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A Case Study in Challenging and Validating Engineering Requirements with Value-Based Techniques

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A Case Study in Challenging and Validating Engineering Requirements with Value-Based Techniques

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
Seth R. Crouch
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Accepted by:
Dr. Gregory Mocko, Committee Chair
Dr. Joshua Summers
Dr. Georges Fadel
ABSTRACT

Requirements are an essential element to engineering design as they are used to focus idea generation during conceptual design, provide criteria for decision making during concept selection, and verify the chosen concept fulfills product needs. Because they are essential to the entire design process, great emphasis needs to be put on ensuring that they are correct. This research focuses on a value-based methodology useful for challenging and validating established requirements. A case study was conducted on an industry sponsored project that attempted to use this process on the requirements that constrain the design of an automotive seat. The case study focused on the challenging of the particular requirements that dictate the adjustable ranges of motion for the seat. These requirements were changed during the case study to represent the realization that the original requirements allowed for over-adjustability. This case study shows that this approach provides persuasive evidence to challenge requirements. This evidence is therefore more effective for challenging incorrect requirements than traditional challenging techniques that rely upon experiential or notional evidence. The case study also shows that value-based thinking is a mode for relating requirements directly to rationale. The results of the procedure followed in the case study are used to propose a potential process for future projects needing requirement challenging.
DEDICATION

“Whatever you do, work at it with all your heart, as working for the Lord, not for human masters, since you know that you will receive an inheritance from the Lord as a reward. It is the Lord Christ you are serving.” Colossians 3:23-24
ACKNOWLEDGMENTS

I would like to take this opportunity to thank Clemson University for allowing me to continue my education here and for the opportunity to work towards a Master’s degree in Mechanical Engineering.

I would like to thank my advisor, Dr. Gregory Mocko for his patience and dedicated investment of time. Without the patience shown by Dr. Mocko, I would not have overcome my tendency to be indecisive or my inability to see big picture impacts.

I would like to thank Dr. Joshua Summers and Dr. Georges Fadel for being a part of my academic committee. The guidance and criticism shown on towards my research is understood and welcomed. Without the strong committee members in the past and the future at Clemson University, degrees such as the one I have received will not merit much honor.

I would also like to thank Johnson Controls, Inc. for the investment placed in higher education. Through the grant for research funded by JCI, I have been provided with avenues to investigate my interests in the field of engineering design while not being financially burdened.
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CHAPTER ONE: MOTIVATION AND SCOPE OF PROBLEM

The overarching objective of this research is to execute a case study that implements value functions and value-based thinking in the design process in order to challenge established requirements. This study will use value-based thinking to provide a means for establishing concrete rationale for requirements and a systematic process for the validation of requirements in the system design process. Many design problems are not clearly defined which therefore increases the difficulty of understanding the design problem [1]. Additionally, researchers have identified that engineering requirements often must be challenged to ensure the requirements are well-founded and justified [2]. With current design processes, there is an unknown level of certainty connected to many requirements, and this ambiguity impedes the process of ensuring correct requirements. Ambiguity, in this sense, is the state of being unable to justify certain conclusions or ascertain the likelihood that the conclusions are correct. Ambiguous requirements or requirement documentation may lead to incorrectly designed products which wastes both time and money [3]. This research will show a process that can increase the certainty and accuracy of requirements both of which lead to an increase in the odds of good final designs.

The design process is critically dependent upon the requirements [3]. Like any systematic process, each successive phase is dependent upon the previous phase, and since the design process begins with listing and defining the requirements, it is clear that the remaining phases will be dependent upon them. The general systematic design
process as described by Pahl and Beitz is shown in Figure 1, and it is broken down into four major phases.

**Figure 1: Systematic design process [4]**

**Systematic Design Process**

The design process begins when a problem is identified [1]. Reasons for new project needs can be discovered through market research, initiated by new technology, or
due to the desire to improve existing products. The first important phase is Planning and Task Clarification where the problem is broken down into obtainable goals that are easier to visualize than the basic problem statement [4,5]. These goals are referred to as the functional requirements of the system. The requirements are written statements of the user needs and desires expressed in a way that is useful in guiding the design process [5]. After additional requirements, or specifications [5,6], are added to the list from other constraining factors, such as the environment in which it is going to be used or safety and governmental regulations, designers can use the whole list as a guideline for generating potential solutions called concepts. These concepts are expanded and altered until there is enough detail to compare them to one another and to assess their ability to perform as needed and desired [5]. There are many different tools for organizing and comparing these concepts, but the metric is constant across all concept comparison tools and that metric is the requirements list. After comparing the concepts with one or more comparison tools, the details of the best few concepts are developed even further. Once these concepts are at a detailed level where verification of their performance can be completed, the final decision is made and the concept that best fulfills the design goals is completely detailed and manufactured.

**Requirements are Vital to the Design Process**

Requirements, which are initially developed at the beginning of the design process, affect all remaining phases of the process [4,1]. The requirement development process is iterative, and while iteration increases the likelihood of proper requirements it does not guarantee it. The requirements are instrumental to the entire project and an
object of dependence, but often in design projects, they are not given the amount of focus (time and attention) one generally would give to a dependence of something else, such as blueprint to a house. In the building of a house, an architect first defines all elements of the house in documentation. The needs and desires of the customers having the house built are incorporated into the blueprints. Similarly, in the making of a requirements list, all relevant information that is known needs to be gathered and considered. Before continuing further with the process and building the house or building, the blueprints need to be validated against the actual desires of the future owners. If the owners plan on having six children, then a two bedroom house will probably not suffice. Validation of the blueprints can be easily done because there is only one interested customer. The process becomes more difficult when the customers are not directly identified and their needs and desires can be quite varied. For this reason, requirements validation can often be neglected during the design process.

**Requirement Challenging**

Because requirements have a large impact on the entire design process due to their use in every phase, requirements that are incorrect have just as large of a negative impact. For this reason, it is critical to ensure that requirements are properly defined. The challenging of erroneous requirements helps to clarify the design problems [2]. Further, requirements that are solution dependent and/or overly constrain the design space should be challenged and changed [2]. Pahl and Beitz recommend that the requirements should be continually refined in order to ensure their correctness and validity to the problem at hand [4]. Sometimes, however, requirements may be
established and then not refined correctly. In these situations, a systematic challenging is necessary; however, there currently exists no requirement challenging methodology [2].

**Requirements are Often Incomplete**

All designed products have requirements that must be met in the design process. Some of these requirements are based on factors such as market demands, current market options, regulations, or manufacturability. Although all requirements must be upheld in final production, the most basic requirements and the ones from which many are derived – the “why” something is designed – should have considerable weight in the design process – especially early in the process. Currently, concepts are selected with tools that compare the concepts based on how well they are projected to meet the differing criteria. Because the assumption is made that all compared concepts meet the most basic need, these tools are not designed to give consideration as to how well the concept might meet the basic requirement. With this in mind, there could be value in analyzing how well a concept does the designed functions.

Considering this analysis along with the criteria selection tools adds new information that could change the outcome of the design process. For instance, if there is a concept that has more functionality in this analysis but seems to be lower on the criteria comparison, then it might move further along into detailed design which the criteria comparison tools alone would not have recommended.

One major problem that arises when attempting to compare functionality is the lack of a scale. Proper requirements have an associated quantity to them [4], so when it comes time to evaluate a concept against them, the concept can be measured in terms of
that requirement, and thus given a performance. Functions, on the other hand, are typically viewed on a binary scale – either the function is completed or it is not. While for some functions this might be acceptable, they are not always viewed in this manner by the consumer. This induces a need for a scale of functional performance, but since the requirements are not written in a manner that facilitates a scale, one must be envisioned. One way to scale functionality is to take elements that contribute to the overall functionality that are measurable and apply a weighted function to them. For instance, if one wanted to know the level of functionality an LCD screen has in terms of readability, one could measure the brightness and contrast that the displays can produce. Readability could then be determined by a function of those two measurable performances. The results could then be optimized or used as a comparison tool when choosing from multiple LCD displays.

To elaborate on this idea of functional analysis a little more, an automotive seating design project will be analyzed as an example in this research. The current process of designing a seat begins with requirements from previously successful seating projects including the requirements for loading and adjustability. The adjustment requirements apply more to the functional performance of the seat and will therefore be analyzed. Any new design must have enough fore/aft, vertical, and tilt adjustability to accommodate a large range of body types. However, merely giving motion requirements does not fully approach the function of the seat. It must have a reason to move, or moving would be an entirely useless function. In fact, the seat must provide a comfortable and safe seating position for a wide range of body types. The motion that is
defined by the requirements is simply the mode by which a design accomplishes this necessary function. If a seat is designed that can comfortably and safely seat any person without adjustment, then it would be unnecessary to design adjustment into the seat.

The seating example will be a demonstration of a design project that has requirement documentation with no rationale documentation. This example will be useful in investigating the overarching objective of this research which is to:

I. execute a case study that implements value into the requirement development stage of a design project in order to challenge the established requirements so that II. the merits of value-based requirement challenging can be assessed from the results of the case study and III. recommendations can be made for challenging requirements on future design projects.

These research objectives have been formulated into research questions as shown in Table 1. The research that follows will show whether or not the hypothesis for these research questions hold true.
Table 1: Research Questions and Hypotheses

<table>
<thead>
<tr>
<th>Research Question:</th>
<th>Hypothesis:</th>
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<tbody>
<tr>
<td>Why should requirements that seem incorrect be challenged, and what is needed to challenge them?</td>
<td>As generations of a project are completed and the original problem description (project goal) becomes more fully understood by designers relative to the changing product environment over time and/or the overarching goals change, the potential arises that reused or legacy requirements will need to be change if challenged.</td>
</tr>
<tr>
<td>How does one discern the rationale of requirements?</td>
<td>Rationale can be discerned by attempting to complete the requirement development process in reverse order.</td>
</tr>
<tr>
<td>How can value-based thinking be used in order to challenge/validate requirements?</td>
<td>Value-based thinking can be a clear means through which a requirement is validated or justifiably challenged.</td>
</tr>
</tbody>
</table>
Outline of Thesis

A depiction of the flow and relevant content for each major chapter of the thesis is provided in Figure 2.
CHAPTER TWO: LITERATURE REVIEW

This chapter provides the foundation for the proposed value-based requirement definition and validation method by providing a discussion on relevant literature. The presented research focuses on defining the concepts and providing examples on how they are used. Some of the literature topics have varying definitions across the design community, so an understanding must be reached on what definition the remaining research will be based. Because the research focuses on validating requirements, there is an overview given on requirements and their roles in the design process. Because the proposed process integrates value into the design process, this chapter also describes how value is currently used and methods using value. This chapter also highlights the importance of validation and the impact it can have on the entire design process.

Requirements in Product Design

Requirements are the most essential components to the engineering design process. They are foundational to every project because they define the needs of the stakeholders of the system to be designed and how to fulfill those needs [3]. One of the first phases in the design process is to write requirements that the design must fulfill [4]. The requirements are written as a list, and this list of requirements, along with the initial design goals, is used as a map for the rest of the project.

Literature has shown there are multiple types of requirements [3,7,8]. This research focuses on two main types of requirements. This paper will refer to them as functional and non-functional, whereas the NASA handbook refers to them as functional and interface [7], and Grady refers to them as performance and design constraint,
respectively [8]. Functional requirements are the most commonly visualized and the easiest to derive from project inception because they are rooted in the original design goals. These requirements are written as performance requirements so that the design can later be evaluated and success and failure can be ascribed to the concepts. The level of functional fulfillment needs to be established from the stakeholders in order to objectively assess the quality of concepts. Performance requirements can be either binary or threshold in nature. A binary requirement is either met or not met; by surpassing these requirements the system is not worth more. Most performance requirements are written as thresholds, meaning that at a minimum (or maximum) the system must meet the requirement and anything exceeding the threshold adds value to the system.

The second type of requirement is the non-functional requirement. These requirements are not based on the intended function of the system, but are derived from external sources. The functional needs of the system – what it must do – constitute most of a requirement list, but there are many external factors that must be considered during the design process. Examples of such requirements are: size constraints which depend on where or how the system will be used or safety requirements which are often set forth by government legislation. These requirements are binary because exceeding them would not add value to the overall system. An example of a binary non-functional requirement is the requirements for vehicle crash loading – these requirements are set up in a worst case scenario, so having a car that can handle an even greater crash does not add value to the system as no one will experience a crash in that manner.
Formulation of Requirements

Requirements are a quantifiable set of demands for a system that represent what that system needs. The first step in establishing the requirements is gathering of information. Figure 3 shows several different areas of consideration that influence the requirement list.

Pahl and Beitz suggest one use checklists and ask questions of the stakeholders such as:

- What are the objectives?
• What properties must it have?

• What properties must it not have?

These questions are a necessary part of the process of transforming the intended consumer’s expectations of the product into a list of statements that the product must be able to complete. It is a process that starts with the beginning of a project, but continues to take place during the entire design process [7]. As new information is realized, the requirements are often adapted to reflect the new knowledge. One of the first steps in the design process is to write requirements that the design must fulfill [4]. However, although these requirements are introduced at the early stage, they are not the same throughout the process. They can and do change based on the decisions made and properties of different concepts [4]. New requirements are often added in response to the concepts that are being assessed. These new requirements can then be used to choose between different concepts. Because the concepts were not envisioned from the start, these additional or altered requirements could not be originally foreseen. The problem that can arise with solution specific requirements is when these requirements are used for redesign of an existing product. Often because requirements already exist from a previous iteration of a project, they are used in the beginning of a new project that is attempting to accomplish the same function(s). By starting with requirements that have already been developed one is assuming that the requirements perfectly represent the functions.
Use of Requirements

Requirements are written in order to give quantifiable assessment of the intended design function(s). So the most important use of requirements is in verifying that the designs meet the needs of the design. This happens on several different levels. First, the requirements are used to filter through designs just after the conceptual design phase. The binary non-functional requirements are most effective in this because the design is either acceptable or unacceptable. This same type of decision making process is used by everyone when deciding between multiple options. An example is deciding on where one wants to eat dinner. Requirements might be cost, type of food, and travel distance. One might start by searching on the internet for restaurants within a certain area; this completely eliminates restaurants that are outside of the preferred travel distance. Next one might not want Oriental or Mexican food, so those restaurants are passed over. What is left is a list of restaurants that can be sorted by relative menu price and a choice made. Designers do the same thing with the binary requirements, by sorting through all of the possible designs. It is also important to note that while a coupon for a restaurant might make a once too expensive restaurant a good choice, a design change to a design might make a concept that was cast out within the list of viable options.

The next set of requirements is used to differentiate concepts. The performance requirements that can be exceeded are used to compare each concept. There are many decision tools that can be used to score each concept on their relative ability to perform each requirement. These scores then allow for the designer to rank each of the concepts and eliminate the ones that obviously do not perform as well as the top few.
After detailed design has been completed, the chosen concept must be compared to the requirements. This process of comparing to the design requirements is necessary in order to verify that it can and will be able to fulfill what it was designed to fulfill [3,9]. The verification process uses testing procedures to represent the situations in which the product will be used to ensure the chosen product design can maintain the level of performance required.

**Design Rationale and Design Intent**

Design rationale is the dictated reason for the presence of a requirement [3], and it should be documented in order to provide clarity and understanding of the requirements or other elements about which it is referring [7]. However, frequently during design, the reasons that would define the design rationale remain only in the minds of the engineers [3]. These reasons that are not explicitly dictated during the design process are known as design intent, as it signifies why a design is as it is and it can be viewed as decision making criteria for a designer [10]. Design rationale may include not only the reasoning for the requirement and how it is structured, but it can also include the justification for it, alternatives considered, and argumentation leading to the decision [11].

