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Understanding the Role of Functions and Interactions in the Product Design

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UNDERSTANDING THE ROLE OF FUNCTIONS AND INTERACTION IN THE PRODUCT DESIGN

A Thesis
Presented to
The Graduate School of
Clemson University

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

By
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August 2011

Accepted by:
Dr. Gregory M. Mocko, Committee Chair
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Dr. Georges M. Fadel
ABSTRACT

Engineering designers often generate design concepts based on a functional understanding of the problem. Many engineering textbooks encourage designers to abstract the essential problem to a higher-level functional representation of the product and subsequently develop solutions to the functional needs. However, a functional perspective of design does not provide a complete view of what the product must do and how the product must interact with users and other parts. To address this, an alternative modeling approach has been developed to complement the traditional functional modeling approaches. Two such approaches include (1) activity modeling to capture the user actions from production through death of a product, and (2) affordance-based design to capture a range of characteristics of a product. There exist opportunities to combine function based and interaction based modeling approaches to an integrated model. Additionally, there is not sufficient experimental data to support the use of such model during the early stages of design.

Thus, the primary objective of this research is to understand the role of functions and interactions in describing a product. In order to accomplish this, two design experiments was conducted: (1) a user study to compare the effect of function models and function interaction models in aiding the designers to develop creative concepts and (2) a card sorting exercise to understand whether users categorize products that are in the market based on the product’s functionality or user-product interaction. In the user study, forty graduate and senior level students are divided into two groups and asked to develop
concept sketches using either the function model (FM) or the function interaction model (FIM) they received. The sketches are then statistically analyzed in terms of quantity and quality. The findings from this study suggest that FM enables designers to develop more number of concepts compared to FIM. However, the quality of the sketches developed by the designers at the concept level is found higher for the FIM. There is no significant difference in the quality of sketches at the requirement level developed using the FM and the FIM. In the card sorting exercise, fifty-three sophomore level engineers categorized consumer products based on the product’s functions and interactions at two levels (low and high). Analyses of the results indicate that users are comfortable classifying products that are either simple (low functionality-low interaction) or complex (high functionality-high interaction). Initial results from this card sorting exercise also suggest that functions of a product get priority over the interactions it has with the user.
DEDICATION

This thesis is dedicated to my mother, Vijaya Ramachandran who has been instrumental in defining my life. She will always continue to be my source of inspiration.
ACKNOWLEDGMENTS

First, I would like to thank Dr. Gregory Mocko for his continuous support and guidance over the past two years. It has been a pleasure to work with him and I believe that I have learned a lot from him. My research is complete because of his patience and belief in me. I would like to thank Dr. Joshua Summers for his instant and useful ideas that helped me to conduct two user study sessions successfully. I would also like to thank Dr. Georges Fadel for supporting me throughout this research. I take this opportunity to thank Dr. Jonathan Maier for sharing his ideas and that helped me to conduct the card sorting exercise in a quick time.

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Finally, thank you to my parents and brother for their unwavering support without which this work would not be possible.

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# TABLE OF CONTENTS

ABSTRACT .................................................................................................................. ii

DEDICATION .................................................................................................................... iv

ACKNOWLEDGMENTS ...................................................................................................... v

TABLE OF CONTENTS .................................................................................................. vi

LIST OF TABLES ........................................................................................................ viii

LIST OF FIGURES ......................................................................................................... x

CHAPTER 1: INTRODUCTION ...................................................................................... 1

1.1 Motivation .................................................................................................................. 1

1.2 Thesis Overview ....................................................................................................... 2

CHAPTER 2: LITERATURE REVIEW .......................................................................... 4

2.1 Function Model ....................................................................................................... 4

2.2 Function Interaction Model ..................................................................................... 6

2.3 Creativity in Engineering Design .......................................................................... 11

2.4 Affordances, Functions and Interactions ............................................................... 13

2.5 Summary and Identification of Research Gaps ....................................................... 14

CHAPTER 3: RESEARCH GOALS ............................................................................. 16

CHAPTER 4: RESEARCH FRAMEWORK .................................................................. 21

4.1 User Study of the Function Model and the Function Interaction Model ............... 21

4.2 Card Sorting Exercise ............................................................................................ 30

CHAPTER 5: INITIAL USER STUDY RESULTS .................................................. 35

5.1 Quantity of Concepts ............................................................................................. 36

5.2 Quality of Concepts ............................................................................................... 37

5.3 Summary ............................................................................................................... 46

CHAPTER 6: RESULTS FROM THE REFINED SCALE ......................................... 48

6.1 Quantity of Concepts ............................................................................................. 48
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 3.1: Research questions, hypotheses and tasks</td>
<td>19</td>
</tr>
<tr>
<td>Table 4.1: List of requirements developed for the study</td>
<td>25</td>
</tr>
<tr>
<td>Table 4.2: Number of functions and flows represented in each model</td>
<td>25</td>
</tr>
<tr>
<td>Table 4.3: Products sorted based on their functionality and interaction</td>
<td>31</td>
</tr>
<tr>
<td>Table 5.1: Number of concepts developed from each model</td>
<td>37</td>
</tr>
<tr>
<td>Table 5.2: Initial scale developed for measuring quality</td>
<td>38</td>
</tr>
<tr>
<td>Table 5.3: Interpretation of kappa values</td>
<td>40</td>
</tr>
<tr>
<td>Table 5.4: Quality score assignment for each concept using the median method</td>
<td>41</td>
</tr>
<tr>
<td>Table 5.5: Inter rater agreement between four raters</td>
<td>41</td>
</tr>
<tr>
<td>Table 5.6: Quality at the concept level</td>
<td>42</td>
</tr>
<tr>
<td>Table 5.7: t-test to compare the means of the two models at the concept level</td>
<td>43</td>
</tr>
<tr>
<td>Table 5.8: t-test to compare the concept quality scores for functional requirements</td>
<td>43</td>
</tr>
<tr>
<td>Table 5.9: t-test to compare concept quality score for non-functional requirements</td>
<td>44</td>
</tr>
<tr>
<td>Table 5.10: Quality at the requirement level</td>
<td>45</td>
</tr>
<tr>
<td>Table 5.11: Quality score for requirements across each model</td>
<td>46</td>
</tr>
<tr>
<td>Table 5.12: Paired t-test to compare means of the two models at requirement level</td>
<td>46</td>
</tr>
<tr>
<td>Table 6.1: Quantity of concepts developed from the two models</td>
<td>49</td>
</tr>
<tr>
<td>Table 6.2 Refined scale for the requirement list</td>
<td>50</td>
</tr>
<tr>
<td>Table 6.3: Refined scale with sample sketches as examples</td>
<td>52</td>
</tr>
</tbody>
</table>
Table 6.4: Iterations for Inter Rater Agreement.......................................................... 60
Table 6.5: t-test to compare the means of the two models at the concept level.............. 62
Table 6.6: t-test to compare concept quality scores for functional requirements ....... 62
Table 6.7: t-test to compare concept quality score for non-functional requirements ...... 63
Table 6.8: Quality score of the concepts at the requirement level.................................. 64
Table 6.9: Paired t-test to compare means of the two models at requirement level........ 65
Table 7.1: A random participant's response with highlighted examples ....................... 69
Table 7.2: Accuracy percentage for each quadrant......................................................... 72
Table 7.3: Products sorted based on their functionality and interaction (repeated)............ 74
Table 7.4: Percent accuracy of products sorted based on functionality and interaction... 77
Table 8.1: Answers to the research questions.............................................................. 85
<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1: Research overview</td>
<td>3</td>
</tr>
<tr>
<td>Figure 2.1: Function model template</td>
<td>6</td>
</tr>
<tr>
<td>Figure 2.2: Function model of a Black and Decker Rice Cooker</td>
<td>6</td>
</tr>
<tr>
<td>Figure 2.3: Function-based design approach with complementary interaction-based approach</td>
<td>8</td>
</tr>
<tr>
<td>Figure 2.4 Initial function interaction model of a Rice Cooker</td>
<td>10</td>
</tr>
<tr>
<td>Figure 2.5: Refined function interaction model of a Rice Cooker</td>
<td>11</td>
</tr>
<tr>
<td>Figure 2.6: Excerpt of an affordance structure</td>
<td>14</td>
</tr>
<tr>
<td>Figure 4.1: Experimental setup for the user study</td>
<td>23</td>
</tr>
<tr>
<td>Figure 4.2: General statement and list of requirements provided to the students</td>
<td>24</td>
</tr>
<tr>
<td>Figure 4.3: Function model of a burrito folding machine</td>
<td>26</td>
</tr>
<tr>
<td>Figure 4.4: Function interaction model of a burrito folding machine</td>
<td>27</td>
</tr>
<tr>
<td>Figure 4.5: Guidelines for interpreting the model and sketching concepts</td>
<td>28</td>
</tr>
<tr>
<td>Figure 4.6: Sample concepts (Labels are added for reading clarity)</td>
<td>29</td>
</tr>
<tr>
<td>Figure 4.7: Figures of the products presented to the participants</td>
<td>34</td>
</tr>
<tr>
<td>Figure 6.1: Example figure #1</td>
<td>54</td>
</tr>
<tr>
<td>Figure 6.2: Example figure #2</td>
<td>54</td>
</tr>
<tr>
<td>Figure 6.3: Burrito folder sketch - Example 1</td>
<td>55</td>
</tr>
<tr>
<td>Figure 6.4: Burrito folder sketch - Example 2</td>
<td>57</td>
</tr>
</tbody>
</table>
Figure 6.5: Quality scores of the concepts at the requirement level .......................... 64
Figure 6.6: Quality scores for the human activity requirements ..................................... 66
Figure 7.1: Accuracy percentage for each product .......................................................... 71
Figure 7.2: Correct function (left) and correct interaction (right) for Q1 ......................... 75
Figure 7.3: Correct function (left) and correct interaction (right) for Q2 ......................... 75
Figure 7.4: Correct function (left) and correct interaction (right) for Q3 ......................... 76
Figure 7.5: Correct function (left) and correct interaction (right) for Q4 ......................... 76
Figure 8.1: Function-based design approach with complementary interaction-based approach (repeated) ................................................................. 82
CHAPTER 1: INTRODUCTION

1.1 Motivation

The objective of this research is to understand the role of functions and interactions in describing a product. The desire to develop highly creative products has made design engineers to continuously work on the various functional modeling techniques. Mechanical design engineers use a wide range of representations to model a particular product. The product can be as simple as a hair dryer or can be a complex system like a helicopter. One commonly encouraged practice is to model products based on its functionality. The baseline function modeling approach used in this research is established in Pahl and Beitz [1]. On the other hand, the user who primarily handles/operates the product is not effectively represented in the function models. The activity diagram, proposed by Otto and Wood [2] complement functional modeling by capturing the user activities from purchase to recycling. However, the information provided in these models is not represented in a single, integrated model. In order to address this issue, a function interaction model (FIM) was developed by Caldwell and Mocko [3] which not only represents a product based on its functionality, but also introduces the user activities as a separate entity within the model. This newly developed FIM includes both the transformative and non-transformative product characteristic. Throughout this research, the transformative characteristics are termed as active functions and the non-transformative characteristics of the product are termed as passive functions.
During the conceptual design phase, it is important that the designers consider both these aspects.

The first part of the research involves comparing the newly developed function interaction model (FIM) with the traditional function model (FM) by conducting a user study. The objective is to determine how the creativity of the designers is affected by providing these models during the early stages of product development. The second part of this research pertains to the user’s perception of how a product would work; whether users categorize various products based on the product’s functionality or based on how they would interact with it. A card sorting exercise was performed in which the participants sorted a wide range of products into four categories based on their functionality and interaction. The overall view of this research is shown in Figure 1.1.

1.2 Thesis Overview

This research work primarily aims to understand the role of functions and interactions in product designing. This is accomplished through two user experiments. The first user study was conducted to understand how engineering use different models in the conceptual design phase and how these models affect creativity. The second card sorting exercise is focused on understanding how mechanical engineering students perceive the interactions and functions of technical artifacts. Chapter 2 reviews the current research practices about function-based and affordance-based design methodologies, introduction to the function interaction model and creativity in engineering design. Chapter 3 discusses the research gaps and the following research
questions planned to address the gaps. The experimental setup and procedure followed to answer the research questions is discussed in Chapter 4.

Chapter 5 and Chapter 6 elaborate the initial results and the results obtained after refining the scale. The initial results obtained from the card sorting exercise are discussed in Chapter 7. The conclusions drawn from this research and the scope for future work are discussed in Chapter 8.

![Flowchart showing research overview]

**Figure 1.1: Research overview**
CHAPTER 2: LITERATURE REVIEW

2.1 Function Model

Function modeling is a widely researched engineering design field. The use of function modeling in the conceptual design phase is discussed in detail by the researchers [1, 2, 4-6] as it helps in broadening the search for design solutions. Function modeling is a systematic process of representing a product through its functions and flows. Pahl and Beitz define function as “the intended input/output relation of a system whose purpose is to perform a task” [1]. Otto and Wood define function as “a clear reproducible relationship between the available input and the desired output of a product, independent of any particular form” [2]. Other definitions of functions include “the required or desired capabilities of a real system that will make it possible for that system to perform its intended goal task [6]” and “a specific process, action or task that a system is able to perform [7]”. A function model assists the designers in converting abstract customer needs to concrete solutions. Function models also help to focus on ‘what’ a product must do rather than ‘how’ the product accomplishes it.

The commonly used function modeling approach is the one proposed by Pahl and Beitz [1]. There are others forms of representing products in engineering design. Umeda et.al [8] proposes Function- Behavior and Structure (FBS) diagram which relates the function, behavior and state of a product and represents the product with its functional description. Gero and Kannengiesser [9] later extended this diagram to Situated Function- Behavior- Structure framework which accounted for the dynamic character of the context.
in which the designing would take place. Galvao and Sato [10] uses affordance as an instrument to understand the relationship between functions and task. Each of these different product representations describes a product’s functionality in different aspects.

The function model representation is reasonably consistent and is a widely practiced product representation method [11]. Hence, the function model (FM) representation, which is promoted by the researchers [1, 2, 12, 13], is used as a baseline in this research. There are three main concepts describing a function model (FM); namely functions, flows and system boundary. In the function modeling approach, the overall function of the product is decomposed into a number of sub-functions. These sub-functions are then connected by a series of energy, material and information flow. A function transforms a set of input flows into a set of output flows. Again flows can be of three types, namely material, energy and signal/information [1]. Some examples of material flows include solids, liquids and gases. Mechanical, thermal, chemical energies are some examples for energy flows and magnitude, display and data are some examples for signal/information flow.

In the first stage of product representation, the functions and flows of the particular product are modeled in a black box. A black box is the highest form of abstraction for a product ignoring its specific details [2]. The black box can later be decomposed into various functions and subfunctions. Figure 2.1 shows the template for a function model that could later be decomposed into functions and sub-functions.
Figure 2.1: Function model template

Figure 2.2 explains the function model of a rice cooker. The primary objective of a rice cooker is to ‘convert raw rice to boiled rice’. There are eight functions and twelve flows. It has two energy inputs namely electrical and human energy; two material inputs namely rice and water and one material output - boiled rice.

Figure 2.2: Function model of a Black and Decker Rice Cooker

2.2 Function Interaction Model

In function-based modeling approach, the non-transformational characteristics of a product are not considered until the embodiment stage of product design. In order to address this gap, the function interaction model (FIM) was developed. The function interaction model (FIM) tries to capture both the transformational and non-transformational aspects of a product early during the product development stage. A
product interacts with the environment and may interact with other artifacts and users. The function based approach does not consider a product’s interactions as a part of the function model. The function-first approach which follows a standard set of function related terminologies tends to delay the non-functional aspects of design requirements [3]. Interactions, which are non-functional aspects of a product is therefore not represented in the traditional functional models. The function interaction model was thus developed which integrates both user and his interactions with the product, in addition to the product’s functionality in a single model [3]. These non-functional aspects are represented as passive functions. The terms active and passive functions are closely associated with the function interaction model and their definitions are provided below,

**Active functions**: These are functions that carry energy flow to control the outcome of the dependent function. For example, the active functions of an iPhone would be ‘sense human material’, ‘process control signal’, ‘convert electrical energy to electromagnetic energy’.

