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Applying axiomatic design principles to the House of Quality.

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APPLYING AXIOMATIC DESIGN PRINCIPLES TO THE HOUSE OF QUALITY

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I. ABSTRACT

This dissertation discusses the construction and use of a new design tool, the Axiomatic House of Quality (AHOQ). Many organizations have experienced problems with the implementation of the current House of Quality (HOQ) model. Problems included excessive development time, costs, and the loss of the customer's requirements. The author believed that the cause of these problems was due to differences in format, and misunderstanding of HOQ terminology. The author assumed that a standard model and terminology would reduce confusion during development and expedite the design process. However, most problems with the HOQ resulted from customer requirement dependencies. These dependencies cause excessive time as design teams attempt to resolve conflicting requirements. It was concluded that a standard model and terminology would not significantly improve the HOQ. Instead, principles and methods of the HOQ would be examined and modified to correct problems with consumer requirement dependencies.

This dissertation discusses the need for changes in the principles and methods used in the HOQ. Several other design tools and methodologies are examined to determine if there are any model characteristics that can assist in a solution to the HOQ problems. From the examination, Axiomatic Design (AD) provides the best solution to the dependency problems. The dissertation examines the methods and principles used in AD, primarily the use of the independence axiom. The information axiom is briefly reviewed, but not applied in this dissertation. The examination also identifies how the independence axiom can be used to resolve dependency issue in design.

After examining and identifying the benefits of AD, both AD and HOQ methods are used to create a new tool (AHOQ) for design. This tool assists in design development using functional requirements dictated by the consumer. These requirements would be independent from each other, allowing changes to the design without effecting other design requirements. The dissertation describes the development of the AHOQ using methods and principles of both AD and the HOQ. Included are the step by step instructions for the application of AHOQ design tool. Each step discusses the purpose, methods, and information required to apply the model for product development. Furthermore, each step includes three examples of AHOQ being applied to product development.

The final sections of this dissertation include discussion on the benefits that AHOQ provides over HOQ, with respect to product development time and cost. Furthermore, future opportunities for the AHOQ model including additional steps for design of manufacturing, the model's application for design evaluation, and the application of AHOQ in system design are also discussed. Finally, a simplified version of the AHOQ is provided in pamphlet form. It is to acts a quick reference guide on how the AHOQ can be applied to real world problems in design. It includes the construction steps of AHOQ using the one of the outlined examples.

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GLOSSARY

Quality Function Deployment (QFD)

- a strategic planning tool that helps combine the interests of both engineers and customers during product development.

House of Quality (HOQ)

- the primary matrix tool of QFD. It is a simple method used to visualise the relationship between customer requirements of a product and its performative characteristics.

Axiomatic House of Quality (AHOQ)

- A modified model of the House of Quality where product design is based on functional requirements. A design matrix replaces the relationship matrix where functional requirements and design parameters are governed by the independence axiom.

Relationship Matrix

- the section or room at the centre of the HOQ which represents the relationship between customer requirements and technical characteristics.

Correlation Matrix

- the roof of the HOQ where technical requirements are correlated.

Voice of the Customer

- the principle of defining the requirements of the product or system specified by the customer.

Axiom

- A self-evident truth or fundamental truth for which there are no counter examples or exceptions.

Design Axioms

- The basic principles, or acceptable stated facts, for analysis and decision making.

Axiomatic Design

- The process of design developed by N. P. Suh using design axioms as a guideline for decision making.

Independence Axiom

- To maintain the independence of the Functional Requirements (FRs).

Information Axiom

- To minimize the information content of the design.

Information Content

- The probability of being able to satisfy a given functional requirement (Suh [10], p.297]).

Principle

- The laws or rules that governing over a system or theory.

Module

- The row of the design matrix that yields a functional requirement when it is provided with the input of its corresponding design parameters.

Tool

- An instrument or apparatus used in performing an operation in the practice of a profession. The HOQ and AHOQ are considered as design tools in terms of their application.

Model

- A miniature representation or emulation of an object or process. The HOQ and AHOQ are considered as models of a design.

Domain

- A specified range of influence.

Consumer Domain

- A specified range influenced by the consumer.

Functional Domain

- A specified range influenced by functional properties.

Physical Domain

- A specified range consisting of physical characteristics.

Process Domain

- A specified range consisting of process characteristics.

Customer Attribute (CA)

- A design attribute derived or requested by the customer.

Functional Requirement (FR)

- A minimal set of independent requirements that characterizes the functional needs of the product in the functional domain.