Rational decisions are based upon information to which the decision maker has access and the values they place on certain pieces of information [12]. By assuming that every decision is rational, relative to the amount of information that is known by the decision maker, and not completely random, every decision must have an intent that supports it. Therefore, every design decision has design intent, whether or not that intent has been expressed in terms of a documented rationale or not.
Rationale is formulated in different ways; for some design projects documentation is established that relates the rationale to the requirements while others use programs to analyze the rationales in search of patterns that might suggest needed change or for errors and inconsistencies [13]. The research of documentation of design rationale covers areas such as general notation method called issue-based information systems (IBIS) [14] and active design documentation (ADD) that is more intentional in documenting the rationale of design decisions [15]. The rationale documentation is concerned with documenting the information relevant to the rational decision making process and less concerned with the values and importance weighting placed on some information that is also used. Rationale documentation is therefore useful for revising, maintaining, documenting, evaluating, and learning from the design, and when it is present, it is useful in determining the original intent of the designer [13].

Design rationale and its documentation have been widely researched, but it is still not commonly exercised [14]. It is often viewed simply as documentation and seemingly more important tasks often push it to the side [14]. Another reason for the lack of rationale documentation during the design process is due to uncertainty. If the designer is unsure what direction the process will go, he or she might not want to record the rationale of the current progress because a change would require an update to the documented rationale [14]. While design intent is necessary for making rational and good decisions during the design process, design rationale is not necessary to complete the design process. Design intent is useful moving forward through the decision making processes, and design rationale is useful for validating the intent and forming a good foundation for
redesign of similar products. Without an established rationale, the design intent must be either assumed to be correct or established ex post facto when requirements are being validated or used in similar projects.

**Quality Function Deployment: A tool to relate user needs to engineering requirements**

Quality function deployment (QFD), particularly the House of Quality (HoQ), is a system with the directive to increase product desirability and market share by better satisfying the customer needs [16]. Tools of the system are designed to make customer needs more visible and link them to the design project [16]. Quality, in QFD, is the relationship between perceived performance and actual performance. High quality products meet the expectations and needs of the customer.

The main focus of QFD is on the customer needs, or customer requirements [17]. These requirements must be related back to the design requirements or there is no guarantee that the manufactured product will illicit any customer desirer. Traditionally, the customer needs are researched through field surveys, focus groups, and questionnaires, but the “quality dimension development approach” is another method to understanding customer need [17]. The quality dimension development approach relies on experts from various parts of a company to develop an understanding of what the most important elements and attributes of the customer needs are. It is understood that the most important attributes could even be sub-elements to the overall depicted need [17].

Once the needs have been established, the design requirements must be formulated from them. This is most often completed with a tool call the House of
Quality (HOQ) [17]. The HOQ is a table organized with customer needs along the rows and design requirements along the columns as shown in Table 2.

Table 2: Sample template for HOQ

<table>
<thead>
<tr>
<th>Customer Importance</th>
<th>Design Requirement 1</th>
<th>Design Requirement 2</th>
<th>Design Requirement 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer Need 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Customer Need 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Customer Need 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The design requirements populating the table are chosen in response to the customer needs. The design requirements that relate to and can fulfill the customer needs are chosen to populate the table and denoted “Design Requirement X”. The table relates the previously identified customer needs to design requirements by populating the table with symbols representing the strength of the relationship between the needs and design requirements. The customer needs are also given a rating in terms of their importance to the customer. This weighting factor is similar to the weighting factor that is used in some concept selection tools. Scales such as 1-10 or 3, 6, 9 can be used. Translating this scale to the design requirements can be important in understanding how to prioritize the requirements during decisions similarly to how weighted decision matrices compare
requirements. The relationship between the needs and the design requirements is then used in a correlation matrix to determine the impact the design requirements have on one another. The correlation matrix is in the shape of a triangle on top of the table which gives the table a house-like appearance and the genesis for the name [17].

**Validation and Verification**

Requirements documents are a collection of all engineering requirements and related documentation for a particular design project or task. They are foundational to the design process, so they are created at the beginning of the project and may be updated or refined throughout the project. They represent many different sources of information that have an impact on how the product will be used. However, this information is not always clear at the beginning of the design process, so they are often altered and amended as the project becomes clearer to the designers. Because they are a compilation of information that is often not initially clear and will ultimately affect the decisions and creative process of design, designers need to put great care in being certain that they are correct. This is the process of validation and verification.

*Definitions of Validation and Verification*

Validation and verification are two very similar words, and they are both very frequently used in reference to elements within the design process. To some designers, the terms are interchangeable and are used to describe the process of confirming that something meets expectations. The terms are used throughout the design process, but are most commonly used in reference to requirements and the testing of the detailed final
concept. One such approach defines validation as the process of comparing the documented requirements against the user needs, and verification as comparing the end product against the requirements [3]. The US Department of Defense [18] defines validation for software development as evaluating the end product against the specified requirements and verification as confirming that the outputs of a system match what should be output given known inputs. Both of these instances of validation and verification – whether they are for requirements, end products, or both – are comparing one set of data against a pre-determined correct set of data.

Another approach to defining validation and verification is to determine what question one is trying to answer. This notion says that techniques of validation are attempting to answer the question, “Are we building the right thing?” and inspects the requirements to determine if they were properly written and technologically feasible. Whereas, verification techniques ask, “Are we building it right?” [19]. The verification process is then directed at the end product and whether or not the product is capable of fulfilling the aforementioned validated requirements [20]. These definitions do offer a bit of differentiability between the terms, but they also differ in what is to be validated and verified. There is definition of requirement validation and product verification, but there is no discussion on requirement verification or product validation.

Grady considers the terms non-interchangeable [21]. Validation is a forward looking process. In the act of requirement validation, one is assessing the degree of difficulty associated with fulfilling each requirement. Validation is a process of reducing the risk associated of success caused by the requirements. During the validation process,
the designer can remove unnecessary requirements that are difficult to fulfill while altering other requirements to increase the chance of success. The verification process is one of comparing an object of interest to preset standards with the outcome representing the level of standard fulfillment the object shows. In design, the verification process occurs once a concept has been detailed. The concept is then compared to the original requirements [21].

In an effort to create uniformity within the design community the Electronic Industries Alliance created a standard that discusses the definitions of validation and verification. They view the validation process for requirements, and it is a way to ensure necessity and sufficiency within the requirements for aiding in the design of appropriate solutions [22]. Verification is a process that is largely used for ensuring that the end product is consistent and meets all of the source requirements [22].

NASA differentiates the process of verifying and validating a product by the intent of the process. The intent of verification is to determine how well a product performs relative to the approved set of requirements [7]. The verification process serves only to ensure that the contractual agreements of the requirement list are met. It does not serve to determine how well the product works – that is validation. The intent of the validation process is to compare the product performance to the expectations of the consumer/customer/stakeholder [7]. Stakeholder needs represent only a portion of the overall requirement needs, so validation of an end product would be a subset of the overall verification process. Because a majority of requirements not defined by stakeholder need are binary, verification processes can be different than validation. The
validation process would focus primarily on how well an end product meets the needs and a verification process would focus on whether or not the requirements are met.

A more general approach to the definition applies validation and verification not only to singular parts of the design process (e.g. validation to requirements and verification to end product), but also to any relevant part of the process. In this approach, verification addresses whether or not an object of interest (e.g. requirement, component, end product) meets its respective requirements. Validation becomes the process of making sure that the object of interest conforms to the needs and expectations of the stakeholder [23]. These definitions are very similar to those defined by NASA, but are more widely applicable to areas outside of end product testing.

Due to the variance in definitions throughout the engineering design community for these terms, a more general set of definitions, is necessary. For the purposes of consistency throughout the remainder of this document, validation and verification will be defined as follows:

- **Validation** – the process in engineering design of comparing an object of interest back to the original stakeholder needs, desires, and wishes.
- **Verification** – the process in engineering design of comparing an object of interest back to the original governing standards by which its performance may be deemed acceptable.

Because the work on the following pages of this paper deals with requirements, validation will be in reference to the validation of requirements, and mean the process of
ensuring that the requirements reflect the needs, desires, and wishes of the stakeholder(s).

This concept of validation can be further described with an example of an ink pen with a requirements list for the requesting that it be designed with screw fits. In order to analyze this requirement, one must relate the pen back to its intended user by attempting to ask how it would be used. If the pen is going to be used until lost or out of ink and then disposed of, then screw fit that enables easy assembly and disassembly would be unnecessary. If the pen was to be used until out of ink and then refilled with new ink, then screw fits would be useful because the user would expect to disassemble and reassemble the pen. In the case of a disposable pen, screw fits should only be used if there is an advantage over another assembly type allowing for a cost savings in some area such as manufacturing cost.

Need for Validation

Requirement validation is addressed once requirements have been established. Making an agreed upon list of requirements is one challenge, but it is not the final challenge. Often, these requirements originate from previous projects or are good estimates of what the system should accomplish. There is frequently assumption in the requirement process due to ambiguous definitions or impossible conditions [9]. These assumptions can manifest themselves in interpretations of customer desires or even quantified representations of “acceptable” levels of performance. Assumptions are made by gathering the available knowledge and applying in the most likely way, and the level of uncertainty plays a large role in how accurate the assumption can be. Because requirements shape the design process from the idea generation phase through the final
product verification phase, it is essential to have requirements that are correctly structured and evaluated. Approximations are also made within the requirement development process. Every requirement needs to be quantitatively defined [4], but it is often difficult to do so at an early stage. The designers, in an effort to complete the first iteration of the requirements, may approximate based on past experience or knowledge what a good value for the given requirement should be. Unfortunately, that approximation (if not documented) can often be taken with the same level of faith in the remainder of the design process as the rest of the requirements [21].

Requirements are written as limitations in order to constrain the design, or solution space. This constraining saves designers the wasted time of exploring any infeasible options [21]. Quantified requirements provide clear borders to that design space, and if written too loosely, requirements do not adequately represent the tasks at hand causing engineers to spend too much time (and money) exploring unnecessary areas of the design space. However, if requirements are written too strictly, then the optimal concept might be needlessly removed from the possible solutions. Figure 4 shows a design space that has an improperly defined requirement R and the correct requirement R'.

24
The solid, blue area represents the area of the design space that would be explored and possibly introduce infeasible options into the solution list.

Validation of requirements occurs by ensuring that the established requirements address all issues presented by the original viewpoint of the system. It also ensures that the requirements do not add any new tasks to the system that were not originally intended [23]. Requirement validation is a process that relates the requirements back to the stakeholder interests. If done properly, validation creates clarity for uncertain requirements and rationale for the unjustified requirements. By reducing uncertainty, risk is lessened for requirements that may be unnecessarily restricting the design space, and it also reduces the need for conservative requirements that may introduce more expense down further down the process. An increased accuracy in requirements leads to more appropriately designed products.
Validation Methods

Validation of requirements occurs by ensuring that the established requirements address all issues presented by the original viewpoint of the system. It also ensures that the requirements do not add any new tasks to the system that were not originally intended [23]. Due to the significant role that requirements fulfill in the design process and the impact that incorrect requirements can have, techniques should be used in a way to systematically validate them. Systematic processes can be clearly explained and repeated; therefore, they greatly reduce the level of assumption and ambiguity in the system. Pahl and Beitz recommend the use of checklists during the requirement development stage. These checklists are useful in organizing and putting emphasis on important things. Questions such as, “What objectives must the solution satisfy” and “What properties must it have” are good for gathering the initial requirements and ensuring that most of the requirements are of the proper format. Pahl and Beitz do not suggest a formal method for validating the requirements once they are established. There is also no systematic way of determining if the quantified values associated with the requirements are the correct ones.

Some validation methods seek to reduce the potential impact that poor or incorrect requirements may have on the final product. These validation methods are designed to mitigate risk. Requirements that are assessed as having the most potential to be incorrect and the requirements that may have the biggest impact on the system design if incorrect are the first to be validated [8].
The first step in determining the necessary requirements for a given system is also part of the first step in ensuring that the requirements are valid: gathering information. This gathering of information can be done through development evaluation testing (DET) [8]. This testing is an organized process of stimulation and measuring. The test attempts to stimulate a response by using a similar product or design concept to determine the response by the user or environment and correlate that response to a set of requirements.

**Value in Design**

The value of an entity represents its “relative worth, utility, or importance” [24]. It is usually described by a scale, such as a monetary unit, that allows for an easy comparison between the values of different entities. The evaluation of value in this chapter and this research is not in a monetary sense. Although an increase in usefulness often correlates to an increase in monetary value, this is not always true. Different scales can be used to represent relative worth, and the change in value across those scales represents the impact different elements have on the overall value of the product. Value scales used in different areas in the design process are explored in the following review of literature.

**Value of Requirements**

Requirements are numerical representations of customer desires, but the individual number quantified in a requirement does not necessarily depict the customer needs represented by that requirement. Using different verbiage can aid in the expression
of the intent of the requirement, but even that may fail to clearly express the needs. The following requirement list will be used as an illustration:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>The product must weigh no more than 5 lbs.</td>
</tr>
<tr>
<td>R2</td>
<td>The product must cost no more than 100 USD to produce.</td>
</tr>
<tr>
<td>R3</td>
<td>The product must meet safety standards including no deflection greater than 0.25 in under a 200 lb load.</td>
</tr>
</tbody>
</table>

In each of these requirements, the language and format is very similar, and they are all properly written requirements. Each one is written as something that “must” be accomplished as most design methodologies teach [8]. They are also written with quantified numbers [4]. Even though they are written properly there is still information not present that, if known, would be helpful to a designer during the process.

The verbiage in each of these requirements implies a binary level of satisfaction. If one were to graph level of satisfaction, or value, of R1 against the acceptable and unacceptable ranges of product performance that the requirements depict, it would look as shown in Figure 5 with the acceptable performance to the left of the threshold and the unacceptable region to the right.
In Figure 5, every design that performs better than the threshold is equally valuable and every design that exceeds the threshold is equally invaluable. As R3 explains, its quantification is based on safety regulations which must be met in order to be produced, but each design that exceeds the safety regulation is perceived as equally “safe.” In this situation, Figure 5 would be an appropriate assessment of value. On the other hand while R1 implies that anything up to five pounds is an acceptable level of performance and everything that exceeds five pounds is unacceptable, a binary threshold might not actually represent the desire of the users. As is often the case with product weight, the best design is one that weighs the least. For example: in automotive design, by decreasing the weight of a part, the overall vehicle performance (e.g. fuel economy, acceleration) typically increases. In this situation, the threshold of five pounds may be the weight of the previous generation and an improvement may be desired, if possible. In this the case, a four pound product with no reduction in other performance attributes is
more valuable than a five pound design, so the value of the weight might look more like Figure 6.

![Figure 6: Value vs. weight based on satisfaction alone](image)

One method used to dictate desires such as a preferred lower weight than the requirement threshold demands is through the use of a secondary list of performance metrics. Pahl and Beitz differentiate types of requirements into demands and wishes [4]. These demands are reflected in Table 3, but the wishes, while considered, are not given any formal organizational structure. Wishes are parameters that are taken into account when differentiating between two designs that are otherwise undifferentiable per the demands.

**Table 4: Hypothetical wish list**

<table>
<thead>
<tr>
<th>W1</th>
<th>The product should weigh as little as possible.</th>
</tr>
</thead>
<tbody>
<tr>
<td>W2</td>
<td>The product should cost as little as possible.</td>
</tr>
<tr>
<td>W3</td>
<td>The product is made from one material.</td>
</tr>
</tbody>
</table>
The wishes begin to show the differences that can be seen between Figure 5 and Figure 6. While statements such as W1 from Table 4 begin to differentiate more valuable performance from less valuable performance, the wishes do not explain the amount of difference in value or the importance placed upon the wish.

*Value in Concept Selection Tools*

The idea generation phase of the design process is one of complete inclusion. No ideas are given passing or failing grades in an attempt to completely explore all of the possibilities within the design space. This level of inclusion is very useful in the beginning of the design process, but once concepts have been generated and a few iterations of detailing have been completed, the concepts can then be compared against one another in an attempt to focus time and effort on fewer concepts for the remainder of the design process [4]. All concepts are evaluated as to whether or not they can meet the requirements and only those that do meet the requirements will be further evaluated. Once the list of concepts has been narrowed down to those that are permissible, the evaluation can take place.

