 size morphological chart had only a single participant evaluated by judge panel #1, so it was not possible to determine if the two judge panels evaluated this group consistently. A statistically significant ANOVA comparison between the two sizes cannot be made only on the basis of the combined judge panel scores (Daniel and Terrell, 1995). The ANOVA test for the combined groups showed that the means were not the same, as is shown in Table 4.11. For judge panel #2, however, no difference was found between the two chart sizes. A statistically significant comparison cannot be made between these two sizes. Based on the average scores alone, shown in Table 4.10, there does appear to be an improvement between the two sizes. Reducing the number of means and functions together may improve the quality of concepts generated with morphological charts.

Discussion

This second study investigated the quality of integrated conceptual design solutions created by designers evaluating four different morphological charts. These morphological charts were prepared for the same pet feeder design problem. The morphological charts had either four or eight functions. The charts had either five or seven means per function. The smallest chart contained 625 concepts, while the largest contained over five million.

The smallest morphological chart, the 4x5, produced the highest quality integrated conceptual design solutions. The lowest quality solutions came from the 8x5 chart. The 4x7 and 8x7 size charts produced concepts of nearly the same quality.

The jury system may have impacted the analysis of this experiment. In an attempt to streamline the jury system, the concepts were split in between jury panels. Unfortunately, the division of concepts resulted in insufficient overlap for the 8x7 morphological chart size between the two judge panels. This may have skewed the results involving the 8x7 morphological chart.

The results of this study suggested some general directions for how to improve the ability of a designer to generate useful concepts from a morphological chart. Removing functions from consideration either improved the concepts generated, or at least was a neutral effect. If the morphological chart has many more functions than means, such as the 8x5 chart, it can be improved by adding means. However if the chart is more square, or has more means than functions, it can be improved by removing means. This experiment found a statistically significant relationship similar to the previous chapter between the two "rectangular" morphological charts. Once again, a chart with more means than functions was found to be better than a chart with more functions that means. There is a more complex relationship at work than merely reducing the pool of possible integrated conceptual designs, because the chart with the largest number, the 8x7, was not the worst chart.

CHAPTER 5

COMPARISON OF THE EXPERIMENTAL STUDIES

The preceding two chapters describe two similar experiments that evaluated the impact of morphological chart size and shape on the identification of promising concepts contained in those charts. The experiments used participants from similar populations and followed similar procedures. This chapter compares significant aspects of the two experiments; specifically the design problem, the design participants, the morphological charts employed, and the experimental procedure. Furthermore, in this chapter, a critique of the two experiments is provided and joint conclusions are drawn.

Design Problem

The design problem in the first experiment was to create a burrito folder, see page 30 of Chapter 3. The second design problem was to create a pet feeder, see page 47 of Chapter 4. Both design problems are developed with the intent that an innovative or not "off-the-shelf" solution is sought and therefore required novel thinking by the participants. A summary comparison of the two design problems is shown in Table 5.1.

Table 5.1: Design Problem

	Experiment #1 (burrito folder)	Experiment #2 (pet feeder)
Design problem	Burrito folder	Device to feed a cat or dog
Evaluation criteria and weightings	low cost (9) easy to clean (3) low number of parts (1)	easy to clean (9) low cost (7) low number of parts (1)
Number of evaluation levels	3	4
Suggested evaluation values	9 (good) 3 (fair) 1 (poor)	9 (very good) 6 (good) 3 (ok) 1 (poor)
Evaluation method	Decision matrix	

The problems shared a common set of evaluation criteria, although the weightings of the criteria changed between the two. This is the result of a different set of needs for the two problems. In each experiment, the judges used the same evaluation criteria and weights as the participants, so this was not felt to be a significant difference between the two experiments. The second experiment used four evaluation levels, while the first experiment used three. The addition of a fourth level enabled a more continuous distribution of possible concept scores. In both experiments, the evaluation levels and weightings were compiled in a decision matrix.