**Passive functions**: These functions do not carry the energy used to control the outcome of a function. Non-functional aspects of a product like user activities are passive functions as they describe actions over the product. Some passive function examples for an iPhone include ‘operate with one finger’ and ‘easy to understand for a user’

The function interaction model (FIM) used in this research is a parallel model, wherein the functions and interactions of a product are represented complementing each other in the model representation. In a function interaction model, the active functions are
placed in the function-based path and the passive functions are placed in the interaction based path as shown in Figure 2.3.

![Diagram](image)

**Figure 2.3: Function-based design approach with complementary interaction-based approach [3]**

The function interaction model of a rice cooker shown in Figure 2.4 was developed based on the rules formulated by Caldwell and Mocko [3]. The user and the activities performed by the user are shown separately from the functions of the product. The rectangles in the model show the active functions or the functions performed by the product. The hexagons show the user activities which are the activities performed by the user over the product. The interactions are represented by diamonds and it shows the interaction between two parts of a product or a product-user interaction. The dotted lines
with a circle at its end represent an enabler. The enablers are the interfaces that facilitate the details of the dependency of the product.

In order to reduce the level of detail presented through the model, the function interaction model was further refined. Some of the features in the initial function interaction model were removed as they were redundant and some features were modified to make the model more readable to the designers. The final function interaction model had the following changes,

1. *The interactions between the products and the user were removed:* The interactions between the product and the user are redundant. In general, the interactions are mapped one to one between the product and the activities. That is, if there are three user activities then there will be three diamonds showing interactions with the device. In this rice cooker example, the only significant interaction between the cooker and the user is while giving the initial inputs to the cooker. Therefore, the interaction ‘manipulate’ is removed (see Figure 2.4).

2. *The function, flow or activity enabler was removed:* The enablers were initially designed along with the interactions to give form based details of the product to the designers. In the rice cooker example, a push button, switch or lever can be used as an enabler. Since the interactions between the product and the user were removed, the enablers were also removed in order to maintain consistency in the model.

3. *The user activities were moved to the top of the model:* In order to make it easy for the designers to interpret, the user activity part of the function interaction model
was moved to the top. This will help the designers to look at the model and visualize a user performing actions over the product.

**Figure 2.4 Initial function interaction model of a Rice Cooker**

One notable feature in the function interaction model is the mode of representing human activities. While the function models represent human/user as human *energy*, the function interaction model represents a human/user as a separate entity or *activity*.
The refined function interaction model for the rice cooker is shown in Figure 2.5. There are four functions, three activities and fourteen flows represented in the FIM. The flows are represented by arrows moving back and forth the user and the machine (rice cooker). It has two material inputs namely rice and water and one material output - boiled rice. The user input required to control the rice cooker is represented as a user activity. This user activity is then converted to a control signal which then converts the input electrical energy to a thermal energy.

Figure 2.5: Refined function interaction model of a Rice Cooker

2.3 Creativity in Engineering Design

A design problem can yield creative solutions by following a set of formalized steps [14]. Many structured idea generation tools used in the conceptual design phase include brainstorming, morphological analysis, collaborative sketching and synectics. In addition
to these techniques, design engineers often use function models to generate multiple solutions. Function based modeling, discussed in Section 2.1, significantly help a design teams in breaking down the design problem and make early decisions. Hence it is one of the most desired tools to generate multiple design solutions [12, 15]. The function models help designers to concentrate on developing design solutions initially for each function and then arrive at a whole concept [16]. In this research, the effectiveness of both the function model and the function interaction model in assisting the designers to develop creative concepts is tested.

Most of the idea generation techniques have two important characteristics in common, namely formalization and externalization [17]. Based on the design problem, the engineers formalize an ideation technique and then the ideas are externalized by either drawing sketches, texts or other means. Free hand sketches are representations of what a designer thinks and are often used in a design process to express ideas [18]. The initial concept drawing sketches show us the designer’s mind at work as he visualizes the as yet non-existent product [19]. For the user study comparing the function model (FM) and the function interaction model (FIM), the participants were asked to sketch and briefly describe their concepts. In order to determine the creativity pertained to the concepts, the sketches were evaluated in terms of quantity and quality. Quantity is the total number of concepts generated and quality is a measure of feasibility of a concept or closeness of a concept to the design requirements [20].
2.4 Affordances, Functions and Interactions

Function-based approach is used as foundation in many popular engineering design texts [21-23]. As an alternative, affordances were introduced in the engineering design to disentangle the relationship between designers, users and products. Norman [24] defines affordance as “the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used”. Maier and Fadel [21] proposed an affordance structure which captures both positive and negative functionality of a product i.e. an artifact must afford what it is intended to do and also afford being used by humans at the end without causing harm. An affordance structure binds the product’s overall function with the user interaction (see Figure 2.6) and addresses various factors like aesthetics, improvement maintenance, manufacturing and sustainability to name a few. Evaluating the effectiveness and usability of a complete affordance structure is beyond the scope of this research. The goal is to identify the role of functions and user interactions, which is an excerpt from the affordance structure, in describing the product. With affordances being identified as a superset to functions and interactions, a closed card sorting exercise was developed to identify its role in product design. Specific details about the card sorting exercise and its procedure are discussed in Section 4.2
2.5 Summary and Identification of Research Gaps

The objective of this chapter is to understand the background for this research. The literature reviewed in this chapter can be summarized as the following:

- Function-based modeling has been widely promoted as a tool that aids the designers in developing creative solutions.

- In function-based modeling approach, the non-transformational characteristics of a product like user activities are not considered until the embodiment stage of product design. The activity diagram which focuses on representing these passive functions captures the user activities from purchase to recycling. Other researchers have also identified the importance of representing non-transformational aspects of a product but the information is not represented in a single, integrated model.

- To address this gap, an integrated function interaction model (FIM) was developed to enhance the ability of the designers in generating creative concepts during the early stages of product development.

Figure 2.6: Excerpt of an affordance structure [21]
• It is important to use the right model to represent a product which is simple enough to allow multiple solutions, yet produce concepts that are close to meeting all the design requirements.

• The functional and interaction requirements are developed, used and addressed by design engineers during early product development. It is also essential to understand how end users (or consumers) prioritize functions and interactions while describing a product.
CHAPTER 3: RESEARCH GOALS

The primary objective of this research is to identify the role of functions and interactions in describing a product. This forms the basis for the main research question addressed through this research. The related questions need to be answered at both the conceptual development stage and the consumer utilization stage of the products.

**RQ0**: How are product functions and interactions and associated representations useful in design?

During the product development phase, it is important to concentrate on both the functional and non-functional aspects of a product. Function-based modeling approaches tend to postpone the non-functional aspects to the later stages of design. These gaps were identified in the previous chapter and the function interaction model was developed addressing this issue. A series of modifications were made to the function interaction model to make it more useful to the designers. Now, it is important to examine if the function interaction model satisfies the reason for its creation, which is assisting designers in generating creative concepts. Two user studies involving senior and graduate mechanical engineering students were conducted to examine the effect of FM and FIM in creativity. With both FM and FIM providing impetus for ideation, our aim is to identify which one of these models is better suited during the conceptual design phase and identify the limitations of each model.

**RQ1**: How do the function model and function interaction model affect the creativity of the designers within conceptual design?
In this research, creativity is measured in terms of quantity and quality of the concepts developed. Quantity is the number of concepts developed during a design session.

**RH1:** The number of concepts developed by the designers using the function interaction model is different from the number of concepts developed by the designers using the function model.

Quality can be defined as conformance to the requirements or the feasibility of an idea to satisfy the needs [20]. While measuring quality, it is recommended to break down quality into different possible levels to get the overall dimension of the process [25]. Selecting the right quality characteristic and the right method to measure the responses is also critical. In this research, the quality of the individual concepts and the list of requirements that were provided to sketch those concepts were identified as the two levels that pertain to the overall quality characteristics of the product models. Therefore, the concept sketches are measured at concept level and requirement level. Quality score at the concept level is the average quality score of all the requirements for a particular concept.

**RH2:** At the concept level, the average quality rating for concepts generated from the function interaction model is different from the average quality rating for concepts generated from the function model.

Quality at the requirement level is measured using the score of all the concepts for a particular requirement.
RH3: At the requirement level, the average quality rating for concepts generated from the function interaction model is different from the average quality rating for concepts generated from the function model.

While the first part of the research focuses on representing product models that will enable design teams to develop new products, the second part focuses on the user’s perception about functions and interactions of different products that they are familiar with.

RQ2: How do users understand the functional and interaction aspects of a designed product?

The hypothesis is that the users categorize products on how they would perceive it to function and how the device permits the user to interact. A classic example is the push plates employed in door handles. The flat horizontal bar allows the user only to push it. The user interacts with the door through the push plates. Similarly, complex products with thousands of parts, like space ships and cars, direct the users to believe that it is complicate to operate. Therefore, higher percentage of product matches will be found in the low functionality-low interaction quadrant (LF-LI) and high functionality-high interaction quadrant (HF-HI). This is because the products in these quadrants are either simple or complex.

RH4: The products sorted in Q1 (LF-LI) and Q4 (HF-HI) will have higher accuracy percentage compared to the products sorted in Q2 (LF-HI) and Q3 (HF-LI)
The next step involves finding the dominating factor of the two; whether it is the product’s function or the interactions that causes the user to categorize a particular product in a particular quadrant. The hypothesis is that users weigh equal importance to both functionality and interaction of a product.

RH5: There is no significant difference between the percentage accuracy for correct functionality and correct interaction of all the products.

The research questions, hypotheses and the tasks addressed in this chapter are shown in Table 3.1.

<table>
<thead>
<tr>
<th>Research Questions</th>
<th>Research Hypotheses</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RQ1:</strong> How does the FM and the FIM affect creativity?</td>
<td><strong>RH1:</strong> The number of concepts developed is different for the FM and the FIM</td>
<td>Conduct a user study involving senior and graduate level mechanical engineering students</td>
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<tr>
<td></td>
<td><strong>RH2:</strong> The quality of concepts at the concept level is different for the FM and the FIM</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>RH3:</strong> The quality of concepts at the requirement level is different for the FM and the FIM</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.2: Research questions, hypotheses and tasks (continued)

<table>
<thead>
<tr>
<th>Research Questions</th>
<th>Research Hypotheses</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RQ2</strong>: How do users categorize a product based on their functions and interactions?</td>
<td><strong>RH4</strong>: The products sorted in Q1 and Q4 have higher accuracy percentage match with the actual product list</td>
<td>Conduct a card sorting exercise involving sophomore (novice) level engineers</td>
</tr>
<tr>
<td></td>
<td><strong>RH5</strong>: There is no significant difference between the accuracy percentage for correct functionality and correct interaction of all the products</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 4: RESEARCH FRAMEWORK

Two design experiments were conducted in order to identify the relationship between functions, interactions and affordances. While the first experiment, which is a user study, evaluates the creativity of the designer during the early stages of design, the second card sorting exercise was conducted to understand how a novice designer (or users) would perceive a product to perform based on its functionality and interaction.

4.1 User Study of the Function Model and the Function Interaction Model

When a design engineer is provided either a function model (FM) or a function interaction model (FIM) and asked to develop concepts based on the model provided, it would be useful to know which of the two models influence the creativity of a designer. In order to determine this, a user study was conducted with senior and graduate mechanical engineering students. User studies are employed in design research to compare different approaches; verify and measure the effect of a new tool with the current one and to explore new grounds based on the results obtained. The objective of conducting user studies is to draw the interrelationship between the models under observation [26].

For this research, a user study was conducted in two sessions in order to increase the population pool. In the first session, fourteen graduate mechanical engineering students participated and the second session was conducted with twenty four senior mechanical engineering students. In both the sessions it was ensured that the participants were
provided with thirty minutes to sketch their design concepts. A brief discussion about the two sessions is provided below.

4.1.1 User group 1: Graduate engineering students

This session had participants from graduate mechanical engineering course ME 870 – Advanced design methodologies. Fourteen students were divided into two groups; one FM group and another FIM group. The experiment was conducted during the normal class hours and usual class room. In this session, a thirty minute presentation about both the models being used in the study was given to all the participants. The reason for having a condensed presentation was that the participants were already exposed to the traditional function models as a part of their syllabus and are new only to the function interaction model. So less time was spent in training the participants. At the end of the presentation, a five minute time was allocated to answer questions from the participants. Three participants from the class had their questions answered regarding the new function interaction model. Following that, thirty minutes was allotted for the participants to sketch their design concepts based on the respective models. Since the students were learning about how to design a user experiment through participation, the remaining ten minutes was used to discuss about how to frame and test hypotheses using a user study as a tool.

4.1.2 User group 2: Senior undergraduate engineering students

Session two had twenty four participants from senior mechanical design engineering course. The participants were randomly divided into two groups and were sent to two
different rooms. One group was exposed to the FM and the other group to FIM. The participants of this session did not have any background of developing or interpreting the functional models. In order to address this, the participants had a detailed thirty minute presentation about the particular model being used by them. Two graduate students (one for function model and the other for function interaction model) gave the presentations simultaneously in two different rooms. However, it was ensured that the user study was started during the normal class hours and the participants received only thirty minutes to sketch their concepts. Both the sessions are aimed at capturing the creativity of the designers when exposed to two different functional modeling approaches. Figure 4.1 shows the experimental setup for testing the effectiveness of the two models under study.

Figure 4.1: Experimental setup for the user study
4.1.3 Problem statements

The design problem chosen for this study is the design of a home use burrito folding machine. This design problem was adapted from a sophomore mechanical engineering course. However, the participants of this user study were not a part of the project when it was conducted. Another reason to choose this design problem was that the students are familiar with the product domain, i.e. relating burritos with household appliances. Therefore, the design problem does not have a current solution in the market and at the same time, the participants can easily relate a common product to various engineering principles. The overall problem statement had a general statement, a list of nine requirements and either the function model or the function interaction model with its appropriate key. The general statement used in the study is shown in Figure 4.2

<table>
<thead>
<tr>
<th>Mr. Smith is hosting a party next month and has invited his colleagues. He wants a new design for a home use burrito-folding machine. The device must adhere to the following design requirements:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Deliver completed burritos at a rate of at least 4 burritos per minute</td>
</tr>
<tr>
<td>2. The device must fit on a counter top</td>
</tr>
<tr>
<td>3. Position empty tortilla to store fillings</td>
</tr>
<tr>
<td>4. Fill the tortilla after proper positioning</td>
</tr>
<tr>
<td>5. Wrap burrito over the filling</td>
</tr>
<tr>
<td>6. Easy to install</td>
</tr>
<tr>
<td>7. Easy to use</td>
</tr>
<tr>
<td>8. The device must be easy to clean after use (&lt;15 minutes and no special tools)</td>
</tr>
<tr>
<td>9. The device must be safe – cause no injury to the user.</td>
</tr>
</tbody>
</table>

**Figure 4.2: General statement and the list of requirements provided to the students**

4.1.4 List of requirements used in the problem statement

Design requirements are a list of customer and market needs. While designing a product, the designers repeatedly compare their concepts with the design requirements [27]. The problem statement used in the study had nine requirements of which three are
functional requirements and six are non-functional requirements. While the functional requirements are statements that define what the product must do, non-functional requirements may be external elements that indirectly influence the function of a product (e.g., cost, size, safety) [2]. In order to test whether a given model is capable of capturing the human interactions, three non-functional human activity requirements are included. These human activity non-functional requirements are developed to capture how the developed concepts accommodate human activities performed over the product.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Type of requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position empty tortilla to store fillings.</td>
<td>Functional requirement</td>
</tr>
<tr>
<td>Fill the tortilla after proper positioning.</td>
<td>Functional requirement</td>
</tr>
<tr>
<td>Wrap burrito over the fillings.</td>
<td>Functional requirement</td>
</tr>
<tr>
<td>Deliver completed burritos at rate of at least 4 burritos per minute.</td>
<td>Non-functional requirement</td>
</tr>
<tr>
<td>Easy to use.</td>
<td>Non-functional human activity requirement</td>
</tr>
<tr>
<td>The device must fit on a counter top.</td>
<td>Non-functional requirement</td>
</tr>
<tr>
<td>Easy to install.</td>
<td>Non-functional human activity requirement</td>
</tr>
<tr>
<td>The device must be easy to clean after use.</td>
<td>Non-functional human activity requirement</td>
</tr>
<tr>
<td>The device must be safe to use.</td>
<td>Non-functional requirement</td>
</tr>
</tbody>
</table>

4.1.5 FM and FIM used in the problem statement

After the list of requirements, the participants were provided with the function model (Figure 4.3) or the function interaction model (Figure 4.4) of the burrito folding machine. In order to remove any bias due to the amount of information provided to the participants through the model, the function model and the function interaction model was developed having almost same number of functions and flows (Table 4.2).