There are many different systematic selection tools used by the design community, but they all have several basic principles. Each one employs the use of a table with the requirements listed in the rows and the concepts being evaluated listed in the columns or vice versa. Each of the concepts is then evaluated for their ability to perform relative to the requirements. The evaluation process of the tools differentiates them the most. Some of the tools employ a symbolic evaluation such as +, - , or ? to evaluate good, bad, or insufficient information [4]. This would be a binary representation
as it is either good or bad – and there is no variance. Other binary scales evaluate numerically with 0, 1, and 2 or -1, 0, and 1. These scales refer to a baseline to make their evaluations. This baseline could be an existing design if the project is attempting to design a new iteration [25]. The concepts can also use multiple baselines by completing the evaluation with each concept as a baseline and then summarizing all of the results. Other evaluation processes do not use a baseline at all and instead attempt to evaluate how well the design may or may not fulfill the requirement [4]. These evaluation tools use a scale that can provide more information than a comparison scale. Some designers use a detailed scale from one to ten, while others use more discrete scales such as 1, 3, 9 or 1, 4, 8. Table 5 shows the qualitative meanings behind the quantitative values for a couple of the scales.

<table>
<thead>
<tr>
<th>Pts.</th>
<th>Use-value analysis Meaning</th>
<th>Value Scale</th>
<th>Guideline VDI 2225 Pts.</th>
<th>Guideline VDI 2225 Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>absolutely useless solution</td>
<td>0</td>
<td>unsatisfactory</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>very inadequate solution</td>
<td>1</td>
<td>just tolerable</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>weak solution</td>
<td>2</td>
<td>adequate</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>tolerable solution</td>
<td>3</td>
<td>good</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>adequate solution</td>
<td>4</td>
<td>very good (ideal)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>satisfactory solution</td>
<td>5</td>
<td>very good</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>good solution with few drawbacks</td>
<td>6</td>
<td>ideal solution</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>good solution</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>very good solution</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>solution exceeding the requirement</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>ideal solution</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The three value scales such as 1-3-9 represent 1 – weak, 2 – medium, and 3 – strong fulfillment of the given requirements [26].

An advantage that these three number scales provide over a detailed ten number scale is that choosing from three options is a lot easier than choosing from ten. When the details of the design are not fully realized, it becomes difficult to evaluate in great detail. Most designers can agree on whether or not a design will be good at fulfilling a specific task and assign it a nine from the 1-3-9 scale, but they may not be sure if they should give it an eight, nine or ten on the less discretized one to ten scale. A second advantage that the more discretized scales have is the ability to create greater differentiable totals from concept to concept. This can begin to be shown with Table 6.

<table>
<thead>
<tr>
<th>Table 6: Concept Selection Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>a) Using a 1-3-9 scale</strong></td>
</tr>
<tr>
<td>R1</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>C1</td>
</tr>
<tr>
<td>C2</td>
</tr>
<tr>
<td>C3</td>
</tr>
</tbody>
</table>

In Table 6a, the second concept (C2) is much better than the other two concepts at fulfilling requirement two (R2), so the total score shows that concept two is a heavy favorite. The rank order of the concepts is the same for the 0-1-2 scale shown in Table 6b as it was in Table 6a, however, the concepts are very closely scored and differentiation between concepts is not as clear.

There are many different scales that are frequently used to quantify the qualitative assessment of requirement fulfillment, but the differences between them are more than just semantic. These scales represent the relative value that is added to the overall system.
by fulfilling a requirement. All three of the requirements in Table 6a carry the same weight, but the level of fulfillment of the concepts does have differing impacts. C2 is three times more valuable than C1 in fulfilling R2. This scale shows that the value of an overall concept increases rapidly as fulfillment increases. Conversely, Table 6b shows a much smaller increase in value to the system due to the fulfillment of R2 by C1 and C2. Figure 7 shows the differences in the perceived value that a few different scales imply.

![Figure 7: Representation of value scales](image)

Deciding when to use which scale usually relies on designer preference, but it should require an understanding of how the requirement being assessed will impact the overall value of the system. As shown in the concept selection process, requirements that must be met, but add no value once they are exceeded are used in the initial step of concept selection to cull out the poor designs. The degree of fulfillment (or over-fulfillment) of the remaining requirements is the biggest factor in differentiating between concepts;
however, it is rare for a design team to assess how the fulfillment of the requirements actually relates to the value of the design. In Figure 8, Pahl and Beitz give some generic value functions that can be used to understand the different ways that the fulfillment of a function can affect the value of the product.

![Figure 8: Various value functions for concept selection [4]](image)

They also discuss the usefulness of using value functions for the decision making process, but contend that the required effort is too high in most situations to warrant the use.

*Utility Theory*

Value is often difficult to conceptualize because it is relative to the situation it is referring due to its lack of units. Economists prefer to view the value of products or decisions with utility in order to make the comparisons more concrete [12]. Utility is measured in a fictitious unit of utiles which aids in its reduction of abstraction over value.
Utility theory is the research emphasis that explores the needs and desires of customers in order to understand how different customers prioritize their needs during decision making. The goal of this research area is to use mathematical rigor to express individuals’ preferences used to make decisions in different situations, including under risk, to predict what decisions might be made in the future. The researchers are then able to apply that same method of prioritization to the design process. By emphasizing the consumer needs in the design process, one can maximize the overall usefulness of the product and increase product impact which ultimately increases sales and profits.

*Definition of Value-Driven Design*

Most non-functional requirements are binary and non-negotiable. This means that if they are not met, then the design is a failure and is either discarded or redesigned. The remaining requirements (mostly functional requirements) are more flexible [3]. This means that it might be possible to partially meet these requirements and still create a product that has value to some customers or a reduced value to all customers. This sacrifice might be worth some trade-off in, for instance, production cost. There are two ways to attempt to express this. The first is through composing the requirements with built-in ranges or with terminology such as target value. These lexical changes can better create an emphasis on what is and is not acceptable from a customer value perspective. The second approach is through a value model. A value model outputs the relative value of the product or system to a consumer by correlating some of the design goals to one other through a mathematical function [3]. Value driven principles apply optimization techniques to the entire design process instead of just the detailed design phase [27].
Instead of requirements being merely binary in nature – acceptable or unacceptable – assigning a value to the performance of the product in relation to the requirements allows the design to possibly perform better overall. The goal of value-driven design is to focus choices and efforts on maximizing the overall system value and not merely on meeting a list of performance requirements [28].

Use of Value-Driven Design

Value-driven design relates two or more functions to one another through the use of a value function. A value function is a numerical model that represents the desires and wishes of the end-user [28]. The benefit of a value model is that two seemingly unrelated goals can be considered simultaneously through the lens of a value model. Value models are generated through data collected relevant to the design goals. This data can be calculated through surveys of potential users or from experiment results. There are also tools such as Quality Function Deployment (QFD) that aid in the understanding of customer needs [28].
Summary of Gaps

A high level perspective of the literature discussed in this chapter is shown in Table 7.

Table 7: Literature Review Overview

<table>
<thead>
<tr>
<th>Requirements List</th>
<th>● List of design goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Intent</td>
<td>● The “why” behind the goals</td>
</tr>
<tr>
<td></td>
<td>● Proper requirements’ intents are based on needs of customer</td>
</tr>
<tr>
<td>Design Rationale</td>
<td>● Documented design intent</td>
</tr>
<tr>
<td>QFD</td>
<td>● A methodology that attempts to form requirements from user needs</td>
</tr>
<tr>
<td></td>
<td>● It documents rationale during requirement formation process</td>
</tr>
<tr>
<td>Requirement Validation</td>
<td>● Process relating requirements back to stakeholder interests</td>
</tr>
<tr>
<td></td>
<td>● Establishes rationale</td>
</tr>
<tr>
<td>Value/Utility</td>
<td>● Mathematical functions that depict user desire relative to change in performance</td>
</tr>
</tbody>
</table>

From the literature, it can be shown that processes for developing and incrementally improving requirements are a well-documented part of the design process [1,4,5,6]. There are many different nuances to the process, but the basic procedure is generally the same. Requirements need to generally answer the questions, “What should the design accomplish?” and, “How should it be accomplished?” These questions are answered rather definitively when written down in a list of demands, but that does not change the often subjective method in which the questions are answered.
Requirements lists are considered binding contracts, and each item listed must be fulfilled; however, this certainly does not mean that once a list is formulated it should be considered inerrant and complete. Requirements are added, removed, and altered as new information comes to light. Because most literature does define the requirements definition process as iterative, most designers understand that when a requirement is flawed, a change is needed. However, most designers do not also take the opportunity to make sure that the requirements that are not obviously hindering the design process are, in fact, proper. There is also a breakdown in the requirement iteration process when a requirement that does not seem correct does not have a strong enough case for why the requirement is incorrect. This is due to the lack of systematic validation processes within the design methodology literature.

Researchers depict a clear picture for the creation of requirements in literature and establish best practices for the ways that requirements should be formulated, but one major step is not often formalized. During the requirement development process, designers should often question the motivation behind decisions [4], but assumed steps, such as this one, can be easily forgotten or neglected. This incorporated step attempts to understand the design intent for requirement decisions and evaluate them as the requirements are formed. By formulating a documentation of the design intent, or design rationale, as a distinct step in the requirement development process, the step becomes more concrete and less of an assumption. Design rationale is frequently not included in the design requirements documentation process. Its lack of inclusion is often due to the seeming lack of necessity and therefore the documentation is viewed as extra work. This
information can be vital for designers desiring a change in the requirements as they currently exist and for future generations of a design project.

Some tools, such as QFD’s HOQ, exist to form requirements based on the user desires and needs. These tools form requirements and rationale simultaneously, but requirements that are formulated by other means are subject to validation processes. These processes are used to formulate the design rationale for existing requirements and ensure that the rationale parallels the user needs and wishes. The steps focusing on design rationale increase the emphasis on the user needs over simply the design requirements.

By considering the functional needs and not simply the requirements as foundational, the designer is able to treat the requirements as guidelines. These guidelines can then be flexible and optimizable in order to maximize the product’s overall functional value. This step can help to remove the subjectivity of the question, by attempting to answer the question, “Are we sure?” The only way to answer a question of certainty without basing the answer in ignorance is by justifying the answer. Validation methods are the justification to uncertain requirements. However, validation methods are often difficult and just as subjective as the requirements themselves. A validation method that is based on the needs and values of the end user, which is also the source of the original problem, will help to remove uncertainty from both the requirements and the validation process. This certainty will increase confidence in the requirements and thus the final product. It will also ensure that the concept being designed, and ultimately produced, is the correct product.
Researchers at the Value-Driven Design Institute (VDDI) would argue that value functions in design are an improvement over requirements. Requirements do represent the level of fulfillment necessary for a design, but they are often inadequate at representing tradeoffs. They are inadequate at representing the level performance that is acceptable given a certain increase in another performance metric. Each requirement is written in such a way as to imply that it could be evaluated independently of all other requirements. However, it is more appropriate to attempt to evaluate all performance metrics together as the designed product performs many different functions in unison.

This research serves to help fill the void in the iterative requirements process by introducing a validation process with a foundation in value-based thinking and modeling in a case study. The goal is to provide a rationale that is not merely a documentation of design intent, but is a mathematical justification for the requirements. This mathematical rationale for the requirements can be used to correctly establish requirements by means other than mere group consensus [6] or estimation. It can also be used to validate requirements that are pre-determined and challenge those requirements that seem to be incorrect. Table 8 shows these research goals and how they are currently fulfilled by different means in the literature as well as how techniques used in the case study will fill the remaining gaps.
Table 8: Requirements of research and their fulfillment by literature

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Fulfilled</th>
<th>Partially</th>
<th>Unmet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement Driven</td>
<td>QFD</td>
<td>Decision Based</td>
<td>Value Driven</td>
</tr>
<tr>
<td>Clearly constrains acceptable design space</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manages decision making tradeoffs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Provides means to develop requirements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Provides means to validate requirements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Provides method for recording rationale</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER THREE: DEFINING THE CASE STUDY

The scientific method was established to form a systematic approach to inquisition. The systematic approach is necessary to increase repeatability. Case study research differs from the normal scientific method in that it is based upon observation of real scenarios and not just orchestrated scenarios [29]. Case studies also do not have a controlled alternate condition to which a comparison can be made [29]. The outcomes are a product of the natural flow of the observed events. The systematic process recommended for case studies to follow begins with the case study planning. The planning steps are:

1. Formulate Research Questions,
2. Formulate Case Study Propositions,
3. Define Units of Analysis,
4. Create Logical Reasoning that Connects Data Collected to Propositions, and
5. Formulate Interpretation Criteria [29].

Once the planning steps are complete, the case can be completed, data from the case can be collected, and interpretation of the data and outcomes can be studied.

1. **Formulate Research Questions**

   These questions most often answer the questions, “how,” and “why,” and the way they are formed is critical to the direction of the case study [29]. In the case study performed in this research, the questions are:
• Question 1: Why should requirements that seem incorrect be challenged, and what is needed to challenge them?

• Question 2: How does one discern the rationale of requirements?

• Question 3: How can value-based thinking be used in order to challenge/validate requirements?

2. Formulate Case Study Propositions

Propositions are based upon the research questions formulated for the case study and are useful in guiding the direction of the case study. They help the researcher to properly bound the information gathered necessary to answer the research questions and helps to properly set up the study. The propositions for this case study are:

• Proposition 1: As generations of a project are completed and the original problem description (project goal) becomes more fully understood by designers relative to the changing product environment over time and/or the overarching goals change, the potential arises that reused or legacy requirements will need to be change if challenged.

• Proposition 2: Rationale can be discerned by attempting to complete the requirement development process in reverse order.

• Proposition 3: Value-based thinking can be a clear means through which a requirement is validated or justifiably challenged.
3. Define Units of Analysis

In order to complete a successful case study, the individual details of the case must be evaluated to ensure it best suits the propositions [29]. The individual, group, organization, event, or process that is studied must closely tie to the larger category that the propositions and research questions are attempting to address [29]. These individual elements that will be analyzed in the case study presented in this research are:

- requirements,
- requirement rationale, and
- changes to requirements.

After the case has been completed, these are the elements that will be described quantitatively and/or qualitatively to provide results from which to draw conclusions.

4. Create Logical Reasoning that Connects Data Collected to Propositions

The third step is important for pinpointing a strategy for the case study, and this strategy is necessary to ensure the data collected is relevant to the propositions [29]. The outcomes of this step are potential observations that, if observed, either validate or invalidate the case study propositions. For this case study the logical reasonings corresponding to the propositions are:

- Reasoning 1: If a multi-generational design project continually reuses requirements across generations, some requirements will be subject to change if challenged.
• Reasoning 2: If during the course of the case, a requirement is given documented justification for their existence, then rationale has been established.

• Reasoning 3: If value functions form the justification by which a requirement is challenged or validated, then value-based thinking is a means to challenge.

5. Formulate Interpretation Criteria

This final step necessary in setting up the case study is critical to forming a strategy that is able to use the collected data from the case study to answer the research questions.

• Criteria 1: Show a design group that reuses requirements with each generation and observe if any requirements need to be changed.

• Criteria 2: Show the documentation of a requirement rationale.

• Criteria 3: Show a requirement that is refined by a value-based approach.

Choosing a Case Study

Now that the case study strategy has been defined, the case to be studied can be chosen. This case must be capable of observing the units of analysis, and if the chosen case cannot do that, then it will not be adequate for drawing conclusions on the propositions. The chosen case followed the requirement challenging process for the requirements constraining the design of an automotive seat. The company funding the project has designed many generations of seats and the requirements experience little change over time. The following chapter will introduce and complete the case that is chosen for this study.
CHAPTER FOUR: CASE STUDY OF REQUIREMENT CHALLENGING IN AN AUTOMOTIVE SEATING DESIGN PROBLEM

The design and development process for a first tier supplier of automotive interiors is used in this chapter as a case representing the attempt to challenge the established set of requirements and demonstrate the potential usefulness of value-based thinking into the requirement challenging process. Furthermore, this case study serves as the foundation into the insight for a process to systematically challenge engineering requirements.