Participants

The participants in these experiments had similar backgrounds, as is summarized in Table 5.2. They were all taking the same second year mechanical engineering course, albeit separated by one year. Most significantly, the actual participants were not the same individuals, but their general relevant characteristic composition was the same. Two different classes participated in experiment #1, but it was demonstrated in Chapter 3 that the two groups performed equivalently, so it is possible to pool their results into a single group. Experiment 2 had only a single class session, so pooled population analysis was not required. It is not possible to compare the participants in experiment #1 and experiment #2 as they worked on different design problems. However, given the similarities between the two groups, it is believed that they are a common population and the joint experiments still provide two useful points of information for this combined study.

Table 5.2: Participants

	Experiment #1 (burrito folder)	Experiment #2 (pet feeder)
Population	Second year mechanical engineering students at Clemson University enrolled in "ME202", a sophomore level mechanical engineering design and kinematics course.	
Number of class sections involved	2	1
Number of participants	25	29
Minimum experience with morphological charts	Lecture on morphological charts presented the week of the experiment as part of regularly scheduled class. Review of morphological charts presented at start of experiment.	
Additional experience with morphological charts	Unknown	
Chance that participants were in both experiments	Unlikely due to the separation in time (1 year) between experiments	

Morphological Charts

Morphological charts of varying sizes were created for both experiments. As is shown in Table 5.3, the first experiment used two different size morphological charts, while the second experiment used four sizes. The increase in number of sizes in the second experiment was done to examine more relationships between the charts. The first experiment examined only morphological charts with more functions than means, or more means than functions. The second experiment created relationships where a change in the number of means at a constant number of functions, or a change in the number of functions at a constant number of means could also be evaluated. This added an additional element of complexity to the second experiment. This extension of the second experiment was a direct result of the findings of the first experiment. The second experiment also used charts capable of generating many more concepts than the first experiment.

Table 5.3: Morphological Charts

	Experiment #1 (burrito folder)	Experiment #2 (pet feeder)
Number of morphological charts	2	4
Sizes (functions x means)	3x5, 5x3	4x5, 4x7, 8x5, 8x7
Method used to change the number of functions	Change level of decomposition	Add or remove specific functions
Method used to change the number of means	Add or remove specific means	
Number of concepts in smallest morphological chart	125	625
Number of concepts in largest morphological chart	243	5,764,801

Experimental Procedure

The two experiments used similar procedures from the participant's perspective. The exception was an increase in the number of concepts for each participant to create. Based on the fact that only one participant in the first experiment did not generate a full number of concepts, the time was sufficient to generate concepts. As a result, the second experiment procedure required that more concepts be generated to encourage the possibility of more novel solutions.

The main difference in the procedure, as can been seen in Table 5.4, related to the judging of concepts. The first experiment used a complicated system to distribute the concepts to be judged among a pool of judges. The second experiment simplified the judging by having two panels of judges each evaluate a group of concepts. Unfortunately, the concepts were not distributed evenly among the judges in the second group, which resulted in a lack of overlap in one chart size between judge panels. Thus, there is a single data point on one chart size (8x7) in experiment two that cannot be compared based on ANOVA. Hence, the conclusions drawn from this chart size are limited.

Table 5.4: Experimental Procedure

	Experiment #1 (burrito folder)	Experiment #2 (pet feeder)
Advance morphological chart training	lecture provided by a mechanical engineering faculty member in a class session before the day of the experiment	
Day of experiment morphological chart training	brief reminder of morphological chart use provided to participants immediately before the experiment	
time allowed to generate and evaluate concepts	30 minutes	
number of concepts for participant to generate	8	10
number of concepts for judging	3 (or more if a tie existed which prevented a clear group of the top 3)	exactly 3
method for accommodating a tie in individual scoring of concepts	Evaluate all tied concepts. Participant score is determined using Equation 3.1	A set of exactly 3 concepts that included the highest ranked concepts was selected
judge distribution system	concepts were divided equally among 5 judges	concepts were split between two judge panels, each consisting of three judges
judge evaluation method	evaluate the concepts using the same decision matrix and weightings as the participants	

Discussion

Although there were some differences between the two experiments, the similarities outweigh the differences. The second experiment builds upon the first and they may be considered together. The most significant differences were the morphological charts, and the change from two sizes in the first to four in the second experiment. This was a beneficial change, because it permitted the analysis of more relationships between the number of means and the number of functions than in the first experiment.