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of functions</th>
<th>Number of flows</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

25
The function model of the burrito folding machine has two material inputs in form of fillings and tortilla and a human energy input. This human energy is then converted to mechanical energy by some means and the obtained mechanical energy performs the required actions to give completed burritos as the output.

![Function model of a burrito folding machine](image)

**Figure 4.3: Function model of a burrito folding machine**

The function interaction model for the burrito folder has the user and the machine as separate entities. The user activity part has three actions to be performed by the user. Unlike the function model in which the user is introduced into the system as a flow, the function interaction model has user and his activities as separate functions. The actions performed over the machine are represented by the flows moving between the user activity part and burrito folding machine part. The burrito folding machine performs its intended function and the user finally removes the completed burrito from it.
4.1.6 Instruction for sketching concepts

The instructions provided to the students before starting to sketch their concepts is shown in Figure 4.5. These are the guidelines developed by the author for interpreting the functional models and creating concepts based on that. The seven points can be used as guidelines and concept sketching can be done through other means also.
1. First identify your system boundaries.
2. Determine the input and output from the model.
3. Identify parts which will satisfy the sub-functions and its flows first.
4. Start from a simple principle – Do not try to accommodate all your ideas in a single product.
5. Assemble the parts based on their logical relationships and working principles.
6. Confirm to the law of conservation – Check if all the energy and mass in input are obtained as output.
7. Are all the requirements satisfied?

**Figure 4.5: Guidelines for interpreting the model and sketching concepts**

4.1.7 Data Collection

As mentioned in the previous section, the participants were asked to sketch their concepts based on the product model provided to them. Only one concept per sheet was allowed and the students were given the freedom of choosing the orientation/view of their concepts. Apart from asking the students to enter their random experiment ID, no steps were taken to record the individual details. Data was analyzed only after both the user groups completed their experiments; User group 1 completed their experiment ten days before user group 2. Thirty-six concept sketches were collected from the user group 1 and seventy concept sketches were collected from the user group 2. Therefore, the two user groups produced a total of one hundred and six concept sketches. Further analysis on the number of concepts is discussed in Section 5.1 and Section 6.1.

The concept sketching sheet provided to the participants is shown in Appendix A. Three random examples of design concept sketches are shown in Figure 4.6. Labels were added to one of the sketch for the purpose of clarity.
Figure 4.6: Sample concepts (Labels are added for reading clarity)
4.2 Card Sorting Exercise

The second part of this research deals with the user’s perception of how a product would work; whether the user classifies a particular product based on its functionality or would classify it based on how he would interact with it. A card sorting exercise was performed in which the participants sorted a wide range of products into four categories based on their functionality and interaction. Simply put, users are provided with a set of cards and asked to group them in a self-selected manner.

4.2.1 Product categorization based on functions and interactions

This exercise follows a closed sorting method, in which the participants are given a set of categories into which they must sort the cards. In this card sorting exercise, forty different products varying in their functionality and interaction was selected. As a rule of thumb, functionality was defined based on the number of parts present in the product. Similarly, the examples for interaction were based on how each part of the product would interact with the users. In order to narrow down the scope of this initial study, part to part interaction is not considered. Based on this the forty products were categorized in four quadrants; ten products in each quadrant. The four quadrants Q1, Q2, Q3 and Q4 respectively are, low functionality-low interaction (LF-LI), low functionality-high interaction (LF-HI), high functionality-low interaction (HF-LI) and high functionality-high interaction (HF-HI). The justification for categorizing the products in a particular quadrant is given below with some examples.
Table 4.3: Products sorted based on their functionality and interaction

<table>
<thead>
<tr>
<th>Functionality</th>
<th>User Interaction</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low &lt; 30</td>
<td></td>
<td>1.  Ruler</td>
<td>1.  Eye gear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.  Ladder</td>
<td>2.  Nail clipper</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.  Hammer</td>
<td>3.  USB mouse</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.  Scissors</td>
<td>5.  Flash light</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.  Door keys</td>
<td>7.  Analog luggage scale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.  Can opener</td>
<td>8.  Bench vise</td>
</tr>
<tr>
<td>High &gt;30</td>
<td></td>
<td>1.  Transmission system in a car</td>
<td>1.  Car</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.  Hard drive in computer</td>
<td>2.  Rifle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.  Chainsaw</td>
<td>3.  Air conditioner</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.  Lathe machine</td>
<td>5.  Vacuum cleaner</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.  Sewing machine</td>
<td>6.  computer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.  Drilling machine</td>
<td>7.  Helicopter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.  Electric motor</td>
<td>8.  Robotic arm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.  Typewriter</td>
<td>9.  CNC machine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10. Wind turbine</td>
<td>10. X ray machine</td>
</tr>
</tbody>
</table>

Q1 (LF-LI): These are usually products made of two or three assembled parts. They number of means through which a user can interact with it properly with its intended purpose is limited. Example: A hammer has two parts, namely a head and a handle. The intended purpose is to deliver an impact through the head over an object safely.

Q2 (LF-HI): The number of individual parts to be assembled for making the product is less than 30. The product enables the user to control its various functions.
through a number of inputs. Example: A coffee grinder has 18 individual parts and the user gives a number of inputs to the grinder depending upon the size of the coffee grain.

Q3 (HF-LI): The products in this quadrant have more than 30 parts. Most parts of the product are isolated or inaccessible to the user. Example: A hard disk drive is sealed in an aluminum box and will not be accessible to the user unless the body is disassembled.

Q4 (HF-HI): The products in this quadrant will have various assembled parts and the user can constantly interact with it. Example: Car is a highly complex product and the passengers while seated inside will have easy access to various functions of it.

Based on these definitions, an experiment was setup to understand the user’s perception about functions and interactions.

4.2.2 Experimental procedure

The closed card sorting study involved sixty-one sophomore level engineering students at Clemson University. The students were asked to model various parts ranging from water bottle to bench vise as a part of their course syllabus and hence have a strong understanding on how to visualize and interpret a product. This class was identified for the study because they involve students who are novice designers having an ability to categorize products based on their working principles.

The study was conducted during the student’s normal class period. Furthermore, to ensure environmental familiarity the participants completed the study in their usual class
room and no special seating arrangement was made. The students were handed the experimental packets as they entered the class. Each experimental packet contained a four-quadrant sheet (see Appendix B) and the pictures of the forty products shown in Table 4.3. The pictures, shown in Figure 4.7, were provided to the students in a random order. A picture sort method has the advantage of providing more visual information, i.e. a picture of a drilling machine would help the participant to visualize the product that he is supposed to sort. The four-quadrant sheet basically had a sheet of paper divided into four quadrants, namely low functionality-low interaction (LF-LI), low functionality-high interaction (LF-HI), high functionality-low interaction (HF-LI) and high functionality-high interaction (HF-HI).

A ten-minute presentation about functions, interactions and affordances was given. Once the presentation was complete, participants were given an opportunity to ask questions. Following that, five minutes were provided to the participants to sort the products based on their functionality and interaction. The participants were instructed to sort every product in a quadrant and no product can be placed in more than one quadrant. No restrictions were placed regarding the number of products in a quadrant; a participant may wish to place more than 10 products in a quadrant. Once the products were sorted, the participants were asked to clip the pictures at the four ends of the four-quadrant sheet. The four-quadrant sheet was then placed back in the packet and the packets were collected from the participants at the end of this fifteen-minute exercise.
Figure 4.7: Figures of the products presented to the participants
CHAPTER 5: INITIAL USER STUDY RESULTS

The user study is used as a tool to answer the first research question on the effect of product models in enabling designer’s creativity. The results obtained from the user study are measured for quantity and quality of the concept sketches. It should be noted that the artistic and sketching ability of participant vary. To address this concern, the evaluators were repeatedly instructed to evaluate the quality of the concepts based on the content rather than the graphical skills. While this cannot be ensured 100 percent, the multiple raters and initial and refined scale, and associated inter-rater agreement study suggest that sketch content was evaluated over sketching ability.

The first three research hypotheses will be tested through this user study. As this is an exploratory research work, \( \alpha \) - value is set as 0.10 throughout the experiment. The level of significance tests are used to a great degree in experimental works, where this probability value can be employed to accept or reject the null hypothesis. More formally, the level of significance is the probability of obtaining a value of the test statistic that is likely to reject the null hypothesis as the observed value of the test statistic [28]. In other words, if the p-value is a small value compared to \( \alpha \) - value then our decision is to reject the null hypothesis or accept the alternate/research hypothesis. In order to justify the results obtained while comparing two product models (FM and FIM) used in the study, the p-value is compared with \( \alpha \) - value and conclusions are then formally made.

There have been studies conducted at Clemson University to address complementary research domains. For example, the user study performed by Thomas
investigates the usefulness and interpretability of the function model at various levels of abstraction. Further, Smith [30] conducted two experiments to determine the relationships between morphological chart sizes and topologies with respect to the quality of concepts. Richardson [31] extended this study to explore the possibilities of using function models instead of function list in the morphological charts to develop higher quality concepts. Finally, Hannah [32] examines the differences between various design representation in assisting designers to extract information. However, the aforementioned design studies have the primary Shortcoming of relying on a single rater to evaluate the outcomes of a design tool and/or method. To address this and build confidence in the results and remove bias from the evaluation, multiple raters were used.

5.1 Quantity of Concepts

The first research hypothesis is stated as “the number of concepts developed by the designers using the FIM is different from the number of concepts developed by the designers using the FM”. Quantity is the total number of concepts generated during a design session. Furthermore, the number of concepts developed by each participant is measured. It can be observed that during a design session the number of concepts developed by the designers using FM is more than the number of concepts developed using the FIM. The results from Table 5.1 also suggest that the FM generate more number of concepts/designer compared to the FIM. The p-value from a two sample t-test which compares the number of concepts generated from the two models affirms that the designers using the FM are able to develop more number of concept sketches compared to the designers who used the FIM.
Table 5.1: Number of concepts developed from each model

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of concepts</th>
<th>Concepts per designer</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM</td>
<td>63</td>
<td>3.15</td>
<td>1.09</td>
</tr>
<tr>
<td>FIM</td>
<td>43</td>
<td>2.15</td>
<td>0.87</td>
</tr>
<tr>
<td>p-value</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

One possible reason for the FIM to have low quantity score maybe because of the specific information provided to the designers. This specificity may drive the designer to develop concepts which are particular and less in number. With user activities and other interactions of the product mentioned in the FIM, the number of ways through which a product can be approached is reduced. In conclusion, our first hypothesis hold true and the FIM is found to have less number of concepts generated in the given time compared to the FM.

5.2 Quality of Concepts

Quality is a scale that describes how best the requirements of a product has been satisfied [20]. Pahl and Beitz state that “quality cannot be achieved simply through testing – it has to be built-in from the beginning of the design process”. Initial stages of a design process involve drawing sketches about the concept; in this user study concept sketches are developed based on the product model (either FM or FIM) provided to the designers. The second and third research hypotheses were developed to test the quality of the concept sketches at concept level and requirement level respectively.

5.2.1 Initial scale developed for measuring quality

In order to measure the concept sketches qualitatively, a three-point scale was developed. One good practice while grading concept sketches is to group them into
several classes (or grades) as it is difficult to measure sketches over a continuous scale [33]. In this research, the sketches are classified into any one of the low-medium or high group. A score of 1-3 or 9 is awarded by four raters individually based on how well each concept sketch satisfies the nine requirements. This initial quality scale was constructed based on the results obtained from a pilot study. The pilot study involved nine graduate students working in the same lab with the author. Every concept sketch from the pilot study was analyzed and a scale was developed based on that. This initial scale, shown in Table 5.2, was used to measure the quality of the concept sketches developed by the designers from user group 1 and user group 2.

Table 5.2: Initial scale developed for measuring quality

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Type of Requirement</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position empty tortilla to store fillings</td>
<td>FR</td>
<td>Low (1) Medium (3) High (9)</td>
</tr>
<tr>
<td>Fill the tortilla after proper positioning</td>
<td>FR</td>
<td>Bad conveyance method</td>
</tr>
<tr>
<td>Fill the tortilla after proper positioning</td>
<td>FR</td>
<td>Bad mechanism</td>
</tr>
<tr>
<td>Wrap burrito over the fillings</td>
<td>FR</td>
<td>Bad mechanism</td>
</tr>
<tr>
<td>Deliver completed burritos at rate of at least 4</td>
<td>NFR</td>
<td>Impossible</td>
</tr>
<tr>
<td>Easy to use</td>
<td>NFR-HA</td>
<td>More than five human activities</td>
</tr>
<tr>
<td>The device must fit on a counter top</td>
<td>NFR</td>
<td>Completely stable once mounted on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>the table</td>
</tr>
</tbody>
</table>

Means to transfer are not efficient Fast and efficient transfer Average Precise filling mechanism Average Machine wraps but not properly Complete wrapping Impossible Maybe Definitely possible More than five human activities Four or five human activities Three human activities Completely stable once mounted on the table Need additional support to be stable The device is not a counter top model
<table>
<thead>
<tr>
<th>Easy to install</th>
<th>NFR-HA</th>
<th>Unfit installation technique</th>
<th>Fair: needs more installation time</th>
<th>Simple procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>The device must be easy to clean after use</td>
<td>NFR-HA</td>
<td>Cleaning takes long/Design makes it hard</td>
<td>Fair amount of time to clean</td>
<td>Smooth finish for easy clean</td>
</tr>
<tr>
<td>The device must be safe to use</td>
<td>NFR</td>
<td>Unsafe/Sharp objects</td>
<td>Safe only for adults</td>
<td>Safe for all ages</td>
</tr>
</tbody>
</table>

5.2.2 Initial Inter-Rater Agreement

Inter-rater agreement (IRA) is used to increase the credibility of the results obtained at the end of an experiment. In this study, the inter rater agreement of the quality scores was calculated by comparing the scores of four graduate students. All four raters had previous experience in grading the responses of the students by either conducting user studies or reviewing student reports. Since more than two evaluators were involved, Fleiss’ Kappa method [34] was applied to get the initial results. This method calculates the degree of agreement between many raters (more than two) involved in grading a concept and the resultant kappa value signifies whether the agreement between the evaluators is purely by chance or has a rational support. Fleiss’ Kappa is found by using the following formula:

\[
\kappa = \frac{P - Pe}{1 - Pe}
\]

where \( P \), is the probability of agreement by chance and \( Pe \) is the probability of agreement that is actually achieved. The obtained kappa value ranges from -1 to 1 and negative values suggest poor agreement. The significance of the obtained kappa value is explained in Table 5.3
Table 5.3: Interpretation of kappa values

<table>
<thead>
<tr>
<th>κ</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0</td>
<td>Poor agreement</td>
</tr>
<tr>
<td>0.0 to 0.20</td>
<td>Slight agreement</td>
</tr>
<tr>
<td>0.21 to 0.40</td>
<td>Fair agreement</td>
</tr>
<tr>
<td>0.41 to 0.60</td>
<td>Moderate agreement</td>
</tr>
<tr>
<td>0.61 to 0.80</td>
<td>Substantial agreement</td>
</tr>
<tr>
<td>0.81 to 1.00</td>
<td>Perfect agreement</td>
</tr>
</tbody>
</table>

All four raters evaluated the concept sketches individually. In order to obtain the average quality score involving four raters, the median value of the four raters was calculated. The median method minimizes the chances of having inaccurate scores. In the median method, the highest and the lowest scores are eliminated and the average of the remaining two raters is computed. For example, consider a case in which four raters assign different values for the same concept. Two raters give a medium value of 3, one rater gives a low value of 1 and the other rater gives a high value of 9. So the final quality score of this particular case using median method is 3. The quality score calculation using the median method is shown in Table 5.4.