Automotive seat design and manufacture for many automotive original equipment manufacturers (OEM) is often completed by first tier suppliers. The first tier suppliers work closely with the OEM to establish the high level objectives of the project. However, the first tier suppliers are often given a detailed requirements document by the OEM, and these requirements can be in the form of either completely detailed manufacturing specifications requiring little or no design work or basic functional needs and the supplier must design the entire product. As is the case for the study presented in this thesis, of Johnson Controls, Inc. (JCI), the requirements are set forth by the automotive OEM which causes design directives to be very focused at an early stage. While the OEM is the purchaser of the seat and immediate customer, JCI is directly developing a product for the OEM and indirectly meeting the needs of the end user – the occupant. New seat projects begin when automotive manufacturers request a new design. The request could be for new features or performance characteristics for the seat in a car
already in production or for a seat design for a car that is not yet produced. All of these factors play a role in the manner in which the seat manufacturer progresses through the design process and which elements make an impact on the requirements list. In this particular project, the goal set forth by the OEM is to:

Design a seat that has a reduced mass and cost while still covering a travel window consisting of 240 mm [± 2.5 mm] of horizontal adjustment and 50 mm [+0/-5mm] of vertical adjustment.

The travel window referred to in the requirements is an area that represents all possible user hip locations. The hip point (or h-point) is a three dimensional reference point that represents the location of the user’s hip joint [30]. The shape of the window is shown in reference to a seat pan and seat back position in Figure 9.
The figure depicts the seat in the lowest and most rearward position. The X shown in the figure denotes the heel point location which is held constant in all evaluations. The circle represents the h-point associated with the shown seating configuration, and the remaining positions in the window would require adjustments in seat position that are shown by the arrows.

**Planning and Task Clarification of Previous Generations**

The first generation of adjustable seat design began when a need was identified by an automotive OEM to design a seat that accommodated a population of people that represent different body types and sizes. The basic goals and needs were addressed in the creation of a requirement list and the general design process was completed. The first
generation of design resulted in a solution that met the original design goals and a specifications list that defined characteristics and details about building and testing the first generation solution. This process is shown in Figure 10 along with subsequent generations of the design process.

Figure 10: Flow chart showing information tracing through design generation

The subsequent generations are oft built upon the success of the previously designed seating solutions. The requirements were simply carried over from generation to generation, and the solution specifications of one generation were applied to the basic requirements of the next. While all proper requirements are rooted in the customer needs, the requirements for later generations of seats are distant descendants. The effect of this process is a set of requirements that are not closely based on the original problem definition causing rationale to be lost or muddled. The process that is demonstrated in
this chapter begins by defining the problem with a focus on the elements that are most valuable to the customer. The relationship between the requirements and the actual problem definition is much more direct. This direct relationship means that the requirements are not as restrictive as ones continuously passed down and altered would be. It also means that the chance of error due to factors such as poor information or improper assumptions is less because there are fewer decisions that have been made impacting the requirements. An example set of requirements that has been inherited from one generation of seat design to another is shown in Table 9.

| Critical Operating Load (Current Draw) - Adjuster | 1R OE Aced Track: 81202Z-TAS A710 M3 C4T 2.2174Sect 120-4 8103Z-STX-A010-M1 SPEC. FR SEAT ASSY (MARKET) §4-5-6 | Load on cushion through H-Point 160kg Load on seat back - 196 Nm about the recliner pivot Voltage - 13.6 ± 0.1V Line resistance - 0.2ohms +/- 0.02ohms Motor condition: Cold Slides shall move FWD 5 - 17 mm/s and RWD 11 - 23 mm/s. The Lift and Tilt shall complete one full cycle with no speed requirements. 13 MDX Criteria: Test method as above, with the following acceptance criteria: HORIZ: Fwd 11.5 - 27mm/s; Rwd 20 - 33.8mm/s; current draw 16A max. VERT: 3 - 15mm/s; current draw 20A max. |

One of the requirements is that the electric motors should not exceed a voltage draw of 13.5V ± 0.1V. In solutions not needing electric motors, this requirement would not be appropriate. It is even possible for this requirement to imply to the designers that the design should use electric motors which would limit the design space.

The second through N\textsuperscript{th} generations were seen as poorly defined because they reused end product requirements from previous generations. This means that these generations did not continuously re-evaluate the problem when re-evaluation could change the design problem or be seen with a different perspective due to newly
discovered information. Reapplying old requirements means that solution specific requirements are guiding the development of new products by over-constraining the design space and forcing the design to be very similar to previous generations.

The following results and efforts of the case study outlined in this chapter are broken into the five most discernible steps. While these steps were not determined beforehand, the natural progression of this process is easily broken into sections that relate to one another.

**Defining the Problem in Terms of Value**

Just as in the previous generations of seat design, for the design of the seat generation demonstrated in this chapter, the OEM first identifies a need for a less expensive and lighter seat and requested that JCI design one to meet their needs. These needs are given in the form of a requirement list that is similar to the list of previous seat generations. In the particular project upon which this research is focused, the objective was to design a new or innovative seat design using a different technological approach from previous seats but still maintain the requirements of the previous generations. The reason for making a newly designed seat was that for the last several iterations, the changes in seat design had been minor, and it was understood that the resulting design was near the optimal configuration for that design. The only way to then vastly improve performance over the existing design would be to generate a new design. The requirements were kept intact because it was understood that the requirements met the needs of the customer (OEM and end user) and the only thing needing improvement was the seat performance within the boundaries of the given requirements.
The original set of requirements regarding structural rigidity was set forth by safety standards. These standards are set by government agencies and all seats must comply with them. There is no flexibility within these requirements. Rigidity and strength of a structure can be increased in most concepts that do not originally meet the minimum threshold through changes such as the addition of bracing or increasing member cross-sectional area. Because every design, with enough additions, should be able to meet the minimum threshold and there is no desire by the user to own a seat capable of withstanding much greater forces than are required by regulation, it was not considered a requirement worthy of challenging or needing of validation.

The remaining requirements are functional requirements and focus on the movement of the seat while being adjusted by the end user. These requirements are defined by an area or “window” within the vertical plane of possible positions that the h-point of the user could be located. The h-point is defined as the location within the vertical plane of the user hip joint. The provided window is the origin of the requirements because the previous generations were successful. The new generations are then required to move in a similar if not the same manner as the older generations because it was known that the older generations (and thus requirements) were satisfactory.

The original requirements were handed down from the OEM to maintain the current window of the current seat design but to reduce weight and cost. The original window was defined by:

- 240 mm [± 2.5 mm] of horizontal adjustment and
- 50 mm [+0/-5mm] of vertical adjustment.

In order to fully understand the movement requirements of fore/aft and vertical motion along with the associated tilt, a MATLAB program was written based upon the geometry of the seat design. A kinematic diagram showing the seat as it is analyzed by the code is shown in Figure 11.

![Figure 11: Kinematic diagram of five-bar seat mechanism](image)

This code uses the geometry of the seat to determine where the user h-point would be located. The code is iterated through all possible seat configurations are analyzed and the h-point and seat tilt associated with each of those configurations is recorded. The resulting plot of all possible h-point positions is shown in Figure 12.
To verify the seat geometry simulation as correct, it was compared against the original requirements. A convex hull was formed from the data points as shown in Figure 13.
The fore/aft adjustment is not truly horizontal and has a 6° tilt incorporated into the design due to mounting the seat at an incline. This tilt of the entire seat can be seen in Figure 11 as the front vertical link is shown mounted at a higher elevation relative to the rear vertical link. The initial position for the window in this global axis is (5, 196), and from this point forward fore/aft adjustment will be in reference to a global axis that is tilted 6°. The vertical adjustment, due to the nature of the current seat adjusters, is also not truly vertical. The 50 mm of vertical adjustment requires an 80 mm adjustment along a 38° angle and also results in 63 mm of additional horizontal adjustment. The window as provided by the seat is shown along with the requirements in a blue dashed outline in Figure 13.
Every functional requirement is based on the original system needs [8], so the best method to understanding the fundamental set of needs is to start with the requirements and trace back up to the original need. Figure 14 shows the qualitative rationale derived from the requirements that formulates the foundation of each of the adjustment requirements.

![Figure 14: Qualitative requirement rationale](image)

By asking the question, “Why?” at each of the requirement levels, the underlying focus of the design can be understood. The goal of the seat design is not to move in fore/aft, vertical, and tilting motions; it is also not an adjustability of the seat; the goal is to provide a safe and comfortable seating experience for all users that represent a wide variety of body types. If a seat design exists that can be safe and comfortable for all users without requiring adjustability then it would accomplish the highest level of requirements while failing each of the lower levels. During requirement development, each level of requirement refinement provides more detail than the previous level, but by choosing which details to add, some details must be left behind. These details could lead to
potential solutions of the highest level requirements. For instance, idea generation for ways to accomplish the highest level of requirement certainly would include adjustability of the seat. It could also include a fixed seat and an adjustable cabin or an amorphous seat that does not adjust but more or less forms to the user’s body (e.g.: bean bag chair). These are potential second level requirements that are lost when further detailing the most basic requirements. For the rest of this research, even if solutions and requirements that are more specific than the highest level requirement are considered, the goal of seating all users in a comfortable and safe seating position is always present in focus.

In order to refine a requirement to a lower level, one must add details to it. If those details are proper and warranted, then the increased level of detail can be productive to the designer; however, if the details are improper then, just as shown in Figure 4, the design space may be improperly limited. For this reason, the specific requirements for fore/aft, vertical, and tilt adjustment were investigated using the value-based validation approach.

The breakdown of original requirements does make intuitive sense. The users of the vehicle in which the seat will be used represent a potentially large variety of body types. Adjustability of the seat is a logical way to accomplish the accommodation of these people. Shorter users will need to be closer to the steering wheel due to shorter arms, higher up in order to see over the steering wheel and dash, and sitting on a flatter seat pan to compensate for the height that will move them up away from the pedals. Taller users will need the opposite, and presumably the remaining body types will be somewhere in between these two extremes. This notional thinking gives the impression
that the adjustability needed is similar to a trajectory and not a large area. There are no users whose body types require them to sit close to the steering wheel and close to the floor; there will also be no user body types demanding the ability to sit far from the steering wheel while up near the ceiling. For this reason, it seems that the notional needs might be best represented by the trajectory shown in Figure 15.

Because the OEM based the requirements on previous generations of seat design, it did not provide a window that through extensive research was proven as the best set of requirements. The adjustment requirements had very little basis for their formation and no evidence at all supporting them as the correct requirements. For this reason, a need was realized for the requirements to be better understood and validated.
**Outcome of step**

During the problem definition step of the process, several key elements are established including:

- an understanding of the need for adjustability,
- the seating configurations, and
- notional needs to accommodate users.

The first element that is established creates an understanding for adjustable seating positions. Operators represent a very large range of body types and dimensions, so to provide all customers with a safe and comfortable sitting experience, the seat will need to represent a range of positions just as variable as the user base. This understanding is the formation of the requirement rationale. The rationale of a requirement or set of requirements must first be understood and established before any validation or challenging of those requirements may take place. Validation methods are processes that relate artifacts back to their original foundations. The original foundations of the requirements must first be established and understood before the requirements can be held against those foundations and challenged.

The second established element of problem definition is the seating configurations. The h-point positions that are provided by the current seating architecture are determined by analysis of the seat structure and form a range of testable outcomes for value. The window of positions is a physical representation of the requirements. The final elements that are established during problem definition are the notional requirement
needs of the customers. By establishing an intuitive understanding of the requirements, a frame of reference is established to further aid in validation. The notional understanding of the user needs is also helpful in fulfilling the second part of problem definition by developing an understanding of the target market.

Collecting Resources to Establish Rationale

Once the problem is more clearly understood, the background information needing to be collected in order to begin establishing the value function becomes more relevant. The most important information encompasses three major areas: anthropometry, comfort, and vehicle data.

Anthropometry

The highest level of requirement stated that the users come in many different body types, so in order to design something that is useful to all people, one must understand all of those different body types. Anthropometry is the measurement of the human physiology. Individual’s body components are measured while in various positions such as standing or sitting, as shown in Figure 16.
There is a large variation among people within a population, but as the sample size of measured people increases, the more accurately the properties of the sample set can represent the whole population. The data collected in the military specification represented men ground troops and aviators from the U.S. Army, Navy, Marines, and Air Force as well as women from the U.S. Army and Air Force. The number of men totaled 14,428 and the women totaled 3,205. There was not an even split between male ground troops (8,977) and aviators (5,451), and the anthropometric measurements were reported with different values, so the numbers were combined to form a singular group of men with a weighted average. For example, one value for the ground troop height is 1.628 m and the equivalent aviator height is 1.642 m. The weighted average is found as shown in Equation (1) by taking the value of the interested data for each category and multiplying them by the respective percentage of the whole that they represent.
The result of the calculation is a height of 1.633 m. This average was calculated for each of the relevant male dimensions. The anthropometric dimensions of interest are listed in Table 10.

### Table 10: Relevant anthropometric dimensions

<table>
<thead>
<tr>
<th>Anthropometric Dimension</th>
<th>Depicted in Figure 16 by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>(1)</td>
</tr>
<tr>
<td>Eye level (relaxed)</td>
<td>(18)</td>
</tr>
<tr>
<td>Buttock-Knee</td>
<td>(28)</td>
</tr>
<tr>
<td>Popliteal</td>
<td>(27)</td>
</tr>
<tr>
<td>Knee height</td>
<td>(26)</td>
</tr>
<tr>
<td>Buttock-popliteal</td>
<td>(29)</td>
</tr>
<tr>
<td>Mid-shoulder</td>
<td>(19)</td>
</tr>
</tbody>
</table>

Any random sample above twenty or thirty samples is considered large enough to be represented by a normal distribution. There are more than enough samples for the data to be represented by a normal distribution. Anthropometric data is generally given in percentiles. These percentiles represent the value for which that percent of people within the population are smaller. For example, the 95\textsuperscript{th} percentile male is 1.864 m tall. This means that 95\% of males in the population from which the data is collected will be shorter than 1.864 m.
Comfort

The details regarding body types of the population allows for the understanding of seating to be investigated. An investigation into the comfort of vehicle seats shows that even though users adjust their seats in many different ways, there are still commonalities across users. Comfort in vehicle seating is most dependent upon three things:

- fit parameter – based on anthropometry and dimensionality,
- feel parameter – based on physical contact between the user and seat, and
- support parameter – affect the posture of the occupant [32].

The last two parameters, feel and support, are more a function for the seat cushion and seat back designs, and neither of those are a focus of this research. This means that comfort, as discussed in this research, is only a function of the fit parameter which is mostly dependent upon joint angles. Body parts that have too little or too much angle between them can cause uncomfortable stress on muscles. The appropriate angles for comfort are usually within a few degrees of the halfway point between a fully-extended and a fully-closed joint. There are several researchers who have conducted studies on comfort of joint angles and made suggestions for the most comfortable range, and these are shown in Table 11.
Table 11: Joint angles ranges for comfort

<table>
<thead>
<tr>
<th>Angle</th>
<th>Rebiffe [33] (degrees)</th>
<th>Grandjean [34] (degrees)</th>
<th>Porter and Gyi [35] (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Back</td>
<td>20-30</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>B. Trunk/Thigh</td>
<td>95-120</td>
<td>100-120</td>
<td>89-112</td>
</tr>
<tr>
<td>C. Knee</td>
<td>95-135</td>
<td>110-130</td>
<td>103-136</td>
</tr>
<tr>
<td>D. Ankle</td>
<td>90-110</td>
<td>--</td>
<td>81-105</td>
</tr>
<tr>
<td>E. Upper Arm</td>
<td>10-45</td>
<td>20-40</td>
<td>16-74</td>
</tr>
<tr>
<td>F. Elbow</td>
<td>80-120</td>
<td>--</td>
<td>80-161</td>
</tr>
</tbody>
</table>

The most important angles for comfort are the back angle, trunk/thigh angle, and the knee angle. Therefore, these are the three angles taken into account for this research. Each of these angles is shown in Figure 17 with the corresponding letters from Table 11.