The joint conclusions between the two experiments are two related general trends. First, in both experiments, a morphological chart with fewer functions than means per function produced higher quality integrated conceptual design solutions. This was the only case tested in the first experiment, and the findings were repeated in the second experiment. The second joint conclusion is that increasing the number of functions makes choosing a good integrated conceptual design solution more difficult. In the first experiment, reducing the number of functions improved the resulting concepts generated. While the second experiment does not directly support this trend, it does support the inverse that increasing the number of functions always resulted in lower quality concepts.

CHAPTER 6

CONCLUSIONS

The hypothesis presented in Chapter 1 was that morphological charts which contained fewer possible integrated conceptual designs would produce higher quality integrated concepts. Based on the experimental studies presented here, the hypothesis did not prove true in all cases. For the study presented in Chapter 4, the morphological chart with eight functions and seven means per function was out of place, based on this hypothesis. It contained the most possible integrated conceptual designs, but it was not the worst. What was confirmed was that the shape of morphological charts can have an impact on the quality of concepts generated from them. Two relationships have been identified that did result in higher quality morphological charts in these experiments. A chart with more means than functions produced better concepts than a chart with more functions than means. Also, adding functions to a morphological chart never improved the results. This second observation has profound implications on the selection of the number of functions to include in a morphological chart. The time and effort needed to create a very detailed functional decomposition will not aid a designer in selecting promising integrated conceptual design solutions from a morphological chart. It is likely that reducing the number of functions will generally improve the success of this task, up to a point. This work does not claim that reducing a morphological chart to a single function will produce better integrated concepts.

Contributions

The experiments described in Chapter 3 and Chapter 4 presents a procedure for generating a large number of integrated conceptual design solutions from different morphological charts. Two similar evaluation techniques (judge panels and judge pools) are used to evaluate the concepts. This procedure could be used for further study of morphological charts and could be used by future work which builds off the work presented in this thesis.

The experimental results described in Chapter 3 and Chapter 4 document the results of undergraduate mechanical engineering students. The results show the impact of morphological chart size and shape on the quality of concepts generated by these students. The morphological chart that proved most challenging for the students to create good integrated conceptual design solutions was one with many functions and few means per functions. This suggests that students should be encouraged to limit the functional decomposition of a problem and concentrate their efforts on means generation if they are going to use a morphological chart in their design process.

Judging Systems

This work employed two different systems for judging the integrated concepts. In both experiments, it was desired to break up the judging to reduce the time required for the participation of each individual judge. The first experiment assigned the integrated concepts to a pool of five judges. Each integrated concept was evaluated by three judges. Each judge was assigned approximately 60% of the concepts generated from each chart. This system was cumbersome to set up, requiring trial and error searches through possible assignments until a pattern meeting the requirements listed above was found. It did achieve a uniform distribution of integrated concepts among the judges.

For the second experiment, a simpler method for assigning integrated concepts to judges was used. For this experiment, six judges evaluated the integrated concepts. Once again, each concept was evaluated by three judges. In this way, each judge evaluated half of the concepts. The collection of integrated concepts was arbitrarily divided into two halves, and each half was evaluated by a judge panel of three judges. The judges worked individually to evaluate the concepts. This system was simpler to set up, not requiring as much time in advance to determine the optimum pattern for assignments. As a result of this system, however, it was necessary to evaluate the validity of combining evaluations from one judge panel with the other. In this analysis, it was found that there was insufficient overlap in one morphological chart size to determine if the judge panels were consistent. If a system similar to the first experiment had been utilized to spread the integrated concepts evenly among judges, it would have reduced the impact of any differences between the judge panels.

In future work, care must be taken with the assignment of evaluations to judges. The ideal situation is to have each judge evaluate all integrated concepts. The logistical concern is that the number of evaluations grows quite large, and each judge must make many evaluations. If the evaluations are distributed among judges, care must be taken in setting up the evaluations such that they will have minimal impact on the statistical analysis of the results. The additional effort needed to set up the evaluations in the first experiment was beneficial in eliminating the need to determine if the work of the judge panels could be pooled for the statistical analysis. In essence, the additional effort in setting up the judging system in the first experiment reduced the uncertainty of the judging results.