Table 5.5 shows the inter rater agreement between four raters using Fleiss kappa. Apparently, most of the requirements have their kappa values less than 0.2, which means there is only a slight agreement between the raters while evaluating the concepts. Previous design engineers have also attempted IRA technique in their research and were unsuccessful in obtaining significant results during their first iteration. This is because the existing metrics focus more on functional aspects rather than non-functional aspects of
the design. Furthermore, the perspective of a non-functional aspect varies from one evaluator to another [35].

Table 5.4: Quality score assignment for each concept using the median method

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Rater</th>
<th>R 1</th>
<th>R 2</th>
<th>R 3</th>
<th>R 4</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (NFR)</td>
<td></td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2 (NFR)</td>
<td></td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>3 (FR)</td>
<td></td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>4 (FR)</td>
<td></td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>5 (FR)</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6 (HA)</td>
<td></td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>7 (HA)</td>
<td></td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>8 (HA)</td>
<td></td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>9 (NFR)</td>
<td></td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

The discussion on the refined quality scale is provided in Chapter 6. As of now, the median score of the four raters is taken as the quality score for a particular requirement of the concept. The obtained score were then used to calculate quality at both the concept level and the requirement level.

Table 5.5: Inter rater agreement between four raters

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Fleiss Kappa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>0.13</td>
</tr>
<tr>
<td>Fill</td>
<td>0.06</td>
</tr>
<tr>
<td>Wrap</td>
<td>0.34</td>
</tr>
<tr>
<td>Deliver</td>
<td>0.02</td>
</tr>
<tr>
<td>Easy to use</td>
<td>0.15</td>
</tr>
<tr>
<td>Counter-top</td>
<td>0.07</td>
</tr>
<tr>
<td>Easy to install</td>
<td>0.02</td>
</tr>
<tr>
<td>Easy to clean</td>
<td>0.03</td>
</tr>
<tr>
<td>Safe to use</td>
<td>0.06</td>
</tr>
<tr>
<td>Overall</td>
<td>0.10</td>
</tr>
</tbody>
</table>
5.2.3 Quality at the concept level

Quality at the concept level can be defined as the average quality score of all the nine requirements for a particular concept. The method for calculating the quality at the concept level is shown in Table 5.6. Median$_{n,9}$ is the score obtained by taking the median value (from the four raters) of the ninth requirement of $n^{th}$ concept. $Q_{CL,n}$ is the average quality score of the $n^{th}$ concept obtained by taking the mean of all the nine requirements in the $n^{th}$ column. The average quality score for all the 106 concept sketches is obtained based on the median value of the four raters.

The second research hypothesis is based on evaluating the quality of sketches at the concept level - the average concept quality rating for the sketches developed from the FIM is different from the average concept quality rating for the sketches developed from the FM.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C1</td>
</tr>
<tr>
<td>1</td>
<td>Median$_{1,1}$</td>
</tr>
<tr>
<td>2</td>
<td>Median$_{1,2}$</td>
</tr>
<tr>
<td>3</td>
<td>Median$_{1,3}$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>9</td>
<td>Median$_{1,9}$</td>
</tr>
</tbody>
</table>

| $Q_{CL}$    | $Q_{CL,1}$ | $Q_{CL,2}$ | ...    | $Q_{CL,n}$ |
It is found that the mean value for the sketches at the concept level is greater for the FIM than the FM. A two sample t-test comparing the average quality scores of the two product models was performed and the resulting p-value is compared with α value. As shown in Table 5.7, the average quality for concepts belonging to FIM is greater than that of the FM and the lower p-value suggest that the difference is significant. In conclusion, RH2 holds true and at the concept level there is a significant difference between the average qualities of concept sketches developed from the two product models.

It is also important to find out how well each concept had satisfied its functional and non-functional requirements. Table 5.8 compares the concept quality score for the functional requirement of FM with the concept quality score for the functional requirement of the FIM. Simply put, the quality scores of ‘position, fill and wrap tortilla’ for each concept developed from FM is compared with the same three requirements of the FIM.

| Table 5.7: t-test to compare the means of the two models at the concept level |
|-----------------|-----------------|
|                 | FM | FIM |
| Mean            | 3.19 | 3.70 |
| Variance        | 1.32 | 0.80 |
| Number of concepts | 63 | 43 |
| p-value         | 0.02 |

| Table 5.8: t-test to compare the concept quality scores for functional requirements |
|-----------------|-----------------|
|                 | FM | FIM |
| Mean            | 2.65 | 3.43 |
| Variance        | 3.30 | 3.39 |
| Number of concepts | 63 | 43 |
| p-value         | 0.03 |
Table 5.9 compares the concept quality scores for the non-functional requirements of the two product models. In other words, the quality scores of the remaining six non-functional requirements for each concept are compared.

**Table 5.9: t-test to compare the concept quality score for non-functional requirements**

<table>
<thead>
<tr>
<th></th>
<th>FM</th>
<th>FIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>3.46</td>
<td>3.83</td>
</tr>
<tr>
<td>Variance</td>
<td>1.68</td>
<td>0.73</td>
</tr>
<tr>
<td>Number of concepts</td>
<td>63</td>
<td>43</td>
</tr>
<tr>
<td>p-value</td>
<td>0.10</td>
<td></td>
</tr>
</tbody>
</table>

The resulting p-value show in Table 5.8 and Table 5.9 is less than or equal to the fixed $\alpha$-value of 0.10. Therefore, the decision is to accept the alternate hypothesis RH2 – there exist a significant difference between the two product models and it is in favor of the FIM. In conclusion, RH2 holds true as the p-value is repeatedly lower than 0.10 as show in Table 5.7, Table 5.8 and Table 5.9. Therefore, at the concept level, the average quality of the concept sketches developed from the FIM is better than the average quality of the concept sketches developed from the FM.

5.2.4 Quality at the requirement level

The quality of concepts at the requirement level is calculated using the mean quality score of all the 106 concepts for each requirement. The tables in the previous section (Table 5.8 and Table 5.9) compare the functional and non-functional requirement of the sketches at the concept level. However, it is important to find out how each requirement is satisfied by the FM and the FIM. The steps involved in calculating the quality at the requirement level is shown in Table 5.10. $\text{Median}_{n,9}$ is the score obtained by taking the
median value (from the four raters) of the ninth requirement of n\textsuperscript{th} concept. \( Q_{RL.9} \) is the average quality score of the 9\textsuperscript{th} requirement obtained by taking the mean of all the ‘n’ concepts in the 9\textsuperscript{th} row.

Table 5.11 shows the average quality score for each requirement. It can be observed that six out of nine requirements favor using FIM. However, the difference between the two product models is significant only for three requirements namely ‘fill tortilla’, ‘deliver four completed burritos per minute’ and ‘easy to use’.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Concept</th>
<th>( Q_{RL} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Median(<em>{1,1}) Median(</em>{2,1}) ... Median(_{n,1})</td>
<td>( Q_{RL.1} )</td>
</tr>
<tr>
<td>2</td>
<td>Median(<em>{1,2}) Median(</em>{2,2}) ... Median(_{n,2})</td>
<td>( Q_{RL.2} )</td>
</tr>
<tr>
<td>3</td>
<td>Median(<em>{1,3}) Median(</em>{2,3}) ... Median(_{n,3})</td>
<td>( Q_{RL.3} )</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>9</td>
<td>Median(<em>{1,9}) Median(</em>{2,9}) ... Median(_{n,9})</td>
<td>( Q_{RL.9} )</td>
</tr>
</tbody>
</table>

The third research hypothesis is defined as: \textit{the average quality rating for concepts generated from the FIM is different from the average quality rating for concepts generated from the FM at the requirement level.} To test this hypothesis, the requirement quality scores of the two product models shown in Table 5.11 are compared. In order to make this comparison, a paired t-test was performed. This is because we are comparing the same requirement in both FM and FIM. In other words, a particular requirement in
the FM is compared with the same requirement in the FIM and their differences are calculated to obtain the p-value.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Type</th>
<th>FM</th>
<th>FIM</th>
<th>Is the difference significant?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>FR</td>
<td>2.86</td>
<td>3.35</td>
<td>No</td>
</tr>
<tr>
<td>Fill</td>
<td>FR</td>
<td>2.76</td>
<td>4.40</td>
<td>Yes</td>
</tr>
<tr>
<td>Wrap</td>
<td>FR</td>
<td>2.32</td>
<td>2.56</td>
<td>No</td>
</tr>
<tr>
<td>Deliver</td>
<td>NFR</td>
<td>3.05</td>
<td>4.30</td>
<td>Yes</td>
</tr>
<tr>
<td>Easy to use</td>
<td>NFR-HA</td>
<td>2.57</td>
<td>3.74</td>
<td>Yes</td>
</tr>
<tr>
<td>Counter-top</td>
<td>NFR</td>
<td>5.84</td>
<td>6.23</td>
<td>No</td>
</tr>
<tr>
<td>Easy to install</td>
<td>NFR-HA</td>
<td>3.46</td>
<td>3.21</td>
<td>No</td>
</tr>
<tr>
<td>Easy to clean</td>
<td>NFR-HA</td>
<td>2.62</td>
<td>2.40</td>
<td>No</td>
</tr>
<tr>
<td>Safe to use</td>
<td>NFR</td>
<td>3.19</td>
<td>3.07</td>
<td>No</td>
</tr>
</tbody>
</table>

As shown in Table 5.12, the p-value is lower than α-value of 0.10; hence we can conclude, at the requirement level, the average quality rating for concepts generated using the FIM is greater than the average quality rating for concepts generated using the FM.

Table 5.12: Paired t-test to compare the means of the two models at the requirement level

<table>
<thead>
<tr>
<th>Requirement</th>
<th>FM</th>
<th>FIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>3.19</td>
<td>3.70</td>
</tr>
<tr>
<td>Variance</td>
<td>1.38</td>
<td>1.11</td>
</tr>
<tr>
<td>Number of requirements</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>p-value (two-tailed)</td>
<td>0.06</td>
<td></td>
</tr>
</tbody>
</table>

5.3 Summary

In this section, the results and conclusion from Section 5.1 and Section 5.2 are summarized.

- Due to the ambiguous (or relatively abstract) representation of interaction between user and the product, the number of concepts developed by the designers using the
FM is greater than the number of concepts developed by the designers using the FIM. **RH1 is supported to be true.**

- The quality scores of the sketches at the concept level is better for the FIM compared to the FM. The functional and non-functional requirements for a sketch developed from FIM has its quality score greater than the sketch developed from the FM. **RH2 is supported to be true.**

- The quality scores of the sketches at the requirement level are better for the FIM compared to the FM. **RH3 is supported to be true.**

- The inter-rater agreement between the four raters is very low. Therefore, there is a need to change the scale that is being used to measure quality and the raters have to be trained. The discussion on the improved scale and the results obtained from that will be discussed in the next chapter.
CHAPTER 6: RESULTS FROM THE REFINED SCALE

The inter-rater agreement (IRA) scores shown in the previous chapter indicate a change in the quality scale used to evaluate the concept. The primary difference between the initial and the refined quality scale discussed in this chapter is the level of objectivity. The criteria for awarding low-medium-high scores were made specific taking examples from the sample sketches. The other difference is the number of raters judging the concepts; instead of four raters, this time two raters went through three iterations and refined the scale continuously until a substantial agreement was attained between them.

The 106 concepts developed during the two user studies were evaluated again using this newly refined scale by two raters. The results from the refined quality scale can be used to test the research hypotheses pertaining to quality. That is, the quality of concepts at the concept level and at the requirement level (RH2 and RH3 respectively) is evaluated again to obtain more dependable conclusions about the two product models.

6.1 Quantity of Concepts

The results for this section will not change since the concepts evaluated are from the same user study. Therefore, the number of responses does not vary and our conclusion about the first research hypothesis holds valid. The table below shows the same results discussed in Section 5.1. In conclusion, the number of concepts developed by the designers using the FM is greater than the number of concepts developed by the designers using the FM.
Table 6.1: Quantity of concepts developed from the two models (repeated from Chapter 5)

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of concepts</th>
<th>Concepts per designer</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM</td>
<td>63</td>
<td>3.15</td>
<td>1.09</td>
</tr>
<tr>
<td>FIM</td>
<td>43</td>
<td>2.15</td>
<td>0.87</td>
</tr>
<tr>
<td>p-value</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.2 Quality of Concepts

Quality of the concept sketches are measured at both concept level and requirement level. A sketch is said to of high quality if it meets all the design requirements. The sketches are graded according to a scale of low-medium-high and in order to get reliable results the scale needs robust. The initial quality scale was nonobjective and hence the scores from the raters were not consistent. In order to address this, the quality scale was refined further.

6.2.1 Refined quality scale with examples

The results discussed in the previous chapter were obtained from the quality scores of four individual raters. However, the agreement between the raters while evaluating the concepts was found to be low. This means, the evaluation scale that was used to measure had to be revised. In order to increase the consensus, two raters were repeatedly trained with sample sketches taken as examples. The two raters were also there in the initial panel of four judges. Table 6.2 shows the refined scale for each requirement. When compared with the initial quality scale shown in Table 5.2, the refined scale helps a rater to look for specific details while grading the concept sketches. Therefore, when a third rater who is blind to the whole process is introduced, the ratings provided by the new
rater will be in consensus with the initial two raters. However, this process of testing by introducing a new member into the panel is reserved for future work.

Table 6.2: Refined scale for the requirement list

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Position empty tortilla to store fillings</strong></td>
<td>Low (1): No storage area or conveyor mechanism available</td>
</tr>
<tr>
<td><strong>Fill the tortilla after proper positioning</strong></td>
<td>Low (1): Filling device completely missing</td>
</tr>
<tr>
<td><strong>Wrap burrito over the fillings</strong></td>
<td>Low (1): Wrapping mechanism is missing</td>
</tr>
<tr>
<td><strong>Deliver completed burritos at rate of at least 4 burritos per minute</strong></td>
<td>Low (1): When the above three requirements also has low scores. The user does most of the activities.</td>
</tr>
<tr>
<td><strong>Easy to use</strong></td>
<td>Low (1): More than five human activities</td>
</tr>
<tr>
<td><strong>The device must fit on a counter top</strong></td>
<td>Low (1): The size is too big and will not stable if mounted on a table</td>
</tr>
<tr>
<td><strong>Easy to install</strong></td>
<td>Low (1): More than 3 independent parts to assemble for the first time.</td>
</tr>
</tbody>
</table>
Table 6.3: Refined scale for the requirement list (continued)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low (1)</td>
</tr>
<tr>
<td>The device must be easy to clean after use</td>
<td>Disassembly is needed to clean the machine. The user transfers filling and burritos by hand, with more chances of spilling.</td>
</tr>
<tr>
<td>The device must be safe to use</td>
<td>All parts are completely exposed without a cover. Sharp edges or pinch points which might cause injury during the operation (motor/electrically driven).</td>
</tr>
</tbody>
</table>

To aid in the understanding of the application of this quality measure, a set of examples are presented in Table 6.4. Following this, two concept sketches were selected from the complete list of 106 concepts; one high end and another low end concept sketch. This was based on the results from the initial study, one concept with a high score and one concept with a low score was selected.
## Table 6.4: Refined scale with sample sketches as examples

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Position empty tortilla to store fillings</strong></td>
<td><strong>Classification</strong>:&lt;br&gt;Low (1): No storage area or conveyor mechanism available&lt;br&gt;Medium (3):&lt;br&gt;High (9):</td>
</tr>
<tr>
<td><strong>Fill the tortilla after proper positioning</strong></td>
<td><strong>Classification</strong>:&lt;br&gt;Low (1): Filling device completely missing&lt;br&gt;Medium (3):&lt;br&gt;High (9):</td>
</tr>
<tr>
<td><strong>Wrap burrito over the fillings</strong></td>
<td><strong>Classification</strong>:&lt;br&gt;Low (1): Wrapping mechanism is missing&lt;br&gt;Medium (3):&lt;br&gt;High (9):</td>
</tr>
<tr>
<td><strong>Deliver completed burritos at rate of at least 4 burritos per minute</strong></td>
<td><strong>Classification</strong>:&lt;br&gt;Low (1): When the above three requirements also has low scores. The user does most of the activities.</td>
</tr>
<tr>
<td><strong>Easy to use</strong></td>
<td><strong>Classification</strong>:&lt;br&gt;Low (1): More than five human activities&lt;br&gt;Medium (3):&lt;br&gt;High (9):</td>
</tr>
<tr>
<td><strong>The device must fit on a counter top</strong></td>
<td><strong>Classification</strong>:&lt;br&gt;Low (1): The size is too big and will not stable if mounted on a table.&lt;br&gt;Medium (3):&lt;br&gt;High (9):</td>
</tr>
<tr>
<td></td>
<td><strong>Refer Figure 6.1– five human activities can be counted.</strong>&lt;br&gt;<strong>Refer Figure 6.2– three human activities can be counted.</strong></td>
</tr>
<tr>
<td></td>
<td>Refer Figure 6.2– Size has been mentioned.</td>
</tr>
</tbody>
</table>
### Table 6.5: Refined scale with sample sketches as examples (repeated)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>The device must be easy to clean after use</strong></td>
<td>Disassembly is needed to clean the machine. The user transfers filling and burritos by hand, with more chances of spilling.</td>
</tr>
<tr>
<td><strong>The device must be safe to use</strong></td>
<td>All parts are completely exposed without a cover. Sharp edges or pinch points which might cause injury during the operation (motor/electrically driven).</td>
</tr>
</tbody>
</table>
Figure 6.1: Example figure #1

Figure 6.2: Example figure #2
Two examples are discussed below. The examples follow a step-by-step procedure of how each concept is graded against each requirement. Table 6.2 and Table 6.4 are used to evaluate the concepts.