![Figure 17: Stick human representation depicting joint angles [33]](image)

Vehicle

There are several points that are important to consider when understanding where and how a person is seated in a vehicle. These points were used as reference points in modeling how the user would be positioned in the seat. The first important position is the
h-point. Since, as explained before, this h-point can change based on the adjustment of the vehicle seat, it is important to begin with the h-point when attempting to evaluate the overall positioning of the user. Everything else about the positioning of the user is dependent upon the positioning of the h-point.

The next important point is the eye location. If the eye location is known, then the user position can begin to be evaluated for safety. It is not enough to consider only the comfort level of the user because the main function of a vehicle is to enable the user to drive. If the user cannot see the road, then driving becomes an impossibility. Statistical studies have been conducted to understand where the eyes of drivers are most frequently located after adjusting the seats [36]. These studies have resulted in what is known as the eyellipse. The eyellipse is formed by a two-dimensional normal distribution and represents the likelihood of user eye placement. The eyellipse along with reference dimensions necessary for determining its position and a few other interior reference dimensions are shown in Figure 18.
The interiors of vehicles are designed with visibility in mind, so when designing the vehicle, the seat placement, steering wheel, and other sight-dependent objects are positioned relative to the eyellipse in order to maximize visibility. Therefore, the eyellipse, as defined in Equation (2), was used as the target eye location.

\[ Z_c = H8 + 638 + H30 \]  \[ \text{[36]} \]  \[ (2) \]

The ground plane and x-axis were oriented along the floor of the vehicle, so H8 was evaluated as zero. H30 is the distance from the ground plane to the seating reference point (SgRP), and it was determined from the orientation of an existing seat design in an existing vehicle. These positions are better visualized in Figure 19, and then the corresponding positions are then dimensioned in
Figure 19: Human model positioned on existing seat architecture (provided by JCI)
Using Equation (2) and the dimensions from Figure 20, the proper eye level can be assessed as 914 mm above the ground floor.

The final reference point that is needed in order to understand how a user is positioned in a vehicle is the heel point. This heel point is denoted AHP in Figure 18 and is located at the base of the pedal. Since every driver must be able to reach the pedals, locating the heel at the base of the pedal is an acceptable reference point. In most vehicles the pedal remains fixed in the vehicle, so for this research the heel will also be assumed to be fixed.

Figure 20 shows the heel point to be 877 mm from the seating reference point.
Positioning of User

Using the anthropometric data along with the different vehicle reference points and where those points are positioned, a program was written in MATLAB to simulate the position of the user. This program receives three inputs: body dimensions, h-point, and back angle. The program is capable of determining positioning for any body type, but it can also be used to analyze the six main percentiles: 5\textsuperscript{th}, 50\textsuperscript{th}, and 95\textsuperscript{th} of both male and females. The back angle is input because it is not dependent upon any other points of interest so each h-point is analyzed with several back angles from within its range of motion. Since the h-point and heel point are known and the length of the two leg segments are also known, the program is able to determine where the knee is located in space. The knee location is determined by calculating the intersection of two circles. One circle has a radius of the upper leg length and the other circle has a radius equal to the lower leg length. The centers of the circles are the h-point and the heel point, respectively. The resulting calculation determines there are two intersection points, and the code eliminates the infeasible leg orientation. The back of the user is positioned parallel to the seat back and the eye location is set vertically above the shoulders. A depiction of this representation is shown in Figure 21.
The program sorts out the impossible combinations to ensure that they do not negatively affect the results. Configurations resulting in knee angles greater than $180^\circ$ were disregarded as well as configurations requiring the h-point and heel to be farther apart than the two leg segments’ combined total length. Once the body components were positioned, the program calculated the angles between body links that are needed in assessing comfort level.

**Outcome of step**

Many resources are collected during this step of the process, but some of the more vital elements that relate the most to the establishment of rationale are:

- anthropometric data,
- comfort assessment, and
• vehicle constraints.

The anthropometric data is directly related to the customer and provides the designers with a concrete model of the customers. The information related to the vehicle dimensions and positioning of the eyellipse and pedals gives the designers a model of the vehicle similar to the model the anthropometric data represents for the users. Both sets of data are capable surrogates for their respective sources. The final collected resource that is essential for relating rationale to the requirements is the comfort assessment. Comfort is perceived by the customer while being positioned within the seat. If comfort was insignificant, then the connection between the seating vehicle and the user would be weak. The requirements would be less dependent upon user need, and therefore, challenging and validating would be less significant.

All three of these elements are essential to understanding how the user perceives value of an automotive seat. While gathering more information about the user-vehicle interaction such as steering wheel position and mirror locations would increase the overall picture of the driving experience, the most crucial elements to establishing seating position value have been established. While more resources will increase the accuracy of a value function, once enough information is known to formulate a value function, remaining resources have a diminishing impact on the overall value.

**Formulate Value Function**

The information gathered that affects both how the system interacts with and impacts the users as well as how the users impact the system is used in the necessary step
of evaluating a value function. Value is assessed on a zero to one scale with one representing a completely fulfilled value, and in order to be able to assess the different components of the value function in that manner, they first need to be normalized. Because a value function is a mathematical representation of user preference and it is not representing just one user but most potential users, it is very difficult to determine correctly on one attempt; it is an iterative process.

Comfort Value

The first focus is on the perceived fulfillment of comfort value provided by the different seating positions and orientations. Once the joint angles were determined, they were assessed against the ranges shown in Table 11. Because these ranges only reflect what is comfortable and what is uncomfortable, a function needed to be formulated to assess actual value within the range. The first approach was a simple linear function that assumes there is no value outside of the acceptable range, there is a value of one at the midpoint of the range, and there is a linear rate of change from the bounds of the range increasing towards the midpoint. This type of function is shown in Figure 22 with the linear distribution of the knee angle.
This type of function is simple and easy to formulate, therefore, it is useful in initial evaluations of the overall system model.

The next comfort value model used was based on further research into the comfort angles. Research sampling user comfort showed that the comfort could be represented by a normal distribution [32]. In this normal distribution the mean is the most comfortable angle for the joint to be positioned and the standard deviation maps the rate of decreasing value away from the mean for both increasing and decreasing angle. Table 12 shows the means and standard deviations that were used to correlate the normal distribution of perceived comfort to the angles of the users in differing positions within the vehicle cabin.
Table 12: Means and standard deviations for preference on different joint angles [32]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thorax Angle</td>
<td>3.8°</td>
<td>6.7°</td>
</tr>
<tr>
<td>Abdomen Angle</td>
<td>32.7°</td>
<td>9.7°</td>
</tr>
<tr>
<td>Pelvis Angle</td>
<td>60.4°</td>
<td>11.7°</td>
</tr>
<tr>
<td>Torso (Hip-to-Shoulder) Angle</td>
<td>28.2°</td>
<td>5.8°</td>
</tr>
<tr>
<td>Hip-to-Eye Angle</td>
<td>9.9°</td>
<td>4.6°</td>
</tr>
<tr>
<td>Thigh Angle</td>
<td>15.8°</td>
<td>5.0°</td>
</tr>
<tr>
<td>Knee Angle</td>
<td>122°</td>
<td>10.6°</td>
</tr>
</tbody>
</table>

Using the mean and standard deviation for a specific joint, the probability density function is calculated with Equation (3)

\[
f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad [37],
\]

where \(x\) is the position being evaluated, \(\mu\) is the mean value, \(\sigma\) is the standard deviation. The probability density for each angle was determined at the mean. For the knee angle with a mean of 122° and standard deviation of 10.6°, the probability density at the mean is 0.0036. By dividing this quantity into each of the probability densities calculated for each knee angle the normalized value is calculated. The distribution can then be represented as shown in Figure 23 with a maximum normalized value of one.
The final comfort value model investigated was based upon the notion that comfort is merely the lack of discomfort [38]. Branton made the observation that people were equally likely to find one position as comfortable as another as long as both were within the range of comfort. Outside of these ranges, discomfort was a function of joint angle, but within the range of acceptable angles most people did not feel a discernible difference in the way they were seated. Figure 24 shows how this understanding of user comfort would be expressed as a binary function.

Figure 23: Normal distribution based value function for knee angle
In this situation there is no value found in a seat position that is outside of the allowable comfort range and thus the function shows a value of 0. Within the allowable joint angle range, the user experiences the same amount of comfort at all positions, and thus, the value is represented by an equivalent value of one.

There was no justification for using the linear value function, as it was not considered realistic. The binary value approach was justified by comfort research that determined human comfort is merely a position where no discomfort is present. For this reason the binary approach was considered a good value model. However, all people are capable of having different comfort ranges and comfort range sizes. By simply using a binary value function, the differences between one user and another would not be well portrayed and the function would merely represent how some users experience comfort. Each of the value functions were evaluated for each of the six major body types and the results are shown in Figure 25, Figure 26, and Figure 27.

Figure 24: Binary comfort value function for knee angle
Figure 25: Linear Distribution of Most Valuable H-point Positions

The linear distribution shows the shortest men and women closer to the front of the vehicle and in a higher seating position as would be expected, but there is a mixing of preferred seating choices from the three tallest body types. By using the linear distribution, it would be deduced that the three taller body types all desire to sit at or near the lowest possible position. This is not consistent with what is understood to be true or consistent with the other body types. For this reason, the linear distribution is not considered viable.
The normal distribution positions the smaller users similar to the linear distribution – close to the front of the vehicle and farther from the floor. The significant difference between the linear and normal distributions is that the trend continues through the rest of the body types. The tallest users find the most use in the seating positions near full-downward, full-rearward.
The final comfort value model evaluated is the binary model. The binary model is a reflection that all positions are equivalent as long as they are not causing discomfort. For this reason, the number of preferred positions is much larger over the linear and normal distributions. This larger number of “preferred” seating positions makes discerning a trend much more difficult. It can also be seen that the preferred positions do not completely hold to the notional understanding of height to general seating position, as some body types are in unrelated positions, such as the 5th percentile men preferring the highest and most forward position and the lowest and most forward position.

The trends are very similar, but the normally distributed comfort value fits the trend that makes most intuitive sense. The linear value function has the 95th percentile males sitting higher than the 95th percentile females and the 50th percentile males prefer two entirely different positions. The binary value function has very broad comfort
positions and also does not represent an intuitive trend. So it was determined that the best representation of comfort for the most number of people was to use the normally distributed value function.

Vision Value

The value of visibility is based on the proximity of the user’s eyes to the location in the vehicle that affords the best visibility. All vehicles are designed around certain standards and the standard governing visibility explains where in the vehicle the user eye is most likely to be positioned. The statistical representation of this eye location likelihood is the eyellipse, and vehicles are then designed around this area. The eyellipse is thus a good estimate of where in a generic vehicle the best visibility will be found. Because there is too much variability from vehicle to vehicle to determine all necessary dimensions to position the eyellipse in the horizontal axis, only the vertical dimension will be considered. The target eye location in the vertical axis was computed using Equation (2). H8 is 0 mm as the ground plane is considered the x-axis; H30 is 276 mm as shown in Figure 20; so the value of \(Z_c\) is 914 mm. This is the vertical position of the centroid of the eyellipse.

The value of the eye position is determined similarly to the process for the normal comfort value function. The mean is considered the vertical centroid value and is then used to represent the mean for a normal distribution. The farther from this mean a seating orientation places the user’s eyes, the lower the value of that position from a vision point-of-view. The vertical displacement from the centroid will be used to determine the value of a given eye position. The eyellipse encloses 95% of all users’
eyes with a vertical axis dimension of 139.2 mm [36]. In a normal distribution 95% of a population is contained within two standard deviations of the mean, so the standard deviation used for this value function is 34.8 mm. The calculation of value for the eye placement is conducted in the same manner as the normally distributed comfort value function. The probability density at the mean was calculated and used to normalize the values of the probability density of at each of the points.

Total Value

Once the value for a position is known for both comfort and vision, the two must be considered together. Because both are on a scale from zero to one, the values are able to be considered relative to one another. In some seating positions the comfort value is high and the vision value is low, or vice versa. At these positions, the overall desirability of this position is not high. If the two values are both acceptable, these positions need to be considered among the acceptable positions. This means that the user would be willing to sacrifice some comfort in order to gain visibility, and vice versa. The ideal seating orientation would be one in which both comfort and vision are maximized; however this position does not necessarily exist, and the optimal seating orientation is the one in which the total value is maximized. The overall value is evaluated with

\[ Value = 0.5 \times Val_{vision} + 0.5 \times Val_{comfort}. \]  

The comfort and value are first considered of equal value and the results closely resemble the intuitive expectations.
**Outcome of step**

The most notable result of the third step is the formulation of value functions. These value models are:

- comfort value,
- vision value, and
- overall value.

Two of the value functions, comfort and vision, are directly related to user preference. These functions are relating individual design goals to the user value. The overall value function combines the two individual values into one overall assessment. This is necessary because the requirements – dictated by seat adjustability – impact both the comfort and vision concurrently. If the seat could be adjusted in such a way that those two values were affected independently, then there would need to be independent requirements connected to each value assessment.

**Mitigate Tradeoffs**

After the value for each of the positions is determined for each of the body types, the information can be analyzed to determine how to optimize these requirements. The first trend to investigate looks at the optimal position and orientation for each of the six body types. These orientations are shown in Figure 28.
The trend does appear to follow intuition – the shorter users find the most value in a high position to increase visibility, forward position to reach the pedals, and flat tilted seat to mitigate increasing the distance from the pedals by raising the seat, the taller users prefer the exact opposite, and the rest are somewhere in between. While two individuals might have the same total height and be within the same overall percentile, one may have shorter legs and a taller torso. This means that not everyone is going to find value in the “optimal” height. The positions and orientations shown in Figure 28 are only optimal for the individuals who are of their respective percentile for every single body dimension. For example, a 50th percentile male must also have 50th knee height, 50th percentile hip-to-knee length, and 50th percentile torso length. Since there still remains variability within each of the percentiles, a range of possible positions is more appropriate. Shown in Figure 29 are the 5% most valuable positions to each of the body types.
The method for determining the 5% most valuable was to first find the most valuable positions – shown in Figure 28 – and determine which positions have a value within 5% of the highest value. Every position that is within 5% of the highest valued position for the respective body types is displayed in Figure 29. The range of positions varies in both vertical and horizontal dimensions, so it is observable that a single point for each user would not represent every high-value position. So in order to represent the variability between users – even users within the same percentile of height – the top 5% most valuable positions for each percentile from 5th percentile to 95th percentile is encapsulated by the solid blue area in Figure 30.
Figure 30: Area Highlighting Top 5% of Seat Locations for 5th - 95th Percentiles

The solid blue area represents a convex hull for the best 5% of seating positions for each body type from five percentile females to ninety-five percentile males at a single percentile increment. The area inside of the red outside border represents the current seating window. The blue solid area, which is essentially the useful area, covers 62.8% of the total available area. This means that 37.2% of the available seating positions are never used for driving applications.

Outcome of step

The mitigation of tradeoffs for this demonstration shows that the seating positions provided by the existing product are in great excess of what is needed in order to provide high value seating positions to all customers. The 37.2% of seating positions that can be
used but are not useful to providing the most comfortable and safe driving positions are a hindrance to the user’s ability to find the appropriate position for him or her.

**Correlate to Requirements**

Now that the needs and values of the customers and end users are more accurately understood, these values can be related back to the original set of requirements and used as a guide in ensuring that the requirements are written properly. Requirements that are based upon the value models and have a value-based perspective are much more likely to promote a design team toward designing a product that is much more valuable to the customer.

![Figure 31: New Window based upon Value Analysis](image)
The original window, as is shown in the red exterior border, provides too much adjustment. There are large portions of the window that will not be used by the customer. If the customer will not use it and it requires extra cost to the seat manufacturer to provide it, there is an overall loss in value because the customer will have to pay more for a seat that affords them nothing more than a seat that could make a smaller window. The new window (depicted in the green, dashed lines in Figure 31) suggests requirement change would then be:

- Fore/aft: 240 mm → 160 mm
- Vertical: 50 mm → 50 mm.

Where the 175 mm fore/aft adjustment is still at the 6° incline like the original window, but the vertical adjustment of 50 mm is achieved through a more horizontal trajectory. Instead of the original 80 mm adjustment at 38°, the new window suggests a 170 mm adjustment at 20°. This maintains the same amount of total vertical adjustment, and therefore, provides a total area reduction of 38%.