Future Work

In these experiments, the attempt was made to generate morphological charts with functions at two different levels of detail. The functions used in these experiments may not have fully accomplished this goal. For further experiments, consideration should be given to generating a new set of functions rigorously linked to the decomposition of the design problem. The functions would be taken from the decomposition at two different levels of decomposition, as illustrated with a generic case in Figure 6.1. The higher level set of sub-functions is outlined in green, while the lower level set is outlined in blue. Developing two sets of means for each set of functions would permit the duplication of the more detailed relationships in the second experiment. The judging system should follow that used in the first experiment with careful allocation of integrated concepts among judges to reduce uncertainty.

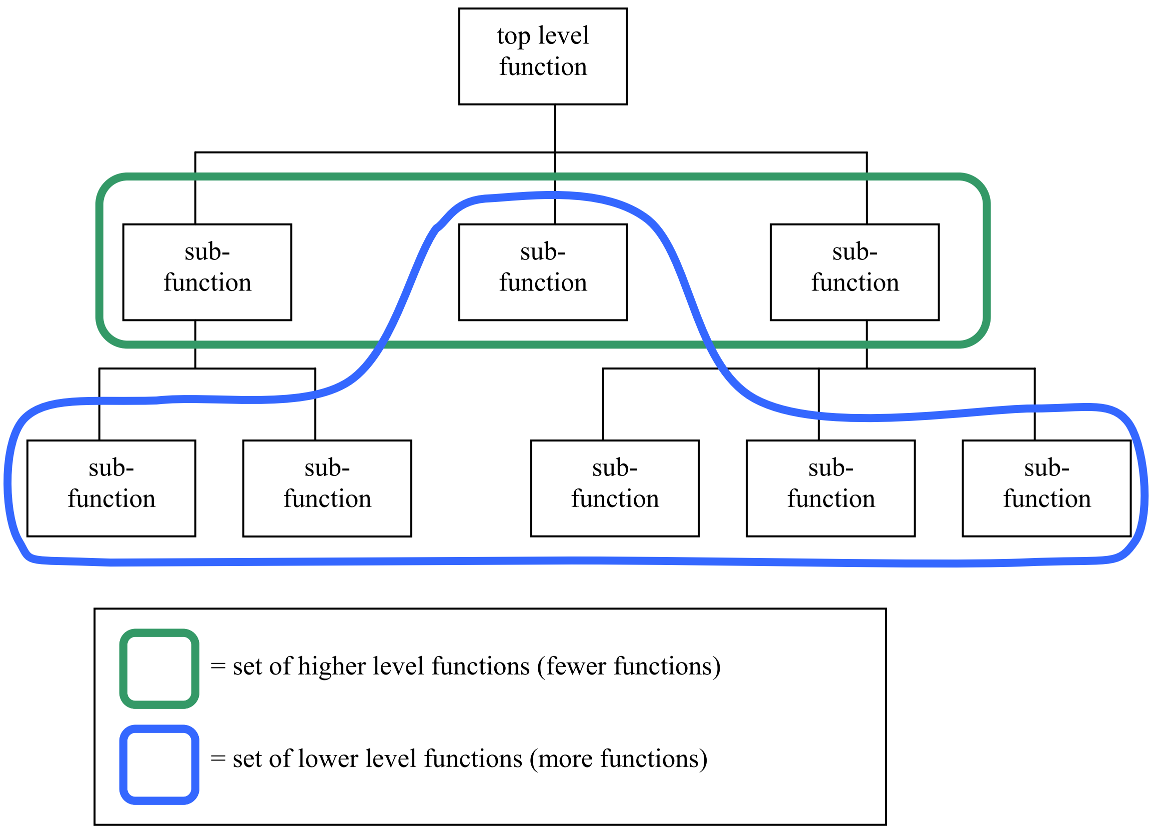


Figure 6.1: Rigorous Set of Functions from a Single Functional Decomposition

Initially, one of the design problems described in this work, or one of similar scope and complexity should be used. This new experiment should be repeated with a similar population of participants to compare with the results described in this work. Further experiments could then be undertaken with participants from a population of designers with a different level of experience.