Design Parameters (DP)

- Key physical variables in the physical domain that characterize the design satisfying the specified FRs.

Process Variables (PV)

- Key variables in the process domain that characterize the process which can generate the specified DPs.

Constraints

- Bounds on solutions.

Physical Constraints

- A constraint placed by the consumer on physical attributes which do not affect the functionality of the design.

Design Constraints

- A constraint that serves as a limit or goal to any of the FRs or DPs of the design.

Design Matrix

- The matrix that displays the design mapping process between FRs in the functional domain to DPs in the physical domain.

Coupled Design

- A design in which a change in one of the design parameters will have an effect on more than one functional requirement. Dependencies in the design exist.

Uncoupled Design

- A design in which changes in one design parameter will affect only its corresponding functional requirement. The design is considered as independent.

Decoupled Design

- A coupled design that can be adjusted or decoupled to achieve independence by resolving design parameters in a particular order.

QFD

- Quality Functional Deployment. See Quality Functional Deployment.

HOQ

- House of Quality. See House of Quality.

AHOQ

- Axiomatic House of Quality. See Axiomatic House of Quality.

AD

- Axiomatic Design. See Axiomatic Design.

FR

- Functional Requirement. See Functional Requirement.

DP

- Design Parameter. See Design Parameter.

PV

- Process Variable. See Process Variable.

CA

- Customer Attribute. See Customer Attribute.

TR

- Technical Requirement. A design requirement used to satisfy a Customer Attribute in the House of Quality.

I. INTRODUCTION TO QUALITY FUNCTION DEPLOYMENT

Quality Function Deployment (QFD) is a strategic planning tool that helps combine the interest of both engineers and customer during product development. It was first developed by Mitsubishi Heavy Industries for the Kobe shipyard in Japan in 1972. QFD is defined (King, 1991) as, "a system for designing a product or service based on consumer demands and involving all members of the producer or supplier organization." It is considered as one of the few pro-active tools in the otherwise reactive field of quality control.

The purpose of QFD is to identify and incorporate the consumers needs during the design of a product; as such QFD is sometimes referred to as the "*Voice of the customer.*" During a product's design phase, the customer's requirements for the product are formulated and evaluated to determine if they can be applied to enhance the product. The objective is to create a product based on what the consumer needs, not what management, marketing, or other "third parties" think the consumer needs. QFD is able to translate the customer's requirements into technical requirements for each stage in the product's development and production cycle. The goal of the QFD process is to create a product that meets the demands of the customer, reduce the risk of misinterpreting customer requirements, and to minimize design changes.

QFD is applied by first determining who are the target customers. This is conducted using a *Planning Matrix*. The target customers are those who intend to use and benefit the most from the designed product. They are surveyed with questions about the product being designed, to determine design considerations that would increase its quality in their eyes. Once all the considerations have been identified, that information can then be used to develop the House of Quality Matrix.

The House of Quality (HOQ) is the primary matrix tool of QFD. It is a simple method used to visualize the relationships between customer requirements of a product and its performative characteristics. It provides three key important pieces of information: 1) The relationship between customer needs and engineering characteristics of the product; 2) A comparison of the designed product with competing products; and 3) A summary of engineering trade-offs inherent in the design.

The HOQ has many uses, but its primary purpose is to translate the customer's requirements into formal engineering targets and to represent the information necessary for the translation in a readable and understandable format (Ramaswamy and Ulrich, 1993). The traditional HOQ matrix consists of four interrelated *sections* or *rooms* (Figure 1). The center room is the primary matrix of the house. Each row represents a customer's requirement (WHATS) and each column represents a design characteristic (HOWS). The requirements specified by the customer are referred to as customer requirements or customer attributes. It has been decided for this dissertation that the two terms are identical, describing the requirements for the design set by the customer. Therefore, both can be used interchangeably. Each cell of the matrix indicates the strength of the relationship between a customer requirement and a design characteristic. If a relationship between design and customer requirements exists, traditional ratings of *strong, medium*, or *weak* would be applied, otherwise it is left blank. The roof of the house is a correlation matrix for design characteristics. It displays the relationships between the design characteristics only. Design characteristics will either complement each other thus improving the overall design of the product, or conflict thus deteriorating the design.