**Example 1:**

Figure 6.3 is an example of a concept sketch having high quality scores for six out of nine requirements.

- **Position empty tortilla to store fillings:** There is a separate provision for storing tortilla in a stack and each tortilla is transferred to the filling zone through a conveyor mechanism. Hence the quality rating for this particular requirement is 9.

- **Fill the tortilla after proper positioning:** The sketch shows two bins, each measuring one foot, on the top. The nozzle from the two bins then mixes the filling over the tortilla. The requirement is satisfied and hence a score of 9 is given.

![Figure 6.3: Burrito folder sketch - Example 1](image)

Figure 6.3: Burrito folder sketch - Example 1
• *Wrap burrito over the fillings:* After the tortilla is filled, a two handed robot folds the burrito. A burrito with more than 3 folds is considered to be complete. This concept makes a two-fold burrito. Hence the score for this requirement is 3.

• *Deliver completed burritos at rate of at least 4 burritos per minute:* The designer has chosen conveyor belt as transfer mechanism. Conveyor belts are usually fast when driven by a motor. In addition to this, robots are used to fold the burritos making the work faster. Therefore, this concept can generate one burrito for every 15 seconds and is given a score of 9.

• *Easy to use:* This requirement is measured based on the number of human activities. There are only two user activities needed for this operation; insert the tortilla in stack and push the ‘On’ button (it is assumed that the whole process is automated and the robot is also controlled by a single switch). As this requires minimal user inputs, a high score of 9 is given.

• *The device must fit on a counter top:* The whole device spans about 10 feet. This is too big for a normal kitchen counter and occupies a lot of space. Hence this model is not suited for placing on top the counter and is given a low score of 1.

• *Easy to install:* Apart from the standard conveyor part of the device, two additional parts have to be installed – Filling bins and wrapping robot. Though this favors easy installing, the whole device is 10 feet long and needs extra hand to install at the beginning. Hence, the quality score for this requirement is given as 3.
• *The device must be easy to clean after use:* The system is continuous and there is no need to remove the tortilla with filling and then place it in a separate zone to be wrapped. This reduces the chances of spillage, making it easy to clean. A score of 9 is given for this particular requirement.

• *The device must be safe to use:* As there are no sharp edges or pinch points left uncovered, this concept is safe when implemented. Hence it is given a rating of 9.

**Example 2:**

Figure 6.4 is an example of a poorly developed concept where the device is basic and the user performs most of the functions that were expected from the device.

• *Position empty tortilla to store fillings:* The sketch shows no provision for storing tortilla. The designer wants the user to manually place the tortilla. Hence this concept gets a low rating of 1 for this requirement.

![Figure 6.4: Burrito folder sketch - Example 2](image)
• *Fill the tortilla after proper positioning:* Filling bins or any other form of holding device is not seen in the sketch. The intention is that the user is supposed to manually apply fillings over the tortilla. So the quality rating for this requirement is given as 1.

• *Wrap burrito over the fillings:* There are four flaps for folding the tortilla with fillings on all four sides. This makes a complete burrito with no release of fillings. This particular requirement gets a rating of 9.

• *Deliver completed burritos at rate of at least 4 burritos per minute:* Since the user has to manually place, fill and wrap the four sides, the time taken to make one burrito will definitely exceed 15 seconds. This requirement cannot be satisfied and hence given a low score of 9.

• *Easy to use:* Six human actions are needed to produce a burrito. Place, fill, and fold the 4 corners one after another. These many human actions are not desired and hence this particular requirement gets a low score of 1.

• *The device must fit on a counter top:* It can be assumed that the whole device will measure about 10” and enable folding a 6” burrito. This can be easily set up on a counter top and a score of 9 is given.

• *Easy to install:* The number of human activities initially needed to set up the device is one. Not many parts are designed in the concept and hence a score of 9 is provided for this requirement.

• *The device must be easy to clean after use:* A four-fold burrito is complete offers no room for spillage. However, the chances of spreading the mix manually on
empty tortilla offers more chance for spilling. This is because the user does almost all the actions and the device is not continuous. So the concept gets a score of 3.

- **The device must be safe to use:** The four flaps to fold a burrito are not enclosed with any protection. When placed on the kitchen counter they are designed to be protruding outside. However, this will not cause serious injury and hence the rating for this particular requirement is 3.

6.2.2 Improved Inter-Rater Agreement

The result of the improved inter-rater agreement (IRA) as a result of the newly refined quality scale is presented in this section. As discussed in the section 5.2.2, there is a need to increase the consensus between the raters in order to obtain agreeable results. When the IRA scores are substantial, the conclusions thus obtained will have greater value since it is the opinion of more than one rater. In order to obtain an improved IRA, two raters who were also a part of the initial panel of four raters, went through a series of training before evaluating the concepts. As two raters are involved, Cohen’s kappa is applied to measure their agreement. The equation for Cohen’s kappa is given below,

\[ \kappa = \frac{Pr(a) - Pr(e)}{1 - Pr(e)} \]

where \( Pr(a) \) is the relative observed agreement among raters, and \( Pr(e) \) is the hypothetical probability of chance agreement [36]. Cohen’s kappa also varies from -1 to 1. If the raters completely agree then \( \kappa = 1 \) and if there is no agreement among the raters other than what would be expected by chance then \( \kappa = 0 \). If there is complete disagreement with no occurrence even by chance then \( \kappa = -1 \).
The results of various iterations for the IRA are shown in Table 6.6. The left column of the table lists the iteration number and the rightmost column in the table shows the overall Cohen’s kappa value for that particular iteration. The IRA for each requirement is also provided. The iterations were conducted with a sample of 10 concepts. After iteration, the kappa value for each requirement and the overall value were calculated. The particular requirement, which had low values, was refined further and their values were improved in the consecutive iterations. After three iterations, almost all the requirements had ‘moderate agreement’. This can be considered significant and finally the two raters evaluated all 106 concepts again. The final results were highly satisfactory as it had an overall Cohen’s kappa value of 0.61 (substantial agreement) and all the nine requirements had either moderate or substantial agreement.

Table 6.6: Iterations for Inter Rater Agreement

<table>
<thead>
<tr>
<th>Iteration</th>
<th>No. of concepts</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
<th>R9</th>
<th>Cohen</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>0.7</td>
<td>0.6</td>
<td>0.8</td>
<td>0.0</td>
<td>0.0</td>
<td>-0.1</td>
<td>0.1</td>
<td>-0.2</td>
<td>-0.5</td>
<td>0.31</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0.4</td>
<td>0.8</td>
<td>0.8</td>
<td>0.9</td>
<td>0.3</td>
<td>1.0</td>
<td>0.0</td>
<td>-0.8</td>
<td>-1.0</td>
<td>0.58</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>1.0</td>
<td>0.5</td>
<td>0.6</td>
<td>0.4</td>
<td>0.3</td>
<td>0.7</td>
<td>-0.3</td>
<td>0.5</td>
<td>0.6</td>
<td>0.46</td>
</tr>
<tr>
<td>Final</td>
<td>106</td>
<td>0.4</td>
<td>0.7</td>
<td>0.7</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.6</td>
<td>0.5</td>
<td>0.5</td>
<td>0.61</td>
</tr>
</tbody>
</table>

With the refined scale and a substantial agreement between the two raters, the quality of concept sketches developed using either the function model (FM) or the function interaction model (FIM) were evaluated again. In order to get the final quality score, the mean scores of the two raters were taken. The second and third research hypotheses will be assessed again with these new quality scores and the results are
provided in the following sections. Therefore, with an improved IRA we can be confident that the results obtained are highly reliable. Appendix C and Appendix D shows the mean score of two raters used for analyzing quality.

6.2.3 Quality at the concept level

In this section the second research hypothesis is revisited. The hypothesis is stated again: the average concept quality rating for the sketches developed from the FIM is different from the average concept quality rating for the sketches developed from the FM. Similar to the procedure followed in the section 5.2.3, t-tests were performed to compare the means of the concepts developed using the FM and the FIM. Following that, each concept was analyzed to find out how well the particular concept satisfied its functional and non-functional requirements.

Table 6.7 shows the results of two-sample t-test which compares the average quality scores of sixty three concepts developed using the FM and forty three developed using the FIM. It is evident that the mean of the concepts developed using FIM (mean=5.58) is greater than the mean of the concepts developed using FM (mean=4.92). In order to find if the difference is significant, the p-value is compared with the standard α value of 0.10. Since the p-value is very low, we can conclude that the average quality for concepts belonging to FIM is greater than that of the FM. This result is similar to the results obtained using the initial quality scale.
Table 6.7: t-test to compare the means of the two models at the concept level

<table>
<thead>
<tr>
<th></th>
<th>FM</th>
<th>FIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>4.92</td>
<td>5.58</td>
</tr>
<tr>
<td>Variance</td>
<td>1.75</td>
<td>1.21</td>
</tr>
<tr>
<td>Number of concepts</td>
<td>63</td>
<td>43</td>
</tr>
<tr>
<td>p-value (two-tailed)</td>
<td>0.008</td>
<td></td>
</tr>
</tbody>
</table>

Next, the requirement fulfillment of each concept is considered. It is necessary for each concept to satisfy its both functional and non-functional requirements. Table 6.8 compares the concept quality score for the functional requirements of FM with the concept quality score for the functional requirement of the FIM. The three functional requirements namely ‘position tortilla’, ‘fill tortilla’ and ‘wrap tortilla’ is compared at the concept level. Table 6.9 concept quality scores for the remaining six non-functional requirements of the two product models.

Table 6.8: t-test to compare the concept quality scores for functional requirements

<table>
<thead>
<tr>
<th></th>
<th>FM</th>
<th>FIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>4.13</td>
<td>5.15</td>
</tr>
<tr>
<td>Variance</td>
<td>3.82</td>
<td>3.07</td>
</tr>
<tr>
<td>Number of concepts</td>
<td>63</td>
<td>43</td>
</tr>
<tr>
<td>p-value</td>
<td>0.007</td>
<td></td>
</tr>
</tbody>
</table>

The mean value of the concepts using the FIM is greater than the mean value of the concepts using FM, as shown in Table 6.8 and Table 6.9. The p-value for functional requirements (p=0.007) and for non-functional requirements (p=0.03) is lower than α-value of 0.10. Similar results were obtained using the initial quality scale (see Table 5.8 and Table 5.9). Therefore, at the concept level, the average quality of the concept
sketches developed from the FIM is better than the average quality of the concept sketches developed from the FM.

**Table 6.9: t-test to compare the concept quality score for non-functional requirements**

<table>
<thead>
<tr>
<th></th>
<th>FM</th>
<th>FIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>5.32</td>
<td>5.80</td>
</tr>
<tr>
<td>Variance</td>
<td>1.46</td>
<td>1.08</td>
</tr>
<tr>
<td>Number of concepts</td>
<td>63</td>
<td>43</td>
</tr>
<tr>
<td>p-value</td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>

6.2.4 Quality at the requirement level

Quality at the requirement level is the average quality score of all the 106 concepts for a particular requirement. Calculating quality at the requirement level helps us to identify how each requirement had satisfied by the two functional models. The third research hypothesis is revisited: *the average quality rating for concepts generated from the FIM is different from the average quality rating for concepts generated from the FM at the requirement level*. The quality ratings for the concepts developed using the FM and the FIM at the requirement level is shown graphically in Figure 6.5. As one can see, seven out of the nine requirements have better scores for the FIM.

Table 6.10 shows the average quality score (same as Figure 6.5) for each requirement. The functional requirement ‘fill tortilla’, non-functional requirements ‘deliver four completed burritos per minute’, ‘safe to use’ and human activity requirement ‘easy to use’ have significant difference in their quality scores. Our initial conclusion based on comparing each requirement is that the quality scores for seven out
of nine requirements are in favor of the FIM. Three out of the seven requirements favoring the FIM have a significant difference in their mean scores.

![Figure 6.5: Quality scores of the concepts at the requirement level](image)

**Table 6.10: Quality score of the concepts at the requirement level**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Type</th>
<th>FM</th>
<th>FIM</th>
<th>Is the difference significant?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>FR</td>
<td>3.29</td>
<td>4.05</td>
<td>No</td>
</tr>
<tr>
<td>Fill</td>
<td>FR</td>
<td>5.57</td>
<td>7.37</td>
<td>Yes</td>
</tr>
<tr>
<td>Wrap</td>
<td>FR</td>
<td>3.54</td>
<td>4.02</td>
<td>No</td>
</tr>
<tr>
<td>Deliver</td>
<td>NFR</td>
<td>3.68</td>
<td>5.74</td>
<td>Yes</td>
</tr>
<tr>
<td>Easy to use</td>
<td>NFR-HA</td>
<td>3.37</td>
<td>5.07</td>
<td>Yes</td>
</tr>
<tr>
<td>Counter-top</td>
<td>NFR</td>
<td>6.02</td>
<td>6.63</td>
<td>No</td>
</tr>
<tr>
<td>Easy to install</td>
<td>NFR-HA</td>
<td>8.24</td>
<td>8.65</td>
<td>No</td>
</tr>
<tr>
<td>Easy to clean</td>
<td>NFR-HA</td>
<td>4.14</td>
<td>4.09</td>
<td>No</td>
</tr>
<tr>
<td>Safe to use</td>
<td>NFR</td>
<td>6.49</td>
<td>4.60</td>
<td>Yes</td>
</tr>
</tbody>
</table>

A pair wise comparison of all the nine requirements was performed to get the overall results for quality of concepts at the requirement level. As shown in Table 6.11, the mean value of the FIM is greater than the mean value of the FM. However, the p-value of 0.13 is greater than the standard α-value of 0.10. Hence our RH3 will not hold true with the standard α-value of 0.10.
Table 6.11: Paired t-test to compare the means of the two models at the requirement level

<table>
<thead>
<tr>
<th></th>
<th>FM</th>
<th>FIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>4.92</td>
<td>5.58</td>
</tr>
<tr>
<td>Variance</td>
<td>3.02</td>
<td>2.74</td>
</tr>
<tr>
<td>Number of requirements</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>p-value</td>
<td>0.13</td>
<td></td>
</tr>
</tbody>
</table>

In conclusion, our third hypothesis which states that, *at the requirement level the average quality rating for concepts generated from the FIM is different from the average quality rating for concepts generated from the FM* will not hold true. Therefore, there is no significant difference between the FM and the FIM in satisfying the given requirements during the conceptual design phase.