Building upon these experiments, potential methods for systematically analyzing the combinations of integrated concepts contained in morphological charts may be investigated. As discussed in previous chapters, a morphological chart can generate a large number of combinations. There are tools that provide systematic testing methods when it is too difficult to test every possible combination, such as the full output of a morphological chart. One such option is provided by the Design of Experiments method. Experiments may be run using orthogonal arrays or using a fractional factorial. These provide a systematic way to test only a subset of all combinations and still derive relationships for the whole set (Hicks and Turner, 1999). Depending on how these tests are set up, they will capture some, but not all, of the interactions between test items.

The combinations in a morphological chart are the product of the number of means for each function. In the morphological chart shown in Table 2.3, there are 36 possible combinations, with only four functions. The number of combinations can grow quite quickly when considering a design with more functions. To test this morphological chart using an orthogonal array and capture all interactions between any two functions would still require 32 experiments. The functions can be considered as A, B, C, and D. The interactions would be AB, AC, AD, BC, BD, and CD. This turns four functions into a total of 10 variables to watch. Orthogonal arrays are not available for every possible number of variables and levels. While Table 2.3 shows four variables with a mixture of two- and three-level values, it is necessary to use an orthogonal array with four levels and ten variables. This experiment requires 32 trials, which is only a reduction of four over just running the whole list of all possible combinations (Phadke, 1989).

The savings in these methods comes from ignoring some, or all of the interactions in the experiments. This is a powerful ability, in that it can greatly reduce the number of experiments to run. The tradeoff with interactions, though, is a flaw for use with analyzing morphological charts. The benefit of a methodical analysis of morphological charts is that it has the potential to pick up on interactions that combine to enhance the design solution. Tools such as Axiomatic Design (Suh, 2001) or the Function-Means Tree (Dym and Little, 2000) are based on making decisions early about the means, but this creates a risk of premature decisions about the means (Dym and Little, 2000). An early decision has the potential loss of not finding a downstream interaction that contributes positively to the design. Such an interaction may not be visible at a higher level where the decision about a means was made.

A different approach will be necessary for a systematic analysis of morphological charts. By filtering and combining functions, it will be possible to reduce the size of the morphological chart. Similar functions may be combined and analyzed as a group together. Similar means may also be grouped, because they would have a less significant effect on the initial analysis. Means may be filtered against how they satisfy design constraints. Means that violate constraints can be eliminated. For example, a particular means may provide a safety concern that cannot be accounted for by other protection. Combinations together may violate constraints as well. For example, while no one means may be too expensive on its own, a certain combination may provide to be too expensive. Weight is another area that “adds” together.

Aygün proposes a method using compatibility matrices to evaluate a system of design variables (Aygün, 2000). Examine the interactions between the constraints and the design variables. In situations where compromises are needed due to conflicts between design variables, a compatibility matrix can be generated with all the possible discrete values of the design variables to look for conflicts between possible values. This method could be extended to a morphological chart analysis as a way to identify the critical functions to include in the morphological chart as well as eliminating incompatible means.

Maier and Fadel discuss the concept of affordance (Maier and Fadel, 2001), which provides a potential tool for seeing how means can combine in a design solution. Byproducts can be considered negative affordances. For example, an airplane requires thrust. Frequently this is provided by a jet engine. A byproduct of a jet engine is noise. The jet engine affords noise, which is a negative affordance. The design of the airplane must now provide something that compensates for this noise. The cabin of the airplane affords noise protection, which is a positive affordance. While in this case, the noise protection properties of the cabin are probably designed to handle the noise of the engine, there could be situations where the positive affordances are incidental to the means, but provide a benefit to the design.

The addition of these tools may provide possible methods for filtering or reducing morphological charts to a manageable level, while leaving the undiscovered interactions intact within the remaining possible integrated conceptual design solutions. This has the potential to increase the usefulness of morphological charts in design.

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