*Outcome of step*

The outcome of the final step of the process uses the results of the data to create new boundaries for the h-point window. This new window is much improved over the original window because it represents the useful positions to the users. Because the necessary analysis in representing the user needs is completed, the conservative requirements can be eliminated and appropriate, justified requirements used in their stead. This step shows that the value-based approach provides a means to establish and
link rationale to the requirements. That rationale can then be used to dictate the details of the requirements.

Discussion

In this particular design problem, there is a realization that the requirements may not be representative of the reality of customer needs. This notional understanding led to the need to either validate or invalidate those requirements through an evidence-based approach. Because the requirements were established prior to the design project, as is the case in many design projects, merely questioning them proves both difficult and insufficient. A method such as the one followed in this case study allows the designers to properly assess the requirements. Even though the events in this case study were conducted in a response to the established requirements, it is also possible to use the value-based approach on requirements while the requirements are being written. Once the initial requirements and problem are established, the value-based thinking can be used to quantify the requirements properly.

The process of requirement validation establishes a connection between the requirements and the stakeholder interests. This is the process of assigning a rationale to the requirements and fulfilling the question of, “Why?” The events in this case study are directed specifically towards providing that rationale. While this method does work well for functional requirements because they are technically rooted in customer desires [8], it does not work well for the non-functional requirements – especially those originating from outside factors such as governmental regulations. Some requirements are not capable of being validated with this method.
Original requirements are developed upon some level of understanding the needs. A value model such as this one, only serves to increase this understanding in a focused method. The more time one spends in researching and developing the model, the more accurate the understanding will be. However, once a model is generated and exhibits justification, it is fulfilling its purpose of eliminating the uncertainty associated with the rationale of requirements. So while some models might have room for improvement and do not completely depict user preference, these models (if based upon fact and not conjecture) do still accomplish the purpose of requirement validation through reduction in rationale uncertainty.

This particular example of the validation process and value model shows a more justified set of requirements, as seen in Figure 32.
It also shows that the newer requirements will save design effort and manufacturing cost because an increase in adjustment range entails new cost [39]. Many requirements, if not sufficiently justified, are written in a conservative manner when quantified. This could be the explanation as to why these requirements were unnecessarily large. However, it is not necessarily always the case that this method will allow the designers to have requirements that are more obtainable and induce money savings. This method is focused on validating the requirements and can just as easily suggest a set of requirements that will add cost to the system. The end product will be the same: a set of requirements that more closely maps back to the user desires thereby making a product that is more desirable to the user.
CHAPTER FIVE: CONCLUSIONS

The overarching objective of this research is to evaluate the design intent and establish the design rationale and justification for engineering requirements in a case study through value-based validation techniques. The events in the case are based on value-based thinking to provide the design project with concrete rationale for requirements and thus validate or invalidate the requirements in the system design process. These events leverages existing value-based techniques, but is not applied to design concepts as is typical, but rather engineering requirements. This research is focused on using value models to relate the most important functional requirements to one another through a value function in order to increase the viability of the system and its requirements. By providing the designer with a mathematical function, this process provides the means to support why the requirements were chosen as they were and increases the designers’ confidence that the product is being designed correctly.

This chapter is organized to show the contributions of this research, the answering of research questions, the limitations and challenges presented by the process, and the future work that should be completed related to this research. The contributions of this research and research questions are explained through the perspective of the automotive seat demonstration. The limitations and challenges of the process that are realized during its development are further discussed, and the future work provides tasks that need to be completed in order to remedy the limitations experienced by the process.
Contributions

The research presented in this thesis contributes to the understanding of requirements in how they are formulated, used, and maintained. Additionally, this research demonstrates the importance of incorporating a value-based approach during the initial development of design requirements and as the design process progresses. The case study developed evaluated the viability of value-based validation within task clarification phase as shown in Figure 33. Finally, this research addresses some of the issues present in current research regarding requirement challenging [2].
This process may be a small deviation from the existing systematic design processes, but it has the potential to make large impacts. Existing research shows commonalities in the problem definition and requirements development stages [3,4], but it does not provide proper modes of action when one or more of these steps have been completed improperly. Engineering design is a social activity [40], and as such, sections of the process are completed by different people or even organizations. In the case of
challenging and validating requirements that have already been established, substantial evidence needs to be used to effectively show a need for change. The process derived from the observations of the case study in this thesis:

- provides a means to challenge requirements – including both
  - justification for so doing and
  - evidence to support the challenge;
- provides a mode to relate existing requirements to rationale –
  - value-based thinking is the path and
  - reduces the uncertainty surrounding requirements;
- creates a means by which requirement validation can occur.

The original requirements for the JCI automotive seat demonstration are shown in Figure 34 to be an inaccurate representation of the occupant (customer) needs. While they do fulfill the needs of the occupant, they also enable the user to be in positions that are not desirable. For example, the previous seat structure enables shorter occupants (5th percentile female) to be located full forward as is desired, but it does not guarantee the occupant is at the proper height. This over-adjustability may decrease the value of the seat by decreasing the likelihood that a customer is able to find an optimal seating position, and, if that position is found, more adjustability will increase the necessary time the user must invest to find the optimal position. A larger window may also need a more complex seat design with greater expense. This representation of how the customers use the products that are currently designed provides a designer with necessary means to
justify challenging the requirements. It also provides a designer with evidence capable of refuting the original requirements.

The method explained in this thesis begins with Defining the Problem in Terms of Value. Unlike the first step of problem definition common to systematic design [1,4,6], this step is more direct in its focus. It is only concerned with the aspects of problem definition that directly relate to the customer value assessment of the product. Safety regulations and manufacturing techniques do not directly impact the perceived value of the product, and are therefore, not considered during value-based problem definition. As shown in the demonstration, elements such as ergonomics and user/product interaction are highly important to the value-based problem definition. These elements are crucial to the rationale of the requirements and by considering them alone, the process provides a clear mode for discerning requirement rationale. The requirements can then more clearly be validated and challenged if necessary because there is a more clear understanding as to why the requirements exist. It must first be established that requirements expressing the need for horizontal seat adjustability are providing the customer with different seating positions relative to the steering wheel and pedals before a statement can be made to the validity of the horizontal adjustability requirement quantification.

The value-based approach also creates a means by which requirement validation can occur. As shown in validation section of the fourth chapter, the h-point positions that were provide by the original seating architecture and requested by the previous requirements were not nearly as useful or valuable as the suggested requirements. The h-
point positions contained within the suggested requirements have a higher frequency of usefulness.

**Addressing the Research Questions**

Each one of the research questions posed in the third chapter is answered in the context of the case study. The demonstration of the automotive seating example provides evidence of the fulfillment of the questions.

**Research Question 1:** Why should requirements that seem incorrect be challenged, and what is needed to challenge them?

**Answer:** Requirements should be challenged because the uncertainty that surrounds requirement(s) may facilitate the design of products that either do not fulfill the actual needs and wishes of the customer or, due to conservative constraints, provide unnecessary functionality at the expense of the customer and manufacturer. Thorough discernment of the requirement rationale reduces the uncertainty surrounding the requirements which makes it possible to challenge the requirements.

Requirements are written in a contractual manner and usually with terminology such as “must” accomplish [3]. Failing to meet the requirements means that the design has failed. Requirements often may not be executed by the same designers who originally draft the requirements, and in these situations, truly understanding the requirements can be difficult. It can also be difficult to challenge the requirements if they appear to be incorrect. There are other factors in the design process, such as lengthy
design projects and large numbers of people involvement [41], that negatively impact the traceability of requirement justification and rationale. The appearance that requirements or project goals are incorrect or over-constraining is not usually a powerful enough reason to persuade the original drafters of the requirements that a change is necessary. Its ineffectiveness could be due to an educational training, company hierarchy, or societal influences [2]. Decisions to alter or challenge requirements based upon assumption may be no more justified than original formation and quantifying of requirements based upon assumption. By relating the requirement back to the original rationale and the true design intent behind the requirements, the executers of the requirements are able to fully understand the requirements and justify pushing back on the original requirements.

In this case the designer is able to relate the rationale to the requirements. The information gathered that is used to relate the requirements to the user needs, formulates a mathematical function of rationale. This reasoning behind the requirements is able to drive any attempt to question and challenge the original requirements or problem goals. Without documented concrete reasoning, the challenger only has notional evidence. This mathematical and visual evidence is a much stronger means to challenging requirements than merely notional interpretations.

Proposition 1: As generations of a project are completed and the original problem description (project goal) becomes more fully understood by designers relative to the changing product environment over time and/or the overarching goals change, the potential arises that reused or legacy requirements will need to be change if challenged.
Reasoning 1: If a multi-generational design project continually reuses requirements across generations, some requirements will be subject to change if challenged.

Criteria 1: Show a design group that reuses requirements with each generation and observe if any requirements need to be changed.

Because each project has the same eventual outcome – the design of an automotive seat - the JCI design process begins each generation of design with the previous generation solution specifications as shown in Figure 10. As each generation of design is completed, it becomes difficult to differentiate between requirements that were formulated as a response to successful solutions and requirements that were based upon customer needs. The requirements of this project were investigated for their validity. Because the design project begins with legacy requirements and those requirements were evaluated as to whether or not they need to be changed, Criteria 1 has been completed. The result of Criteria 1 is that during the course of the case, the requirements dictating fore/aft and vertical adjustment were changed to requirements that reflect more justifiable reasoning. This result parallels Reasoning 1 such that a multi-generational design project did need requirement changes. Due to the fulfillment of Reasoning 1, Proposition 1 is supported by the evidence in the case.

Research Question 2: How does one discern the rationale of requirements?

Answer: Rationale is determined through the construction of value and needs as they pertain to the problem statement and requirements.
Requirement rationale is the reasoning behind the requirement, and all proper requirements are rooted in the customer needs. If a requirement is not rooted in the needs of the customer or in limitations imposed by the environment in which the product will be used, then the requirement is unnecessarily restricting the design space. These requirements are improper requirements and should be removed or altered. Therefore the best way to derive the requirement rationale is to attempt to view each requirement from what it would provide the customer if it were achieved. The first two steps of the process attempt to break down the requirements and problem definition with the question, “Why?” The designers are then able to define the rationale for the project and its specifications. This questioning sets up the process of developing a value function. It also uses the answers to the questioning of requirements to mathematically relate the consumer needs to requirements.

The validation method defined by this research and demonstrated by the automotive seating example gives a step by step process for relating the requirements to the user desires. This process examines the importance each of the requirements of interest to the users and through one unifying value function is able to map those requirements to user needs. Once the mapping is formulated, it is used to quantify the requirements so that the requirements more accurately reflect the needs of the users. The generation of a value model is not always straightforward and clear. It is also not guaranteed that mistakes will not be made even with the value model. However, the values models do strongly encourage and facilitate the designer to trace the reason behind the requirement.
Proposition 2: Rationale can be discerned by attempting to complete the requirement development process in reverse order.

Reasoning 2: If during the course of the case, a requirement is given documented justification for its existence, then rationale has been established.

Criteria 2: Show the documentation of a requirement rationale.

The JCI design process begins each generation with inherited requirements. Therefore, the requirement development process is not completed with each generation. During the examined case, the requirement subject to being challenged was first broken into different levels of requirements as shown in Figure 14. With each level, the requirement became more generic until it represented the need of the customer. This process of completing the requirement development process in reverse documents the rationale and completes Criteria 2. Because Criteria 2 has been fulfilled, Reasoning 2 has been established as documented justification for the adjustment ranges of the seating window has been established. This case is thus successful in supporting Proposition 2.

Research Question 3: How can value-based thinking be used in order to challenge/validate requirements?

Answer: Value functions are useful in linking the user needs to the requirements because they use requirements as the inputs to the model and the outputs are in the form of user desire.

Value functions are normalized objective functions that are written in order to represent multiple factors that are unrelated except in their importance to the customer.
The units are normalize because not all performance measures that have an impact on the value of a product are mathematically possible to be combined or added together because they are measured in different units. These functions can be determined through experiment and market research or through research that has already been completed as shown in the demonstration with comfort. Once the model is formulated, it becomes a predictive model of how customers will perceive the performance of the product. The model generated for user comfort was shown to represent how specific users would position a vehicle seat, and allowed for the requirements to be modified to provide a seat that accomplished only what was necessary to add value to the system. Value models are surrogates for the user which allow designers to understand how to quantify the requirements so that as they restrict the design space they are capturing the most valuable areas within the design space.

Intuitively it is known that users of shorter stature will prefer sitting closer to the steering wheel so that they can reach it, higher up to increase visibility through the windshield, and on a flatter seat to increase their ability to reach the pedals that is limited by an increased seat height position. The opposite position is true for the tallest users for the opposite reasons. It was shown in the demonstration that the value model considers the most valuable seating positions for people of all statures to be along a trajectory between the full-forward and full-up position and the full-rearward and full down position. The value model is able to predict where specific users would most likely sit in a vehicle.
Proposition 3: Value-based thinking can be a clear means through which a requirement is validated or justifiably challenged.

Reasoning 3: If value functions form the justification by which a requirement is challenged or validated, then value-based thinking is a means to challenge.

Criteria 3: Show a requirement that is refined by a value-based approach.

The case described in Chapter Four focuses on using value functions to represent user needs. The value functions serve as a surrogate for the individual users, and can provide an even more justified requirement rationale. Criteria 3 is shown to be fulfilled in Figure 32 because the adjustment window requirements are greatly reduced in response to the value function analysis. Reasoning 3 is established in the case study because the value based process was used to not only justify changing the requirements, but also used to suggest new requirements. Therefore, the case was successful in supporting Proposition 3 in that value-based thinking can be used as a means to challenge or validate a requirement.

Limitations and Challenges

Limitations to Validation of Research

The process proposed in this thesis is a product of a case study, and some limitations do exist. The first limitation of this research is due to the limited number of design problems to which the value-based approach has been applied. The process has been demonstrated through an industrial design project, and confidence in the approach is based on this single design project. While the project does possess many challenges and
characteristics typical of industry design projects, and confidence in its applicability to many design projects is therefore high, the validity of the approach cannot be confidently generalized to all design projects.

Secondly, because this process is only applied to a design project for which the systematic design process has not been fully completed, the impact that the process has on design outcomes is not completely clear. The outcomes of the process are validated design requirements which are used in the same manner as the requirements that are established prior to using the value-based validation process. It is established that the systematic design process works for facilitating the design of a product, so because the outcomes of this validation method are requirements that are more justified than the initial requirements, the outcome of a project that utilizes this process should be a product that is no worse than completing the systematic design process without the value-based approach.

Limitations to the Value-based Approach

A potential limitation of the process is that it may be design project specific. Design specificity becomes an area of concern when it is not clear during requirement decomposition and problem definition how far to decompose the rationale. It is also a concern for gathering relevant information to formulate a value function when the necessary amount of information is not explicitly defined. In the case study a notional understanding of the problem provided a guide to indicate when the results were most likely representative of reality. In a design problem void of previous experience, notional understanding is non-existent and necessary information gathering is open-ended.
Another limitation to the process is the reliance upon the customers to formulate the value functions. Without information gathered directly from customers by the designers or through previous research, as in the demonstration, this process exhibits very similar limitations to traditional requirement-based design. If information is not directly gathered from the users by some means, then assumptions and estimations are needed to fill the gaps. The farther away from a real sampling of the users, the larger the uncertainty around the results will be – just as is shown in requirement formulation.

The value-based approach provides designers with the means to challenge and validate requirements. However, it does not provide the designers with the understanding of when requirements should be challenged. While all requirements should be justified and based upon reasonable rationale, knowing when requirements are at a high risk of being incorrect is difficult and not addressed in this research. There are times, as shown in the automotive seat demonstration, when expert understanding of a situation can lead to disagreement with requirements. When these situations arise, the designer needs to build confidence in the suggestion that the requirements should change, and he or she needs to understand to what the requirements need to be changed. The value-based approach is able to accomplish these.
Future Research Questions and Tasks

Future Research Question 1: What impact does the value-based approach have on the final solution of the design process?