To investigate the effect of including human activities as functions instead of separate entities and flows in the function interaction model, three human activity requirements are analyzed. The requirements are (1) easy to install, (2) easy to use, and (3) easy to clean. Figure 6.6 shows the average quality score for the three non-functional human activity requirements. It is important to note the slight nuance that the only human activity requirement with a significant difference was ‘easy to use’. The requirement ‘easy to use’ is a direct measure of number of human activities; lesser number of activities contributes to higher score. This particular human activity requirement represents the product when it is being used. However, the requirements ‘easy to install’ and ‘easy to clean’ represents the activities performed over the product before and after it is being used. These requirements are not represented in either of the models and hence there was no significant difference in the quality scores of the two models. This is an
important observation noticed during the analysis. Therefore, in order to generate concepts that capture the human activity requirements of a product it must be explicitly represented within the model.

![Figure 6.6: Quality scores for the human activity requirements](image)

6.3 Summary

This section summarizes the results and conclusion drawn from Section 6.1 and Section 6.2 are summarized.

- With an overall Cohen’s kappa value of 0.61, the inter-rater agreement between two raters is substantial. Therefore, with an improved IRA we can be confident that the results obtained regarding quality of sketches developed using either the FM or the FIM are highly reliable.

- Due to the ambiguous (or relatively abstract) representation of interaction between user and the product, the number of concepts developed by the designers using the FM is greater than the number of concepts developed by the designers using the FIM. **RH1 is supported to be true.**
• The quality scores of the sketches at the concept level are better for the FIM compared to the FM. The functional and non-functional requirements for a sketch developed from FIM has its quality score greater than the sketch developed from the FM. This result is similar to the initial result. **RH2 is supported to be true.**

• At the requirement level, though the average quality score for the sketches developed using the FIM is greater than the average quality score for the sketches developed using the FM the difference in the quality is not significant. The FIM had better quality scores for seven out of nine requirements, of which three had a significant difference. This result is different from the initial result. **RH3 is supported to be not true.**

• ‘Easy to use’ is a non-functional human activity requirement which had a significant difference in its quality score. The other two human activity requirements namely ‘easy to install’ and ‘easy to clean’ did not show any difference in the quality scores between the models. The FIM had ‘Use HE to operate machine’ as a separate entity in the user activity part of the model. Hence in order to generate concepts that capture non-transformational aspects (or passive functions), it must be explicitly represented within the model.
CHAPTER 7: CARD SORTING EXERCISE RESULTS

The card sorting technique is used to reveal the conceptual structures, or categorizations by individuals [37, 38]. An important part of user’s knowledge is the categories which they use in their day-to-day life [39]. Therefore, it will be interesting to identify how users categorize the products they use. In this research, a product’s functionality and interaction are tested for its priority. The results from the closed card sort exercise will help design engineers in identifying whether novice designers (or users) categorize products based on the product’s functionality or interaction. The experimental procedure for the closed card sort exercise is discussed in the Section 4.1. Each participant was asked to sort the pictures of forty products. An example response is shown in Table 7.1. Four responses from the participant are highlighted in green to explain. The participant has placed ruler in the third quadrant (Q3), eye gear in the first quadrant (Q1), transmission system of a car in the third quadrant (Q3) and car in the fourth quadrant (Q4). The second column, which is the reference column, indicates the actual quadrant where the product had to be placed.

The data from this closed card sort exercise were analyzed for accuracy. Accuracy is measured by the percentage match of the participant’s sort with the actual sort. Accuracy can be used to determine how exactly each participant matched their response against the actual response. The following sections present the initial results of the card sorting exercise and seek to answer the second research question: How do users categorize a product based on their functions and interactions?
Table 7.1: A random participant’s response with highlighted examples

<table>
<thead>
<tr>
<th>Product</th>
<th>Reference Quadrant</th>
<th>Student # 21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruler</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Ladder</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Hammer</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Pen</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Scissors</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Lego toys</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Door keys</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Can opener</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Screwdriver</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Coffee mug</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Eye gear</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Nail clipper</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>USB mouse</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Stapler</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Flash light</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Vegetable cutter</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Analog luggage scale</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Bench vise</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Alcohol detector</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Coffee grinder</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Transmission system in a car</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Hard drive in computer</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Chainsaw</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Watch</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Lathe machine</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Sewing machine</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Drilling machine</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Electric motor</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Typewriter</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Car</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Rifle</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Air conditioner</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Camera</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Vacuum cleaner</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Laptop</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Helicopter</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Robotic arm</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>CNC machine</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>X ray machine</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
7.1 Accuracy of Each Quadrant

The accuracy test is performed to interpret how participants classified products based on their complexity. In order to find the accuracy, each student’s product sort is matched against the actual product sort list. The card sorting results were quantitatively analyzed to see the difference between functions and interactions. The accuracy percentage of each product is showed in Figure 7.1. A quick visual glance shows that the products in Q4 (HF-HI) have a higher accuracy percentage compared to the other quadrants. Also, the products in Q2 and Q3 (LF-HI and HF-LI respectively) have lesser accuracy percentage. In the following sections, the result of each quadrant is analyzed to answer the fourth research hypothesis, which is formally stated as: *The products sorted in Q1 (LF-LI) and Q4 (HF-HI) will have higher accuracy percentage compared to the products sorted in Q2 (LF-HI) and Q3 (HF-LI)*
Figure 7.1: Accuracy percentage for each product
Table 7.2 shows the overall accuracy percentage of each quadrant. The combined accuracy percentage for Q1 and Q4 (48.33%) is greater than the combined accuracy percentage of Q2 and Q3 (32.39%). Therefore, the fourth research hypothesis holds true. This implies that users find it easy to categorize products which are either simple or complex. Two example products are discussed here; door keys and helicopter. Door keys have a percentage match of 47.2% in the low functionality-low interaction quadrant and helicopter has a percentage match of 75.5% in the high functionality-high interaction quadrant. Door keys are primarily made of a single part and the user interacts with it by inserting into the door hole - this is a simple task. Helicopters, on the other hand, have thousands of parts and the user has to interact with the helicopter continuously to operate it. This fits with our hypothesis as users identify products easily based on their functionality and interaction when they are either simple like door keys or complex like helicopters.

<table>
<thead>
<tr>
<th>Quadrant</th>
<th>Functionality</th>
<th>Interaction</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>Low</td>
<td>Low</td>
<td>42.33</td>
</tr>
<tr>
<td>Q2</td>
<td>Low</td>
<td>High</td>
<td>31.94</td>
</tr>
<tr>
<td>Q3</td>
<td>High</td>
<td>Low</td>
<td>32.83</td>
</tr>
<tr>
<td>Q4</td>
<td>High</td>
<td>High</td>
<td>54.34</td>
</tr>
</tbody>
</table>

In conclusion, it is clear that the users perceive products based on its complexity. But how much does this complexity involve functionality and user interaction? To what extent the functionality and user interactions influence users to sort different products and
if so, is there a significant difference between functions and interactions? The next section 7.2 seeks to answer these questions.

7.2 Accuracy of Correct Functionality and Correct Interaction

In this section, the contribution of functions and interactions in describing a product is evaluated. For this research, functionality was defined based on the number of parts present in the product. As the number of parts increase, the functionality of the product also increases. Low functionality means the product is composed of less than 30 parts and high functionality products have more than 30 parts. The details of the number of parts in a product is obtained from the design repository [40]. The definition for interactions is based on how each part of the product would interact with the users. In other words, a product is said to have high user interaction if the user has accessibility to most parts of the product. Based on these definitions, the actual product sort list was developed (see Table 7.3)
Table 7.3: Products sorted based on their functionality and interaction (repeated)

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>User Interaction</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>&lt; 30</td>
<td>1. Ruler</td>
<td>1. Eye gear</td>
</tr>
<tr>
<td></td>
<td>2. Ladder</td>
<td>2. Nail clipper</td>
</tr>
<tr>
<td></td>
<td>3. Hammer</td>
<td>3. USB mouse</td>
</tr>
<tr>
<td></td>
<td>5. Scissors</td>
<td>5. Flash light</td>
</tr>
<tr>
<td></td>
<td>7. Door keys</td>
<td>7. Analog luggage scale</td>
</tr>
<tr>
<td></td>
<td>8. Can opener</td>
<td>8. Bench vise</td>
</tr>
<tr>
<td>High</td>
<td>1. Transmission system in a car</td>
<td>1. Car</td>
</tr>
<tr>
<td>&gt;30</td>
<td>2. Hard drive in computer</td>
<td>2. Rifle</td>
</tr>
<tr>
<td></td>
<td>3. Chainsaw</td>
<td>3. Air conditioner</td>
</tr>
<tr>
<td></td>
<td>5. Lathe machine</td>
<td>5. Vacuum cleaner</td>
</tr>
<tr>
<td></td>
<td>6. Sewing machine</td>
<td>6. computer</td>
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<td>7. Drilling machine</td>
<td>7. Helicopter</td>
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<td></td>
<td>8. Electric motor</td>
<td>8. Robotic arm</td>
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<tr>
<td></td>
<td>9. Typewriter</td>
<td>9. CNC machine</td>
</tr>
<tr>
<td></td>
<td>10. Wind turbine</td>
<td>10. X ray machine</td>
</tr>
</tbody>
</table>

Products in a quadrant are counted for correct functions horizontally and correct interactions vertically. For example, consider

Figure 7.2 which shows the range of correct function and correct interaction for Q1. A product is said to have correct functionality if it lies in either Q1 or Q2 and correct interaction if the product lies in either Q1 or Q3.
Similarly Figure 7.3 shows the range of correct function and correct interaction for Q2. In this case, if a product has to have correct functionality it has to be sorted in either Q2 or Q1. Likewise, for the product to be classified as correct interaction it has to be either in Q2 or Q4.

Figure 7.4 and Figure 7.5 shows the criteria for correct function and correct interaction in Q3 and Q4.
In Table 7.4, each quadrant is compared for its percentage accuracy for correct function and correct interaction. A trend can be noticed when comparing the second and third column of the table; the percentage accuracy for correct function is always greater than the percentage accuracy for correct interaction. Besides this comparison, a two sample t-test was also conducted to check if the difference between correct function and correct interaction across each quadrant is significant. The standard \( \alpha \) value is set as 0.01 to reduce the possibility of an error. Apart from Q1 (LF-LI) which has p-value greater than \( \alpha \), the other quadrants have a very low p-value. This means that the difference
between functions and interactions within a product is significant. This could be due to the fact that, for simple products like scissors, pencil or hammer in Q1 (LF-LI), the participants might have found difficulties in distinguishing the product’s functions and interactions. However when there is an increase in interaction (LF-HI), function (HF-LI) or both function and interaction (HF-HI), the participants were able to sort them in the right functions and interactions. The results to evaluate the firth hypothesis, which states that *there is no significant difference between the percentage accuracy for correct functionality and correct interaction of all the products*, are summarized in Table 7.4.

### Table 7.4: Percent accuracy of products sorted based on functionality and interaction

<table>
<thead>
<tr>
<th>Product Quadrant</th>
<th>% Correct function</th>
<th>% Correct interaction</th>
<th>p-value</th>
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</thead>
<tbody>
<tr>
<td>Q1</td>
<td>66.7</td>
<td>64.3</td>
<td>0.44</td>
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<tr>
<td>Q2</td>
<td>62.8</td>
<td>44.3</td>
<td>0.00</td>
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<tr>
<td>Q3</td>
<td>68.7</td>
<td>46.2</td>
<td>0.0002</td>
</tr>
<tr>
<td>Q4</td>
<td>78.7</td>
<td>65.1</td>
<td>0.0237</td>
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</tbody>
</table>

The results indicate that there is a significant difference between product functionality and interaction. In conclusion, RH5 does not hold true since there is a significant difference between user’s perception about functions and interactions of a product, with users giving preference to functionality over interactions in describing a product.
7.3 Summary

In this section, the results and conclusion from Section 7.1 and Section 7.2 are summarized.

- Products are sorted based on their complexity. The accuracy percentage for the products in Q1 and Q4 suggest that when the products are either too simple or too complex, the user have little difficulties is categorizing them based on functions and interactions. RH4 is supported to be true.

- Users perceive functions and interactions to be different. Functions of a product get priority over the interactions that the user has with the product. RH5 is supported to be not true.
CHAPTER 8: CONCLUSIONS AND FUTURE WORK

8.1 Research Contributions

The research presented in this thesis details the execution of two design experiments. A user study and a card sorting exercise were conducted to understand the role of functions and interactions in product design. The major contributions from this research are summarized as:

1. Established experimental protocol to evaluate how different product representations affect the creativity of designers during the early stages of product design. The two models studied are namely, the traditional function models (FM) and the newly developed function interaction model (FIM) which has a parallel approach to function-based and interaction-based modeling.

2. Statistically analyzed and provided evidence that the integrated function interaction model (FIM) when compared to the function models (FM) will result in less concepts, but concepts with a higher quality.

3. Provided insight to the designers about how novice designers (or users) differentiate between the functions of a product and interactions they have with the product.

4. Experimentally supported that designers are able to clearly differentiate between a product’s functionality and interactions and the functions of a product get priority over the interactions that the user has with the products.

The background on the current uses of functions, interactions and different modeling approaches are explained in Chapter 2. Two research questions and the
associated research hypotheses are developed in order to address the research gaps. Answer to each of the research questions are provided in the subsequent sections.

8.2 Answering the Research Questions

RQ1: How do function model and function interaction model affect the creativity of the designers within conceptual design?

The experimental procedure was developed to ascertain how the FM and the FIM affect creativity of designers during conceptual design (see Chapter 4). The concepts, represented as sketches with annotations, are collected from the experimental participants, and evaluated for quantity and quality. Statistical analysis for quantity and quality are discussed in Chapter 5 and Chapter 6. The results for quantity indicate that the number of concepts developed per designer is higher for the FM (3.15 ± 1.09) than for the FIM (2.15 ± 0.87). Further, quality is evaluated from two perspectives. In the first, the quality of concepts at compared for each designer and representation type. The second compares concepts relative to each requirement and representation type (see Table 5.6 and Table 5.10). Initially, a panel of four raters independently evaluated the concepts. The inter-rater agreement between the four raters was found to be low (Fleiss Kappa = 0.10). Therefore, the scale used for measuring quality had to be revised. Two raters from the initial panel went through three iterations to obtain a substantial agreement (Cohen Kappa = 0.61). The refined quality scale is shown in Table 6.2 and Table 6.4. The results based on the new scale are discussed in Section 6.2.3 and Section 6.2.4. There is sufficient evidence to conclude that the quality at the concept level is higher for the FIM (5.58 ± 1.1) when compared to the FM (4.92 ± 1.32). At the requirement level, the
average concept quality using the FIM is greater than the average concept quality using the FM. However, the difference in the quality is not statistically significant (see Table 6.11).

Another important observation from the user study can be used to support the FIM which follows a parallel function-based and interaction-based approach for concept generation. Figure 8.1 shows the framework for FIM in which the active functions are placed in the function-based path and the passive functions are placed in the interaction-based path. The interaction (or human activity) model is developed based on the interaction (or human activity) requirements. The burrito folder design problem has three human activity requirements. ‘Easy to use’ is a non-functional human activity requirement which had a significant difference in its quality score. The other two human activity requirements namely ‘easy to install’ and ‘easy to clean’ did not show any difference in the quality scores between the models (refer Table 6.10). The FIM had ‘Use HE to operate machine’ as a separate entity in the user activity part of the model (see Figure 4.4). Hence in order to generate concepts that capture non-transformational aspects (or passive functions), it must be explicitly represented within the model.
RQ2. How do users understand the functional and interaction aspects of a designed product?