Future Research Task: Complete the systematic design process of a project in parallel with different people. One group uses the value-based approach in addition to the systematic process while the other simply uses the systematic process.

As just explained, a limitation to the validity of the current process is the lack of certainty that the process will produce products that are more closely representative of the user needs than the existing approaches will. By completing the design process with the value-based methodology with one team of designers while, concurrently, another team completes the same design project with the traditional systematic design process, an understanding of the actual impacts the process may have on a final product can be better understood.

Future Research Question 2: How much effort (time and money) does developing a value function require?

Future Research Task: Use the process on a design projects while highly documenting the amount of effort put into the value-based parts of the design process.

The second research question is posed because this process was developed while applying it to the automotive seating project, and therefore, it is unclear how much effort the process would actually require in a regular design environment. By using the process
as it is now on a design project and documenting the amount of effort in terms of time and money spent pursuing the value-based portion of the design process, the amount of effort that would need to be budgeted for this additional process would be clear.

Future Research Question 3: Is the amount of effort beyond what is necessary for the traditional systematic design process that is required to establish a value function and implement it into the design process justified by the value of the return?

Future Research Task: Compare the results from the first two research questions – potential impact of the value-based process against the amount of effort realized through the execution of the process – to give a clear understanding of the potential risks and rewards.

By comparing the results of the first two future research questions, one can begin to understand the affects, both positive and negative, that the value-based validation approach may have on the design process. The first research question investigates the potential positives the process may have on the final product and how effective it is at providing a product that best matches user needs. The second research question evaluates the negative impact the process has on the overall design process. Since the value-based process is an addition and not a substitution for an existing phase, it will require more time and money than the design process that does not include it. This tradeoff can now be assessed after both of these research questions have been answered.
Future Research Question 4: When is it warranted to apply the value-based approach? Should it be used every time, every time there is reasonable doubt in a requirement, or some other metric?

Future Research Task: Complete a user study that applies the value-based design approach to different types of projects.

The projects do not have to be completed, but the requirements need to be validated. Afterwards, the challenges and advantages that may be present in some types of design projects can be observed. These aspects that differ from project to project can then be used to formulate considerations and guidelines to help designers understand when it may be advantageous to use the value-based validation approach and when it may not be advantageous.

Future Research Question 5: What aspects of the target customer population dictate whether or not to use this method in the design process?

Future Research Task: Apply risk management techniques to the requirements in order to evaluate which requirements, if changed, make the most impact on the value of the product and require the least amount of investment to investigate.

Attempting to use this process with a design project subject to elements of user desire that are not already well-researched and understood would require establishing that understanding first. Instead of relying upon existing research – such as the comfort assessment of joint angles in the seating demonstration – the designers would need to
conduct research through means such as user studies, surveys, and polls. Assessing the necessary amount of time and money required for this type of research would be crucial in determining if relating the requirements to a value function is worth the monetary investment. The odds of altering the requirements list would need to be large enough to warrant the risk.
APPENDICES
APPENDIX A: MAINFILE OF SEAT ANALYSIS CODE

% MAIN PROGRAM
% Author: Seth Crouch
% This is the main file that organizes multiple functions for analyzing
% seat structures, anthropometric data, comfort value assessment,
% vehicle
% dimensions, driving vision value assessment, and overall seating
% position
% value.

clear
close all
tic
label = {'5th Women','5th Men','50th Women','50th Men','95th Women','95th Men'};

modelboo = menu('Choose Model type','Major Percentiles','Some percentiles','Specific Person','Perc Range');
percentiles=[1,2,3,4,5,6];
lbl=label;
len=6;
if modelboo == 2
    percentiles=[];
lbl=[];
lab = label;
lab{7}='Done';
percentiles = menu('Choose',lab);
while percentiles(length(percentiles)) ~= length(lab)
    lbl{length(lbl)+1}=label{percentiles(length(percentiles))};
    lab{percentiles(length(percentiles))}=' ';
    percentiles(length(percentiles)+1) = menu('Choose',lab);
end
percentiles(length(percentiles))=[];
len=length(percentiles);
elseif modelboo == 3
    percentiles=1;
    userheight = inputdlg('What is the model height (in)?');
    userheight = str2double(char(userheight))*25.4;
    usersex = menu('Model Gender','Female','Male');
    len=1;
elseif modelboo == 4
    beg=str2double(char(inputdlg('Beginning percent:')));
    last=str2double(char(inputdlg('Ending percent:')));
    len=(last-beg+1)*2;
end
excelboo = menu('Output to Excel?','Yes','No');

plotboo = menu('Which display plots if any?','None','Both','Seat','Human')-1;
valboo = menu('Which comfort value model to use?', 'Linear', 'Normal', 'Binary');

outplotboo = menu('Which output plots if any?', 'None', 'All', 'Select'); plots=[];
if outplotboo == 3
    titles = {'Optimal HPs with the angle of back and seat pan', ...
    'Optimal HPs based on Comfort, Vision, and Value Function', ...
    'All Possible HP locations', ...
    'Top 9x% of HPs in terms of value for each percentile', ...
    'Eye location associated with each optimal HP and top 1X% of HPs', ...
    'Human Model(s) Positioned in Optimal Configuration'};
    titles{7}='Done';
    plots = menu('Choose',titles);
    while plots(length(plots)) ~= 7
        titles{plots(length(plots))}=''
        plots(length(plots)+1) = menu('Choose',titles);
    end
    plots(length(plots))=[];
end

angboo = menu('Computational intensity', 'Thorough', 'Average', 'Fast');
if angboo == 1
    ang_increment = 5;
    numpos=46740;
elseif angboo == 2
    ang_increment = 7;
    numpos=4305;
else
    ang_increment = 15;
    numpos=2296;
end
hparray = zeros(numpos,4);
eyex = zeros(numpos,len);
eyey = zeros(numpos,len);
comfval = zeros(numpos,len);
visionval = zeros(numpos,len);

%% Gathering inputs from the Human Model, Vehicle Model, and Seat Model

if modelboo == 3
    humanmodel = linklength(userheight,usersex);
elseif modelboo == 1
    humanmodel = humanmodel();
elseif modelboo == 2
    humanmodeltemp = humanmodel();
    perctemp = percentiles; humanmodel=zeros(7,length(percentiles)); temp=1;
    while isempty(perctemp) == 0
        [r,c]=size(humanmodel);
humanmodel(:,temp) = humanmodeltemp(:,perctemp(1));
perctemp(1) = [];
temp = temp + 1;
end
else
    humanmodel = humanincrem(beg, last);
end

[heel, eyeline] = vehicle();

[hpoint, seatpanangle] = five_bar_seat(ang_increment, plotboo);

%% Iteration of loops where each body type of interest is placed each
% into possible hpoint position and each possible back angle. The
% vision and comfort values are determined for each of those positions.
index = 1;
count = 0;
[r, c] = size(humanmodel);

for i = 1:length(hpoint)
    for backangle = 40:-ang_increment:15
        [angle, eyex(index,:), eyey(index,:)] = humanposition(humanmodel, [hpoint(i,1), hpoint(i,2)], backangle, heel, plotboo);
        hparray(index,1) = hpoint(i,1);
        hparray(index,2) = hpoint(i,2);
        hparray(index,3) = backangle;
        hparray(index,4) = seatpanangle(i,1);
        for k = 1:c
            visionval(index,k) = vision(eyeline, eyey(index,k));
            if angle(1,k) == 'a' || ...
                % When hip point is too far from pedals
                angle(3,k) - hparray(index,4) < -5 || ...
            % When leg intersects seat cushion
                angle(3,k) - hparray(index,4) > 10 % When leg is too far off of seat
                comfval(index,k) = -10;
            else
                comfval(index,k) = comfortvalue([hparray(index,1), hparray(index,2)], backangle, angle(:,k), excelboo, label, k, valboo);
            end
        end
        index = index + 1;
in = i;
    end
end

%% Evaluating the Value Function
[value, comfmax, opthpcomf, vismax, opthpvis, valmax, opthpval] = valuefunc(hparray, comfval, visionval);
toc

%% Outputting to Excel
for k=1:c
    if excelboo == 1
        xlswrite('value.xlsx','hpXpos','hpYpos','backangle',...'
            seatpan angle','Vision Value','Comfort Value',...'
            Total Value'),label{percentiles(k)}
        xlswrite('value.xlsx',hparray,label{percentiles(k)},'A3')
        xlswrite('value.xlsx',visionval(:,k),label{percentiles(k)},'E3')
        xlswrite('value.xlsx',comfval(:,k),label{percentiles(k)},'F3')
        xlswrite('value.xlsx',value(:,k),label{percentiles(k)},'G3')
    end
end

%%

if isempty(find(plots==1))==0 || outplotboo==2
    %% Plots the optimal HP and the angles of the seat back and seatpan
    for k = 1:c
        [ang(:,k),ex(k),ey(k)]=humanposition(humanmodel(:,k),[opthpval(k,1),opt
            hpval(k,2)],opthpval(k,3),heel,0);
            seatx(k) = opthpval(k,1)+50*cosd(ang(3,k));
            seaty(k) = opthpval(k,2)+50*sind(ang(3,k));
            backx(k) = opthpval(k,1)-50*sind(opthpval(k,3));
            backy(k) = opthpval(k,2)+50*cosd(opthpval(k,3));
    end
    figure
    ttl=title('Optimal HPs with the angle of back and seat pan');
    set(gca, 'FontSize', 15);
    h = get(gca, 'title');
    set(h, 'FontSize', 20);
    hold on
    colors={'k','b','c','g','m','r','y','w'};
    color=colors;

    for k = 1:c
        plot([seatx(k),opthpval(k,1),backx(k)],[seaty(k),opthpval(k,2),backy(k) ]
            ,color{k})
        axis equal
        axis([0 500 0 300])
    end
    legend(lbl);
end

%%

if isempty(find(plots==2))==0 || outplotboo==2
    %% Plots the optimal HP trend for each percentile
    figure
    hold on
    axis equal
```
axis([0 500 0 300])
ttl=title('Optimal HPs based on Comfort, Vision, and Value Function');
set(gca, 'FontSize', 15);
h = get(gca, 'title');
set(h, 'FontSize', 20);

plot(opthplin(:,1),opthplin(:,2),'g')
plot(opthpnorm(:,1),opthpnorm(:,2),'r')
plot(opthpcomf(:,1),opthpcomf(:,2),'r')
plot(opthpvis(:,1),opthpvis(:,2),'c')
plot(opthpval(:,1),opthpval(:,2),'k')
legend('Comf','Vision','Value')
plot(opthpcomf(1,1),opthpcomf(1,2),'ro')
plot(opthpvis(1,1),opthpvis(1,2),'co')
plot(opthpval(1,1),opthpval(1,2),'ko')

end

if isempty(find(plots==3))==0 || outplotboo==2

figure
ttl=title('All Possible HP locations');
set(gca, 'FontSize', 15);
h = get(gca, 'title');
set(h, 'FontSize', 20);
hold on
axis equal

plot(hparray(:,1),hparray(:,2),'.y')

end

if isempty(find(plots==4))==0 || outplotboo==2

perx=80; % Percent interested in examining
for i=1:c
    k2=1;
    for k=1:length(value)
        if value(k,i)>((100-perx)/100)*valmax(i)
            topcomf(k2,i*2-1)=hparray(k,1);
            topcomf(k2,i*2)=hparray(k,2);
            k2=k2+1;
        end
    end
end

figure
ttl = title(['Top ',num2str(perx),'% of HPs in terms of value for each percentile']);
set(gca, 'FontSize', 15);
h = get(gca, 'title');
set(h, 'FontSize', 20);
hold on
```
colors={'.k','.b','.c','.g','.m','.r','.y','+y','.w'};
color=colors;
for k=1:c
    plot(topcomf(:,k*2-1),topcomf(:,k*2),color{k-floor((k-1)/6)*6})
end
legend(lbl);
axis equal
axis([1 500 1 300])

if isempty(find(plots==5))==0 || outplotboo==2
    % Plots the eye location for the top percent across all percentiles
    ind=1;
    [x,y]=size(topcomf);
    for i = 1:c
        for k = 1:x
            if topcomf(k,i*2) ~= 0
                [angle1,eyex1(ind),eyey1(ind)] = humanposition(humanmodel(:,i),[topcomf(k,1),topcomf(k,2)],opthpval(i,3),heel,0);
                ind=ind+1;
            end
        end
    end
end
figure
subplot(2,1,1)
plot(eyex1,eyey1,.')
axis equal
ttl=title('Eye location associated with each optimal HP');
set(gca, 'FontSize', 15);
h = get(gca, 'title');
set(h, 'FontSize', 20);
subplot(2,1,2)
plot(eyex1,eyey1,.')
axis equal
ttl=title('Eye location associated with top 1X% of HPs');
set(gca, 'FontSize', 15);
h = get(gca, 'title');
set(h, 'FontSize', 20);
rot = 6; % degrees
figure
title('Human Model(s) Positioned in Optimal Configuration');
for k=1:c
    x(1)=opthpval(k,1)-50;
    y(1)=opthpval(k,2)-50;
    x(2)=x(1)+b*cosd(opthpval(k,4));
    y(2)=y(1)+b*sind(opthpval(k,4));
    x_2=x(1)-f*cosd(90-opthpval(k,3));
    y_2=y(1)+f*sind(90-opthpval(k,3));
    subplot(3,2,k)
    plot(x,y,'g-')
    axis equal
    hold on
    subplot(3,2,k)
    plot([x(1),x_2],[y(1),y_2],'g-')
    axis equal
    [angle2, eyex2, eyey2]=humanposition(humanmodel(:,k), [opthpval(k,1), opthpval(k,2)], opthpval(k,3), heel, 1);
    ttl=title(label(k));
    set(gca, 'FontSize', 15);
    h = get(gca, 'title');
    set(h, 'FontSize', 20);
end

%%
end
APPENDIX B: FIVE BAR ANALYSIS

function [hpoint, seatpanangle] = five_bar_seat(ang_increment, plotboo)
if ang_increment == 5
    hpoint = zeros(7790, 2);
    seatpanangle = zeros(7790, 1);
elseif ang_increment == 7
    hpoint = zeros(2583, 2);
    seatpanangle = zeros(2583, 1);
elseif ang_increment == 15
    hpoint = zeros(820, 2);
    seatpanangle = zeros(820, 1);
end

% See figure for description of variable
a = 120; % mm   \ Values are measured from linkages in rm 136
b = 345; % mm   \ f

C = 60; % mm   \ |____|b__________|

d = 120; % mm   \    \  \  \c

e = 385; % mm   \ |<------e-------->|d

f = 400; % mm

rot = 6; % degrees - the rotation of the floor mount

h_point_x = 150; % mm
h_point_y = 145; % mm
R = [cosd(rot) -sind(rot); sind(rot) cosd(rot)];

backrest_angle = 100; % degrees - this is the angle of backrest relative
to the seat pan - it should stay fixed over the motion, positive CCW

i = 1;
in = 1;

for tilt_angle = 90:ang_increment:180 % angle between b and c
    for angle = 135-rot:-ang_increment:90-rot
        effective_link = sqrt(b^2+b^2-2*b*c*cosd(tilt_angle));
        phi = asind(c*sind(tilt_angle)/effective_link);
        [theta32, theta42] = position_analysis(a, effective_link, d, e, angle);
X1(1,1) = 0;
Y1(1,1) = 0;
X1(2,1) = a*cosd(angle);
Y1(2,1) = a*sind(angle);
X1(4,1) = X1(2,1) + effective_link*cosd(theta32);
Y1(4,1) = Y1(2,1) + effective_link*sind(theta32);
X1(3,1) = X1(2,1) + b*cosd(theta32+phi);
Y1(3,1) = Y1(2,1) + b*sind(theta32+phi);
X1(5,1) = e;
Y1(5,1) = 0;

BX(2,1) = X1(2,1) + f*cosd(theta32+backrest_angle);
BY(2,1) = X1(2,1) + f*sind(theta32+backrest_angle);

hpointx = X1(2,1) + h_point_x*cosd(theta32+phi+45);
hpointy = Y1(2,1) + h_point_y*sind(theta32+phi+45);

%Rigid body rotation based on seat angle
X2 = cosd(rot).*X1 - sind(rot).*Y1;
BX = cosd(rot).*BX - sind(rot).*BY;
Y2 = sind(rot).*X1 + cosd(rot).*Y1;

%H-point rigid body
slideinc = 6;
for slide = 0:slideinc:240
    hpointx=hpointx+slideinc;
    hpoint(in,1) = hpointx*cosd(rot) - hpointy*sind(rot);
    hpoint(in,2) = hpointx*sind(rot) + hpointy*cosd(rot);
    seatpanangle(in,1) = asind((Y2(3,1)-Y2(2,1))/b);
    in=in+1;
end

BX(1,1) = X2(2,1);
BY(1,1) = Y2(2,1);

if plotboo == 1 || plotboo == 2
    plot(X2,Y2,'-rs','LineWidth',2,...
    'MarkerEdgeColor','k',...
    'MarkerFaceColor','g',...
    'MarkerSize',1);
xlim([-150 500]);
ylim([0 500]);
hold on

plot(BX,BY,'-rs','LineWidth',2,...
    'MarkerEdgeColor','k',...
    'MarkerFaceColor','g',...
    'MarkerSize',1);

plot(hpoint(1+41*(i-1),1),hpoint(1+41*(i-1),2),'-bs',...
    'LineWidth',2,...
'MarkerEdgeColor','k',...
'MarkerFaceColor','g',...
'MarkerSize',10);

F(i) = getframe;

hold off
pause()
end
i = i + 1;
end
end
APPENDIX C: HUMAN MODEL

If the six major percentiles are requested, then this function is executed:

```matlab
% Seth Crouch
% Code pulls anthropometric data from an excel spreadsheet

function [humanmodel] = humanmodel()
% Columns Women 5th, Women 50th, Women 95th, Men 5th, Men 50th, Men 95th
% Rows Height, Eye level, Buttock-Knee, Popliteal, Knee Height, Buttock-popliteal, midshoulder

humanmodel = xlsread('humanmodel.xlsx');
```

The data that is imported from excel is displayed in Table C1.