A card sorting exercise was conducted to understand whether users categorize various products based on the product’s functionality or how they would interact with it (see Chapter 7). As shown in Table 7.2, the accuracy percentage for products in Q1 (LF-LI) and Q4 (HF-HI) is higher when compared to the products in Q2 (LF-HI) and Q3 (HF-LI). The complexity of a product has an effect on the user’s perception about functions and interactions. The results suggest that users find it easy to categorize products which are either simple or complex. Section 7.2 discusses about the
contribution of functions and interactions in describing a product and the priority given by the users between the two. Table 7.3 compares the percentage accuracy of products based on correct functionality and correct interaction. Apart from Q1 (LF-LI) which has p-value (0.44) greater than α (0.01), the other quadrants have a very low p-value. However, when there is an increase in interaction (LF-HI), functionality (HF-LI) or both functionality and interaction (HF-HI), the participants had little trouble in sorting them in their right functions and interactions quadrants. It has been noticed that the percentage accuracy for correct function is always higher than the percentage accuracy for correct interaction. Therefore, functions of a product get priority over the interactions.

8.3 Research Conclusions

The two design experiments cover a product at different production phases – the user study addresses the product at early stages of development and the card sorting exercise addresses the categorization of the products based on its functionality and interaction. The conclusions from the two design experiments and the answers to the research questions are shown in Table 8.1. The first three conclusions are drawn from the user study. The number of concepts developed by the designers using the function model is higher than the number of concepts developed by the designers using the function interaction model (see C1). The higher number of concepts may be attributed to the relatively abstract (or ambiguous) representation of the function model. Since the function interaction model is more specific and introduces the product’s form early in the design stage, the number of means through which the product can be approached is
reduced and the quantity is found to be low. However, the overall quality is higher for
the concept sketches developed by the designers using the function interaction model
(see C2). The third conclusion is based on the quality at the requirement level and there
is no significant difference between the concept sketches developed by the designer
using the two product models (see C3). The results from the card sorting exercise are
used to answer the second research question. The users categorize products based on its
complexity – it is easy to sort when the products are either simple or complex (see C4).
The fourth hypothesis is further extended to identify the user’s ability to differentiate
between functions and interactions. The functions of a product get priority over the
interactions that the user has with the product (see C5).

The conclusions from this research work will therefore help design engineers to
understand better about the current design practices involved in developing concepts and
the user’s perception about the product. Therefore, when the products are developed by
the designers that directly represent the user needs and perception, the product is more
likely to succeed in the market.
Table 8.1: Answers to the research questions

<table>
<thead>
<tr>
<th>Research Questions</th>
<th>Research Hypotheses</th>
<th>Accept/Reject</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQ1: How does the FM and the FIM affect creativity?</td>
<td>RH1: The number of concepts developed by the designers is different for the FM and the FIM</td>
<td>Accept</td>
<td>C1: Designers using the FM developed more number of concepts</td>
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<td>RH2: The quality of concepts at the concept level is different for the FM and the FIM</td>
<td>Accept</td>
<td>C2: Designers using the FIM developed better quality concepts</td>
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<td></td>
<td>RH3: The quality of concepts at the requirement level is different for the FM and the FIM</td>
<td>Reject</td>
<td>C3: There is no significant difference between FM and FIM for the quality at the requirement level</td>
</tr>
<tr>
<td>RQ2: How do users categorize a product based on their functions and interactions?</td>
<td>RH4: The products sorted in Q1 and Q4 have higher accuracy percentage match with the actual product list</td>
<td>Accept</td>
<td>C4: Users find it is easier to categorize products based on their complexity</td>
</tr>
<tr>
<td></td>
<td>RH5: There is no significant difference between the accuracy percentage for correct functionality and correct interaction of all the products</td>
<td>Reject</td>
<td>C5: Functions of a product get priority over the interactions.</td>
</tr>
</tbody>
</table>
8.4 Future Research Opportunities

Several other research opportunities have been identified that will substantiate the current results and also improve the usefulness of different modeling approaches employed at various stages of design. The recommendations for future work include:

- The traditional functional models are built upon the structured Functional Basis. The next step will involve developing such controlled and standard vocabulary for the function interaction model. \textit{RQ: How will incorporating structured vocabulary into the function interaction model affect the quality of the concepts developed?}

  Current literature in Affordance-based design has recommended the establishment of affordance structures to describe technical artifacts. However, the identification of affordances are largely dependent on the design group responsible for realizing the product. The controlled vocabulary of the functional basis has been proposed as a useful tool for increasing the repeatability, and thus the reuse, of product functional descriptions. A similar research avenue should be explored to describe interactions within a product.

- An experiment to determine the effect of requirements listing provided along with the problem statement. In this experiment, one third of the participants will be given only the requirements and no other product representation models. \textit{RQ: How will graphical and textual representation of the requirements affect the creativity of the designers?}

- The consistency of the quality scale can be investigated by introducing a third rater, who is completely blind to all the iterations made by first two raters, into the
judging panel and check for the new IRA. Likewise, the low-medium-high scale for quality is quantified as 1-3-9 in this research. Future work may include changing this scale to 1-2-3 or changing from a three point to a five point scale. The new results thus obtained can be verified with the results from this research. RQ: How will altering the quality scale at different levels modify the results obtained in this research?

- In the card sorting exercise, the definitions of functions and interactions used to develop the actual sort list are basic. The functionality of a product was defined based on the number of parts and interactions are limited to product-user interactions. The definitions of the functions, interactions and affordances from the literature can be gathered and a similar card sorting exercise can be performed where the participants sort the definitions. With this we will be able to clearly identify if the definitions currently available in the literature represent the user’s perception about a function and interaction. The definitions of both functions and interactions must always be separable. The definitions of affordances may be interchanged with either functions or interactions. RQ: How do users differentiate the definitions of functions, interactions and affordances in the current literature?
APPENDIX A

Concept sketching sheet

Points to remember:

1. Please specify the view for your concepts. (Top/Front/Perspective)
2. Either a front, top or perspective view is enough. Do not draw the same concept in different view.
3. Please provide properly dimensioned and labeled sketches.
4. Provide explanation for your sketch at the bottom.
5. Only one concept per page.

ID:

VIEW: Top/ Front/ Perspective

Explanation:
**APPENDIX B**

Four quadrant sheet used in card sorting exercise

<table>
<thead>
<tr>
<th>Low functionality and Low interaction</th>
<th>Low functionality and high interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>High functionality and Low interaction</td>
<td>High functionality and high interaction</td>
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</table>
## APPENDIX C

**FIM - Mean Score of Two Raters Used in the Analysis**

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<th>Student ID (n=43)</th>
<th>Position</th>
<th>Fill</th>
<th>Wrap</th>
<th>Deliver</th>
<th>Easy to use</th>
<th>Counter-top</th>
<th>Easy installation</th>
<th>Easy to clean</th>
<th>Safe to use</th>
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Function Structures and Function Interaction Model – An Introduction

Raveesh Ramachandran
raveesr@clemson.edu

Advisor: Dr. Gregory M. Mocko
October 19, 2010
Outline of the presentation

- What is a Function (4)
- Basics of Function Modeling and its application (5-16)
- Introduction to Function Interaction Modeling (18-25)
- Creative Concepts (27,28)
- Steps to sketch concepts (29,30)
FUNCTIONS
**Function Structure**

- Function – A function is a statement of a clear, reproducible relationship between the *available input* and the *desired output* of a product [Otto and Wood].

  ![Diagram of mechanical energy conversion](image)

- What a product ‘does’ or is ‘intended to do’.

  **Fig 1: Alternator in a car**

  **Fig 2: Home use Generator**
Basics of Function Modeling

- Function Model – A systematic way to describe a system’s function
- A function structure is a solution neutral representation of the process of converting a set of inputs to a set of outputs [Pahl & Beitz]
- Does not provide a ‘single solution’.
## Basics of Function Modeling - Definitions

- **System** – An entity that is connected to the environment by means of inputs and outputs at its boundary.

- **Boundary** – Separates entities and relations of interest from the environment / surroundings.

![Diagram of System and Boundary](image.png)
Basics of Function Modeling - Definitions


- Signal – Physical form in which the information is conveyed.

- Energy – Ability to make something happen [Otto & Wood]. No transfer or conversion of matter or signal without energy.
## Basics of Function Modeling

- **Black box** – Greatest, overall need of the product.

- Black box can be decomposed into sub-functions and flows.
- **Sub-function** – Component of a product function based on corresponding subtask.
- Summation of all sub-functions must be equal to the product function.
Basics of Function Modeling

- Product Abstraction – Ignoring the particular details.
- Generalization points to the crux of the problem.
- Multiple solutions
Basics of Function Modeling

- Sub function – Component of the primary function
- Supports the main function
- Do they follow a logical and consistent sequence?
Black Box Decomposition
Need for Function Modeling

- Systematic transition from customer needs to concrete solutions in forward engineering – Not seeking previous experience alone

- *What* to be achieved is important – Not *how*

- Creativity is enhanced at each level of decomposition

- Tradeoffs are explored
Usage of Function Structures

- Broadly used for both forward and reverse engineering

Forward Designing – Used in this study

1. Problem Statement
2. Function Model
3. Design, Development and Production
4. Final Product

Reverse Engineering:

1. Select a product
2. Analysis of each component
3. Function Model
4. Report Statement
Laws of Conservation in Function Modeling

Example 1: Bread Toaster (Mass)

Example 2: Electric Motor (Energy)
Design Repository Example – Rice Cooker

FUNCTION

OUTPUT
Fig: Function Structure of a Black and Decker Rice Cooker from Design Repository (OSU-DR)
INTERACTIONS
Function Interaction Model

- Function Interaction Model captures an artifact's functions, interactions and user activities
Function Interaction Examples

- User Interaction

The driver physically touches the steering wheel to provide information to the car.
Function Interaction Examples

- Product Interaction

USB mouse physically touches the port in laptop to initiate the flow of information between them.
Function Interaction Examples

- Environmental Interaction

When the glider lands, the property (pressure) of air and water around it changes.
Difference - Function and Interaction

- Function Structure – Transformative descriptions – Material, energy, signal flow through artifact

- Interaction Model – Non-transformative descriptions – Interaction of artifact with other artifact, a user or the environment.
FUNCTION INTERACTION MODELING
Need for Function Interaction Modeling

- Ambiguity in representation—Two Artifacts with almost same function can create problem during ideation.
- Example: Lawn mower and hair trimmer
CONCEPT SKETCHING
Expectations

- Describe what you have drawn
- Use your own style of representation
- Concept sketching tests your ability to communicate well and not your artistic skills
Using the models to sketch concepts

1. First identify your system boundaries.
2. Determine the input and output from the model.
3. Identify parts which will satisfy the sub-functions and its flows first.
4. Start from a simple principle – Do not try to accommodate all your ideas in a single product.
5. Assemble the parts based on their logical relationships and working principles.
6. Confirm to the law of conservation – Check if all the energy and mass in input are obtained as output.
7. Are all the requirements satisfied?
Start Sketching your ideas …….
APPENDIX F

Slides Presented to the Participants of the Card Sorting Exercise

Slide 1

Card Sorting of Products

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April 21, 2011
Outline of the presentation

- What is a Function
- What is Interaction
- What is an Affordance
- Card Sorting Procedure
What is a Function

- Function – A function is a statement of a clear, reproducible relationship between the available input and the desired output of a product [Otto and Wood]
- What a product ‘does’ or is ‘intended to do’.

Fig 1: Alternator in a car

Fig 2: Home use Generator

- Functionality of a product depends upon the number of parts
What is an Interaction

- Interaction is a kind of action that occurs as two or more objects have an effect upon one another.

The driver physically touches the steering wheel to provide information to the car.
Design Repository Example – Rice Cooker

INPUT

FUNCTION

OUTPUT
What is an Affordance

- Affordances are the perceived and actual properties of the thing, primarily those fundamental properties that determine how the thing could possibly be used [Norman]
- Affordances provide strong clue to the operations of things

- Affordances are based on how each part of the product would interact with every other part and user
Difference - Functions and Affordances

- Functions are form independent and affordances are form dependent.
- Example of a suitcase handle - The function is satisfied but the affordances differ.
Card Sorting Procedure

- Sort the set of products based on its functionality and affordances
- The products must be present in any of the four quadrants
- Clip the cards around the four corners of the paper
Start sorting your products…….
<table>
<thead>
<tr>
<th></th>
<th>List of products</th>
<th></th>
<th>List of products</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Air conditioner</td>
<td>15.</td>
<td>Eye gear</td>
<td>29.</td>
</tr>
<tr>
<td>6.</td>
<td>Can opener</td>
<td>20.</td>
<td>Ladder</td>
<td>34.</td>
</tr>
<tr>
<td>7.</td>
<td>Car</td>
<td>21.</td>
<td>Laptop</td>
<td>35.</td>
</tr>
<tr>
<td>9.</td>
<td>CNC machine</td>
<td>23.</td>
<td>Lego toys</td>
<td>37.</td>
</tr>
<tr>
<td>12.</td>
<td>Door keys</td>
<td>26.</td>
<td>Rifle</td>
<td>40.</td>
</tr>
<tr>
<td>13.</td>
<td>Drilling machine</td>
<td>27.</td>
<td>Robotic arm</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX G

Concept Sketches from the User Study

ID: 1

VIEW: TOP/ FRONT/ PERSPECTIVE

Explanation:

- The folding mechanism will have weight sensors to allow/track quantity of fillings.

Folded Buns/Hot dogs

- Similar to indicate you need to pull

Buns/Hot dogs (stock is empty)

Inside of the machine

- int. mechanism (detected on next sheet)
Explanation:

1. We need a mechanism to allow the above
   movement of the folding mechanism. (Either
   use a cam or electrical motor).

2. Speed of at least 4 revolutions/minute
   obtained by selecting
   appropriate motor speed.
Explantion:

Human places tortilla on conveyor belt and inserts fillings into funnel. Human then cranks the belt until the tortilla is under the fillings and stops. Human pulls out trap door to drop fillings. Human continues cranking again until burrito drops into folding trough. Burrito slides down onto plate and human removes burrito.
Human places tortilla on platform. Human inserts fillings onto loading ramp and the fillings slide down onto tortilla. Human folds hinged flaps of platform over to fold burrito. Human pulls platform along slides and then removes the burrito.
VIEW: TOP/FRONT/ PERSPECTIVE

Explanation:

The set of guides in Figure 1 ensures that all three sides are parallel. The grip is placed on a fixed guide in the front, and the blade is engaged in a shallow angle to guide it to the desired position. The blade slides into the blade guide until it is raised to the desired angle. The blade is then lifted by hand, and the blade slides to the desired angle, after which a locking mechanism secures it in place.

Referring to the figure, identically slides the blade to Plate 2.
Explanation:
In the above concept, a known interaction is added to the slice beneath without filling or filling or filling. Once the slice has been located, the bottom will lift up and allow the required filey onto the slice. For this to close, a filey snaps onto it, thus securing the sliding mechanism.
Explanation:

Ball cup mounted under a filling tray handle rotating to dispense the proper amount of filling onto a tortilla. First handle coming out the front is a track profile that folds one side then goes over the locator & holds the other side up. Then the other lever is used to roll the bean up.
Explanation: Filling holder at the top, human turns handle, then draw up for then turns flap that fold tortilla. The flap then actually rotates the filling dispenser to. Spring platform at bottom loads tortilla.
Explanation:
1. Lay 1 fabric in a long way (mechanical stretch)
2. Fold fabric short way (mechanical stretch)
3. Fold fabric short way (mechanical stretch)
4. Fold final long way (mechanical stretch)
5. Insert fillings (mechanical compress and stretch)
VIEW: TOP/FRONT/PERSPECTIVE

Explanation:
As crank rotates, actions are performed in order of
1. fill gas container
2. fill gas container
3. fold short
4. fold short
5. fold long
6. etc.
Explanation:

L1 = load burrito.
L2 = load filler

S1 = wrap burrito (any fold, short fold, short fold, long fold)

L1 = eject burrito / load new tortilla.

Auto burrito loader.
Explanations:

1. The burrito sits on the filling table so it is a flat square board. The burrito sits in the middle with filling not going outside dotted circle section. The table is folded along ab cd ef gh and unfolded leaving the tortilla folded. It is then folded along ac and ad to reveal folded burrito.
Explanation:

This device is much less simpler, but still makes the task of hand-to-hand picking much simpler and easier. It would also have a better chance of meeting the size constraints.
Explanations:

Toppings go into hopper, which travels in order to spread them evenly. Tortilla is inserted into base. The cup at the end of the turn crank is attached, and the push bar positioned. Push knob to begin fold, rotate crank to complete.
Explanation:

Add toppings to hopper. Position tortilla such that it rests on the three pins. When top hinge is pushed, the three wedges engage the pins in order (1, 2, 3) in order to complete the fold.