<table>
<thead>
<tr>
<th></th>
<th>Women 5th</th>
<th>Women 50th (calc)</th>
<th>Women 95th</th>
<th>Men 5th</th>
<th>Men 50th (calc)</th>
<th>Men 95th</th>
</tr>
</thead>
<tbody>
<tr>
<td>height (1)</td>
<td>1542</td>
<td>1641.5</td>
<td>1748.612</td>
<td>1741</td>
<td>1863.934</td>
<td></td>
</tr>
<tr>
<td>eye level (relaxed) (18)</td>
<td>662</td>
<td>720.5</td>
<td>768.356</td>
<td>779</td>
<td>830.6671</td>
<td></td>
</tr>
<tr>
<td>Buttock-Knee (28)</td>
<td>531</td>
<td>581.5</td>
<td>604.8223</td>
<td>632</td>
<td>656.8666</td>
<td></td>
</tr>
<tr>
<td>Popliteal (27)</td>
<td>380</td>
<td>418.5</td>
<td>441.6995</td>
<td>457</td>
<td>491.3104</td>
<td></td>
</tr>
<tr>
<td>Knee height (26)</td>
<td>469</td>
<td>512</td>
<td>547.4221</td>
<td>555</td>
<td>600.8666</td>
<td></td>
</tr>
<tr>
<td>Buttock-popliteal (29)</td>
<td>434</td>
<td>480</td>
<td>499.9888</td>
<td>526</td>
<td>545.3778</td>
<td></td>
</tr>
<tr>
<td>midshoulder (19)</td>
<td>537</td>
<td>581</td>
<td>627.5449</td>
<td>625</td>
<td>682.6671</td>
<td></td>
</tr>
</tbody>
</table>

If a specific body type and sex is requested, then this function is executed:

```matlab
% Seth Crouch
% Program outputting the dimensions of different body segments for a specific individual based on sex and height

function [dim] = linklength(userheight,usersex)

%% Averages and Standard Deviations for Differing Body Links in mm
human = xlsread('humanmodel.xlsx','means&stds');

%% Determination of Approximate Body Link Lengths from Input Height and Sex
p = normpdf(userheight,human(1,usersex),human(9,usersex));
```
dim(1,1)=userheight;
for k=2:7
    dim(k,1)=norminv(p,human(k,usesex),human(k+8,usesex));
end

If a range of body percentiles in increments of one percentile are requested, then this function is executed:

% Seth Crouch
% This function outputs the anthropometric data for a range of percentiles.
% The range is in increments of 1 percent.
function [humanmodel] = humanincrem(beg,last)

%% Averages and Standard Deviations for Differing Body Links in mm
human = xlsread('humanmodel.xlsx','means&stds');

%% Determination of Approximate Body Link Lengths from Input Height and Sex
index=1;
for k=beg:last
    for i=1:2
        for d=1:7
            humanmodel(d,index) = norminv(k/100,human(d,i),human(d+8,i));
        end
        index=index+1;
    end
end

The data that is being imported from excel into MATLAB for the linklength function and the humanincrem function is shown in Table C2.

Table C2: Averages and standard deviations for the normally distributed anthropometric data for both women and men

<table>
<thead>
<tr>
<th>Averages</th>
<th>Women</th>
<th>Men</th>
</tr>
</thead>
<tbody>
<tr>
<td>height (1)</td>
<td>1641.5</td>
<td>1748.612</td>
</tr>
<tr>
<td>eye level (relaxed) (18)</td>
<td>720.5</td>
<td>768.356</td>
</tr>
<tr>
<td>Buttock-Knee (28)</td>
<td>581.5</td>
<td>604.8223</td>
</tr>
<tr>
<td>Measurements</td>
<td>Mean 1</td>
<td>Mean 2</td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>Popliteal (27)</td>
<td>418.5</td>
<td>441.6995</td>
</tr>
<tr>
<td>Knee height (26)</td>
<td>512</td>
<td>547.4221</td>
</tr>
<tr>
<td>Buttock-popliteal (29)</td>
<td>480</td>
<td>499.9888</td>
</tr>
<tr>
<td>midshoulder (19)</td>
<td>581</td>
<td>627.5449</td>
</tr>
<tr>
<td><strong>Standard deviations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>height (1)</td>
<td>60.48632</td>
<td>70.10476</td>
</tr>
<tr>
<td>eye level (relaxed) (18)</td>
<td>35.56231</td>
<td>37.87909</td>
</tr>
<tr>
<td>Buttock-Knee (28)</td>
<td>30.69909</td>
<td>31.63784</td>
</tr>
<tr>
<td>Popliteal (27)</td>
<td>23.40426</td>
<td>30.15864</td>
</tr>
<tr>
<td>Knee height (26)</td>
<td>26.13982</td>
<td>32.48907</td>
</tr>
<tr>
<td>Buttock-popliteal (29)</td>
<td>27.96353</td>
<td>27.59212</td>
</tr>
<tr>
<td>midshoulder (19)</td>
<td>26.74772</td>
<td>33.50893</td>
</tr>
</tbody>
</table>
APPENDIX D: VEHICLE DIMENSIONS

% Seth Crouch
% This function outputs the dimensions of the vehicle interior that affect
% where and how a user will position his or her seat

function [heel,eyeline] = vehicle()

heel = [920,0]; % position in the xy plane where the heel is located
890+30 (pos of sgrp)
H30=268; %125 from five_bar program
H8=0;
eyeline = 638+H30+H8; % inches above the ankle is where the eyeline is located
% Seth Crouch
% This program uses the body dimensions of the person(s) of interest, 
% the positions of the hpoint and heel, and the backangle to determine 
% the joint angles of the user(s). The angles and eye location are 
% output. 
% A plot of the user is displayed if requested.

function [angle,eyex,eyey] = 
humanposition(humanmodel,hpoint,backangle,heel,plotboo)

% Determination of Coordinates for Link Endpoints (joints)
[r,c] = size(humanmodel);
for k=1:c
    midshoulx = hpoint(1)-humanmodel(7,k)*sind(backangle);
    midshouly = hpoint(2)+humanmodel(7,k)*cosd(backangle);
    eyex(k) = midshoulx;
    eyey(k) = midshouly + (humanmodel(2,k)-humanmodel(7,k));
    [kneexx,kneeyy]=circsolv2(humanmodel(6,k),humanmodel(4,k),hpoint(1),hee
l(1),hpoint(2),heel(2),2);

    if isreal(kneexx(1)) == 1 && isreal(kneeyy(1)) == 1
        kneex=kneexx(1);
        kneey=kneeyy(1);
        again=0;
    elseif isreal(kneexx(2)) == 1 && isreal(kneeyy(2)) == 1
        kneex=kneexx(2);
        kneey=kneeyy(2);
        again=0;
    else
        again=1;
        kneex=kneexx(1);
        kneey=kneeyy(1);
        plotboo=0;
    end

    while again ~= 1
        if kneey>hpoint(2)
            kneeangle=atand(abs(heel(1)-kneex)/abs(kneey-heel(2)))+atand(abs(kneex-hpoint(1))/abs(kneey-hpoint(2)));
        else
            kneeangle=90+atand(abs(kneey-hpoint(2))/abs(kneex-hpoint(1)))+atand(abs(heel(1)-kneex)/abs(kneey-heel(2)));
        end
            %determine correct knee pos:
            if kneeangle > 180
                kneex=kneexx(2);
                kneey=kneeyy(2);
                again=again+0.5;
            else
            end

end

APPENDIX E: HUMAN KINEMATIC ANALYSIS
\texttt{\%\% Determination of Joint Angles}
\begin{verbatim}
if isreal(kneex) == 1 && isreal(kneey) == 1
    angle(1,k) = atand(abs(kneey-heel(2))/abs(heel(1)-kneex)); %leg angle
    angle(2,k) = atand(abs(heel(1)-kneex)/abs(kneey-heel(2)))+atand(abs(kneex-hpoint(1))/abs(kneey-hpoint(2))); %knee angle
    angle(3,k) = atand(abs(kneey-hpoint(2))/abs(kneex-hpoint(1))); %seat angle
    angle(4,k) = (90-angle(3,k))+(backangle); %hip angle
else % This happens when the hip point is located in a position such that the user cannot reach the pedals
    angle(1,k) = 'a';
    angle(2,k) = 'a';
    angle(3,k) = 'a';
    angle(4,k) = 'a';
end
\end{verbatim}

\texttt{\%\% Plotting of Simulated Person}
\begin{verbatim}
if plotboo == 1 || plotboo == 3
    plot([real(eyex(k)),midshoulx,hpoint(1),real(kneex),heel(1)],
         [eyey(k),midshouly,hpoint(2),real(kneey),heel(2)])
    axis([-500 1000 0 1000])
    pause(.05)
end
\end{verbatim}
APPENDIX F: COMFORT VALUE FUNCTION

% Seth Crouch
% This function receives information about the hip point location, seat
% back angle, and body angles in the given seating configuration.
% These
% are then used to determine the value of comfort experienced by the
% user.
% Depending on the selection of the person running the code, a linear,
% binary, or normal value function will be evaluated.

function [comfval] =
comfortvalue(hp,backangle,angle,excelboo,label,k,valboo)
kneeangle=angle(2,1);
seatangle=angle(3,1);
hipangle=angle(4,1);

if valboo == 1
  %% Linear value function
  if backangle < 20 || backangle > 30
    backvallin = 0;
  else
    backvallin = (5-abs(25-backangle))/5;
  end

  if kneeangle < 95 || kneeangle > 135
    kneevallin = 0;
  else
    kneevallin = (20-abs(115-kneeangle))/20;
  end

  if hipangle < 95 || hipangle > 120
    hipvallin = 0;
  else
    hipvallin = (12.5-abs(107.5-hipangle))/12.5;
  end

  comfval = mean([backvallin,kneevallin,hipvallin]);
elseif valboo == 3
  %% Binary Value Function
  if backangle < 20 || backangle > 30
    backvalbin = 0;
  else
    backvalbin = 1;
  end

  if kneeangle < 95 || kneeangle > 135
    kneevalbin = 0;
  else
    kneevalbin = 1;
  end
if hipangle < 95 || hipangle > 120
    hipvalbin = 0;
else
    hipvalbin = 1;
end
comfval = mean([backvalbin,kneevalbin,hipvalbin]);
else
    % Normal curve value function
    % This analysis assumes a normal distribution of comfort and calculates the
    % peak dependent value on the normal curve at the average. It then uses
    % this value to normalize the dependent values to 1.
    kneeavg = 122; kneestd = 10.6; %Knee angle (in plane of leg and
    thigh segments)
    backavg = 28.2; backstd = 5.8; %Torso (Hip-to-Shoulder) angle
    seatavg = 15.8; seatstd = 5.0; %Thigh angle (side view w/ respect to horizontal)
    normknee=normpdf(kneeavg,kneeavg,kneestd); %magnitude of normal
    function at mean used to normalize curve to 1
    kneevalnorm = normpdf(kneeangle,kneeavg,kneestd)/normknee;
    normback=normpdf(backavg,backavg,backstd);
    backvalnorm = normpdf(backangle,backavg,backstd)/normback;
    normseat=normpdf(backavg,backavg,backstd);
    comfval = mean([backvalnorm,kneevalnorm]);
end

% Evaluating the Value function and outputting all data to an Excel
% spreadsheet
% Value function is currently an even weighted average of each comfort value
if excelboo == 1
    xlswrite('comfortvalue.xlsx',' ',' ',' ',' ',' Linear',' ',' ',' Normal','
    ' ',' ',' ',' ',' ','hp','point x','hp','point y','back
    angle','back','knee','hip','AVERAGE'...
    ',back','knee','seat','AVERAGE'},label{k})
    xlswrite('comfortvalue.xlsx',hp,label{k},'A3')
if valboo == 1
    xlswrite('comfortvalue.xlsx',backvalin,label{k},'D3')
    xlswrite('comfortvalue.xlsx',kneevalin,label{k},'E3')
    xlswrite('comfortvalue.xlsx',hipvalin,label{k},'F3')
    xlswrite('comfortvalue.xlsx',comfval,label{k},'G3')
elseif valboo == 3
    xlswrite('comfortvalue.xlsx',backvalin,label{k},'D3')
```matlab
xlswrite('comfortvalue.xlsx',kneevalbin,label{k},'E3')
xlswrite('comfortvalue.xlsx',hipvalbin,label{k},'F3')
xlswrite('comfortvalue.xlsx',comfval,label{k},'G3')
else
    xlswrite('comfortvalue.xlsx',backvalnorm,label{k},'D3')
xlswrite('comfortvalue.xlsx',kneevalnorm,label{k},'E3')
xlswrite('comfortvalue.xlsx',comfval,label{k},'F3')
end
end
```
% Seth Crouch
% This function receives information about the where the eyeline should
% be in the vehicle and the location of the user's eye. It then
% calculates the value of the eye location based on a normally
% distributed eyellipse whose dimensions were experimentally determined
% to contain 95% of users eyes.

function [visionval] = vision(eyeline,eyey)

mu=eyeline;
sdx=139.2/4;
normx=normpdf(mu,mu,sdx);

visionval=normpdf(eyey,mu,sdx)/normx;
APPENDIX H: OVERALL SEAT VALUE FUNCTION

% Seth Crouch
% This function is the overall value function for the seating problem. It
% receives as inputs the value of the seating position to the user in terms
% of his or her ability to see and ability to sit comfortably. These are
% then combined into one overall seat value.

function [value,comfmax,opthpcomf,vismax,opthpvis,valmax,opthpval] =
valuefunc(hparray,comfval,visionval)

%%% Evaluating the Value function
value = .5*comfval + .5*visionval;

[comfmax,comfpos] = max(comfval);
opthpcomf = hparray(comfpos,:);
[vismax,vispos] = max(visionval);
opthpvis = hparray(vispos,:);
[valmax,valpos] = max(value);
opthpval = hparray(valpos,:);
REFERENCES