Release hinge and remove.
Explanation: Key parts of concept

1. A top box with flip to store fillings & help to fill tortilla
2. Slot to fill burrito (tortilla)
3. Motor & Roller from both sides to fold burrito
4. A slab- mounting arrangement to keep/place tortilla
Explanation:

1. Mechanism just like human hands to wrap burrito.
Explanation:

Steps:
A) User fills bag (A) w/ fillings and applies non-stick to B and C.
B) User places tortilla on device
C) User squeezes bag, which deposits fillings on tortilla
D) User pulls holding wheel, rotates (C) 180°, then B 180°
   then slides C 180°.
E) User removes completed burrito and replaces w/ tortilla. (Repeat C-E)
F) To clean device, A is removed and wiped and device is wiped
Explanation:

Similar to other concept,
- Turtles clings to pan - pull out position.
- After pulled, turtles is pulled off of device onto a plate.
- User inserts another turtle and process is repeated.
Explanation:

1) Place tortilla on conveyer belt.
2) Load the filler with tortilla fillings.
3) Filler injects tortilla filling on a tortilla at a constant rate.
4) Human picks up & passes to a man at table A.
5) He folds the tortilla & serves.
Explaination:

1) Human A places tortillas in sequence & passes to human B
2) Human B fills tortillas with fillings using a gun loaded with fillers
3) He passes them to human C who folds the tortillas & serves from the table
Explanations:

1) Tronex: machine loads the circular rotating table with torrices.
2) Human 1 aligns & fills filler into torrices.
3) Human wraps the torrices & removes.
Explanation:

1) Load tumits & fillings into the machine.
2) Tumits are stacked inside machine.
3) Human 1 presses start button.
4) Tumits is transported to a rack inside the machine fillings are injected to it.
5) Machine transports it out, where human 2 picks, maps & removes...
Explanation:

1) Tortillas are stacked on a table.
2) Robotic arm picks & transports to a table where human A is stationed.
3) Robotic arm drops tortilla on table where human B adjusts, wraps & removes.
The tortilla is positioned between the two arms. The valve in the filling holder is opened, and fills the tortilla.

The spring-loaded arms slide out, then push on the tortilla around the filling. Finally, the side spring-loaded arms fill the tortilla inward over the filling.
The burrito is placed in the slot in the device to initially fill it upwards. The sloped surface holds the filling in place. The spring loaded arm then rolls the burrito into the tortilla. The spring loaded arm then rolls the burrito into the tortilla. The burrito is sitting on a sloped surface, so once the tortilla is filled the arm returns allowing the burrito to slide out.
Explanation: Concept for filling into open tortillas much like a soda bottle filling plant, when the burrito is below the nozzle, a pre-measured amount of filling leaves the nozzle and enters the tortilla. Tortillas are on a belt.
Explaination: Tortillas are located on the belt by concave mouldings on the belt so the mouldings are roughly the shape of the tortilla to allow it to "catch" the tortilla much like a shuffleboard + pusher match (or a baseball and mitt)
Explanation:

Front view
VIEW: TOP/ FRONT/ PERSPECTIVE

Explanation:

Top view

The tortilla holder and filling holders flip up to dump items onto the conveyor belt.
The burrito is inserted into a roller and pulled across (indicated by "movement") as also conveys it like a slide bar.
Tortilla upright on conveyor is filled with its fillings and positioned in mold or inserted by human. Then, a robot closes the protruding remains on the tortilla. Then the mold is inverted so the burrito can slide out.
Explanation:

Note: Assume buffalo cone diameter is 10".

Places are 1" squares.
More burrito folding

Folded:
Sides of burrito

Arms:
Fold ends of burrito

Explanation: Arms will fold sides of burrito
The hinged device is designed such that the tortilla is placed and ingredients are added by hand. The hinged flaps are then folded together one after another to fold the tortilla over on itself. (in the specified order)
Explanation: This is for storing and pouring out filling. The filling is stored in a can in a holder which pivots at the mouth. A pull causes to lift up on the can pouring out some of the contents and stops when the handle is released.
Explanation: Shells are stored in a vertical stack. When the user turns the hand crank of the conveyor, friction pulls one shell from the bottom of the stack. When the shell is under the filling storage, the user pulls a lever that rotates a cylinder a specified angle to dispense a specific amount of filling. As the shell moves down the conveyor, one side of the shell moves up a curved folder which flips the edge and the filling. A second folder flips the other side on the finished product and lands on a plate that is removed by the user.
Explanation:
Explanations: Shells are stored in a vertical bin and one is dispensed when the lever is pulled. A specific amount of shells is dispensed when the lever is pulled. A hand crank is used to lower the shell on the bin, while lowering the folders flip upwards as a user removes the bin.
Explanations: This is a side view showing the container with an open glass door in the bottom for the fillings to release.
Explanation:
The tortilla is inserted from the right side and it slides down a ramp where a held circle stops it. The stops are positioned to the right and the tortilla is correctly positioned by the stops. The stops have pins that are connected to a cam that is connected to an actuator. The actuator is then connected to a cam that releases the stops when the process is complete.
Explanation: This shows the platform that the tortilla will be placed on. After the filling/mayo is deposited on the tortilla, clamping mechanisms would slide along the AA and BB tracks to properly fold the tortilla. The tortilla could then simply be placed on the platform and alignment could be performed by milling out a sized slot that the tortilla could fit into. This entire platform could ride on a track; therefore, after the tortilla were folded, the platform could deliver the product to the proper customer/sink area.
The machine will convert HE to ME through the use of a hand crank and a gear train. The gear train is connected to a drive shaft that will have multiple cam/follower systems attached that will regulate the proper timing of the different steps.
How much power is needed?

Explanation:
In order to heat the burritos, they must be heated from room temperature in 15 sec. The burrito most likely weighs about 150g. When full, \[ Q = (150\text{g}) \times (0.8)(70^\circ \text{C} - 27^\circ \text{C}) \]
Final temp: 70°C
\[ Q = 5160 \text{J} \quad P = \frac{5160}{15} = 344 \text{ watts} \]
Device should be putting out 344 Watts to meet time requirement.
Explanation: A timer is triggered to start the conveyor belt and give a delayed start to the lever under the funnel. The tortilla and ingredients are placed by hand prior to the signaling of the timer. The conveyor transports the tortillas and ingredients will dump onto the tortilla as it arrives underneath the funnel. The tortilla will then be transported until it falls off the conveyor where it will fall into a cup, allowing it to wrap over the burial.
I am not unintelligent, I do not understand the notation and I know it looks wrong but cannot put it in proper format.
VIEW: TOP/FRONT/PERSPECTIVE

Explanation:
Explanation: The tortilla positioning is done by inserting a single tortilla into a slot in the side, which then slides down a ramp, coming to rest against the bumpers.
Explanation:

1) entrance will be closed on flat surface of plate
2) filling will be put into the funnel
3) a flap on the bottom side of the funnel will keep contents in the funnel until the feed crank is turned & the flap opens
4) the force of the filling falling onto the tortilla will push it into the trough
5) two flaps will then slide forward, one at a time, folding the ends of the tortilla completely over the fillings
The triangle piece follows the provided path on a groove and rotates at the same time, wrapping one edge of the tortilla into the cluster of itself.
Human inserts tortilla onto a plate which then retracts into the device. The column holding the tortilla rotates adding the desired fillings. The plate then folds itself to wrap the burrito and deliver the finished product.
**Explanation:** System to fill tortilla with fillings

- The hopper will have the filling inside it and when the tortilla is in place, the filling will be inserted into the tortilla.
Explanation: Human places tortilla on base and adds fillings. Human then moves hinged doors to fold the burrito and releases the doors to release it.
Explanations: The user places a blan tortilla on the belt, probably a “tortilla stream.” In 5 seconds, so that it will stick to itself. A mechanical arm lifts the tortilla and places it on the tortilla as it passes at the filling station. Simultaneously, another filled tortilla is wrapped by mechanical bands in order shown in the diagram. The completed burrito can be then removed by the user.
Explanation: Human places one end of the tortilla in the clamps, adds the fillings and the rotates the clamps using the handle. The burrito will roll into itself and the the clamps will be released.
Explaination:
Tortilla is placed on conveyor. As it travels under the biro fillings are dropped into the tortilla. Then it travels into the folding mechanism. Each end folds the tortilla into a burrito shape and then the burrito travels to the final position.
Explanation:

Part A lifts the sides of the shell and folds them in so it can be contained while rolled up.

Part B uses air suction to stick to the shell and folds the fillings then.

Part C then uses the same method and folds the final end over.
Explanation: Filling dispenser moves back and forth on two rods via rope and wheels. Door at bottom opens by a lever.
Explanation: Human power the device which releases a single tortilla onto a conveyor belt. The fillings are then added and mechanical arms wrap the burrito.
Explanation:

Terrillus slide down into chamber by use of rollers.
The folding chamber has four angled sides with hinges half way up.
Explanation:

Cooking 4 burritos in a minute
- This will cook 4 burritos at a time by placing them evenly on the angled grill
Explanation: Two surfaces with interlocking striations should be used because storage is simpler when the device fully closes. Why not use flat surfaces? Burras are expected to have a texture which a striated surface can provide.
Explanation:
The conveyor belt brings the tortilla forward from the bottom of the static. It stops in the middle, the filling is dispensed from a container above the open tortilla. The filling is dispensed, then the left side folds in on the hinge. The right side then folds up and in to fold the tortilla. Lastly, the bottom folder pushes to fold the bottom half of the tortilla. Now folded, the conveyor belt moves the burrito in the direction of the loading and out of the machine so that the operator can safely remove the completed burrito. It is easy to clean, and we are able to make at least four burritos per minute, depending on the speed of the conveyor and folding action.
Hinged drawer sides moved by mechanical levers.
Explanation: Each funnel can be filled with a different type of filling for the burrito. A valve exists on each funnel so that materials can be changed each time. There will be 6 funnels at top in lines so that the fillers can be reached. There is also a universal stopper that is activated by the controller. The material then empties into the large funnel and makes its way to the tortilla.
**Explanation:** Remove burrito

- How the human will grab the handle and rotate the right half of the burrito maker about the fixed point.

- The burrito will then be placed on the plate and be ready to eat.
Examination: Cooking Burrito

The grill will pass down inside to grill the outside of the burrito
Explanation:
Wrapping Tortilla around Fillings

- This machine will fold the tortilla closed after the filling is inserted inside.
- The right side will fold first then the left side will fold to close the burrito.
Explanations: Arms of machine will move up and over to fold burrito.
Description:

Hand operated conveyor belt moves burn to slide for storage/delivery on flat surface. Burn to slides for storage/delivery.
Explanation:

Each shell is individually placed on separate spring loaded sheets which will flap them onto the loading platform.
VIEW: TOP/FRONT/PERSPECTIVE

Explanation: EXPANDED VIEW OF CONCEPT 16.7, ALSO INCLUDING 16.1
Explanation:
1. Open hatch, place tortilla inside with fillings.
2. Close hatch, push button.
3. Belt (top) turns nothing limits, belt under spring suspension maintaining contact with tortilla top surface as rolling is possible.
Explanation:

spaced out evenly, not slid allowing for bottle placement in system, yet still held together to reel bands into roll shape.
VIEW: TOP/ FRONT/ PERSPECTIVE

Explanation:

Tube smaller than burr, allows fill to enter burr to shell and not push shell out. Then push sheets. Once fillings are fully added.
1. Rollers connected to motors move the tortilla in place & position.
2. The filler spins and fills the burrito.
3. The side rollers fold the ends and the side folder folds one side and runs in a position.
4. Belt moves toward the burrito to roll it closed and reverses to convey burrito and restart process.
Explanation:

Platform for tortilla is segmented into folding areas. Platform will also drop one end when finished to allow burrito to slide out.

Only a portion of burrito folding device

1 tortilla gets placed on device each time
Explanation: **Filling Dispenser**

1. Can hold fillings for up to 5 darts.
2. Pull out tab for each one to dispense filling.
3. Angled chute for centralized distribution.
VIEW: TOP/FRONT/PERSPECTIVE

Position burrito in correct orientation
- Collapse plate to allow gravity to position tortilla
- Vibrating plate to remove frictional forces from preventing tortilla to fall into place

How does it get tortilla on the plate?

Claw to grab tortilla & move it onto plate

Explanation
Fill tortilla using a sliding dispenser that releases filling down center of tortilla.

Dispenser moves on tracks.

Filling point is fed into tortilla.

Plate has filling points on angles to cool filling.
ID: 11-3

VIEW: TOP/FRONT/PERSPECTIVE

Explanation:

Dispenser receives filling from tank.
Explanation:

This subsystem is designed to hold the barite once all of the materials have been placed inside. The design in the top left is the complete design, while the other three figures break down the design into two subsystems. The first is simply three metal plates on a sturdy platform held together with a bolt. The two sides can swing upwards, which will hold the ends of the barite. The second function is to actually hold the barite so that the barite rests on a plate and the bolt is used to hold them together.
Explanation: The submarine above is used to store and pick things. It is a second ship with a streamlined hour maker.
This design would be a hand-cranked tortilla mill. The user would load the desired filling in the top container and the first bridle on the cornucopia hill by the hand crank. Turning the hand crank will move the tortilla into position under the filling container. The filling container will drop its contents at the right moment by the use of a generator which is the tortilla and filling moves down the line, another generator which will be used to engage the hinged folding plate, folding the edge of the tortilla over the filling. The final step is a vertical translating roller which will grip the tortilla and completely fold it as it exits the cornucopia hill.
Fillings are put into a hopper. Tortillas are set on a conveyor belt that is driven by a motor. HE is converted to HE by use of a switch. The tortilla is moved into the basin where fillings are dropped on it. A panel lid is held by a bracket. Another conveyor belt is powered to move the completed burrito down the second set of rollers into the hopper. The user can remove
Explanations: Positioning/filling done by user
Folder: fixed middle panel. Side panels fold over (most
likely motor driven) to fold burrito in tri-fold. These
side panels move one at a time. Activated by switch.
Funnel positions tortilla, conveyor belt carries/positions tortilla, fillings added, conveyor belt moves tortilla/fillings into chute that gets narrower and rolls burrito, rolled burrito is deposited into hopper.
Explanation:...
Explanation
Each gear has a Rocket Mechanism that only allows motion in forward. The direction of each Rocket Opposes the other.

Manager controls截至's gate at.

Gears will attach to a "Filling" mechanism and a "Rolling" mechanism. Spring loading from the spring by rotating eccentric. An empty fill is provided.

Explanation:
VIEW TOP/FRONT/PERSPECTIVE

Explanation:

- Slow Energy
- Human Input
- Fill Bottle
- Roll Bottle
- a Final Quick Better Roll
- Motion back out to Release
- Build from Rolling mechanism for user to remove.
Explanation: A tortilla is placed on left side of hand-driven conveyor system. As tortilla moves to right, a rib engages a release lever, allowing filling to be ejected onto burrito. As burrito exits system, angled side flaps lift edges of burrito to fold them over.
Explanation: A hand-driven cam depresses a plunger which forces fluid onto the hand-plied wrinkle. As the cam continues to turn, the plunger retracts and a lever is engaged to fold the burrito.
Explanation:

Once the dowels have pinched the tortilla, the disc will roll the burrito off. The dowels will then be removed by being slid out axially by the pinching mechanism.

This disc + motor

Mechanism to pinch dowels rod

φ of above burrito
**Explanations:**

HE turns on motor 1 which causes a cam to rotate. The cam pushes in a push rod connected to 3 plates covering the exits of the storage containers holding the fillings. The cam moves push rod to the right, uncovering storage containers to allow fillings to fall onto tortilla. This push rod turns on motor 2 which is connected to a gear that spins to move the tortilla platform in order to push it up a ramp. When tortilla reaches flat portion of ramp, its weight causes the fold on the ramp to collapse, which folds the tortilla and...
REFERENCES