ROOMS OF THE HOUSE OF QUALITY

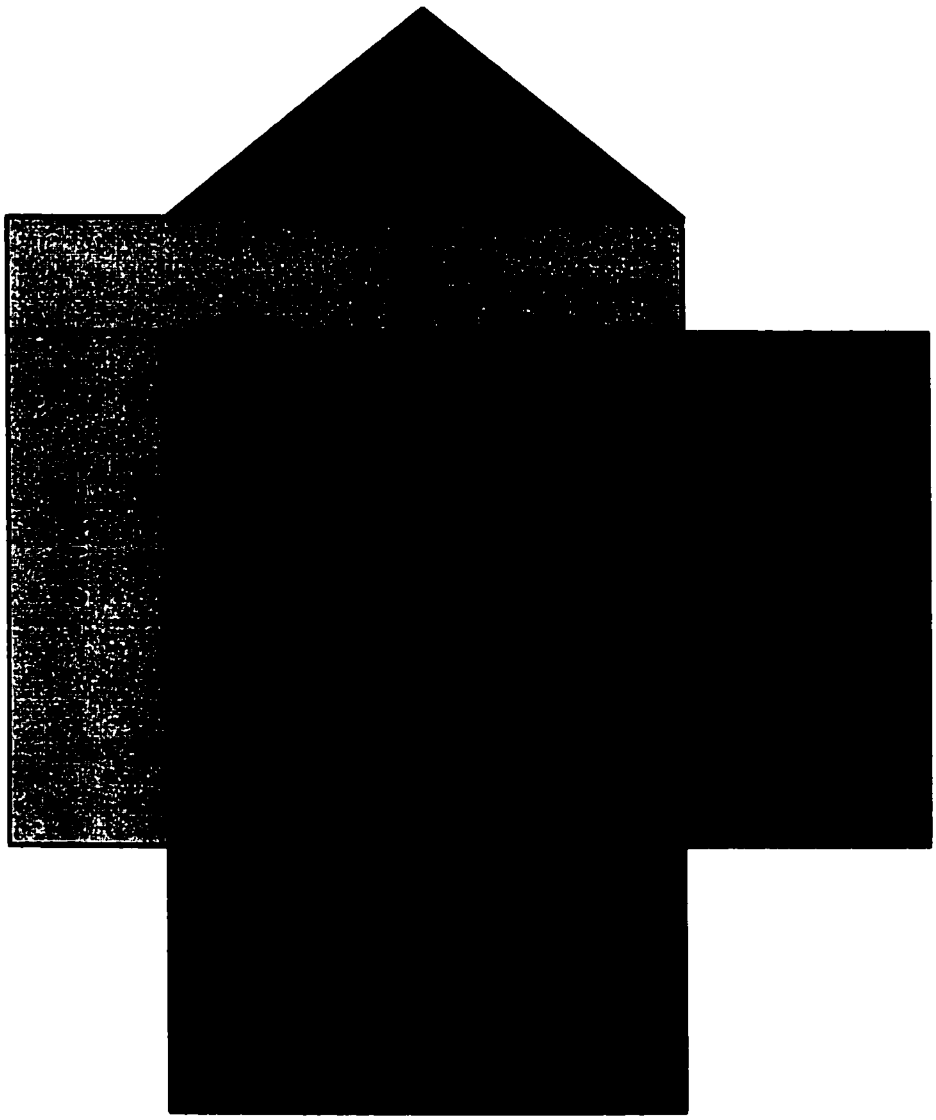


Figure 1 – Rooms of the House of Quality
A framework of the HOQ model identifying each room in the model. Consumer attributes are listed along the left, and technical requirements are listed above. The Relationship Matrix displays the relationships between all customer attributes and technical requirements. The Correlation Matrix displays the relationships between the technical requirements only. The Competitive Assessment section is used to determine how well each product achieves the consumer's needs. The Bench Marking or Basement section provides quantitative measurements for the technical requirements.

The room at the right is the competitive assessment. It displays how the product compares with competing comparable products, and is based on the customer requirements listed in the center room. The final room is known as the basement. The basement is used primarily for benchmarking the design requirements of the product against those of its competitors, and for summing quantities in other parts of the matrix.

With the use of HOQ, a design team would be able to determine the necessary design characteristics for a good product. Furthermore, the matrix displays where their product stands against competing products with respect to both quality and consumer requirements.

Currently, more and more companies are using QFD and HOQ to design a product based on consumer demands. However, with the increased use of QFD many alterations are being made so that it can be tailored to each individual company. Most of these alterations occur in the structure of, and values in the HOQ. With changes in the HOQ, problems may occur in its application and compatibility across a supply chain: a HOQ that works for one department or company may not work for another.

The different formats used for the HOQ can create many problems. With an increasing amount of variations in the HOQ, it becomes difficult to identify the standard or generic HOQ. Compatibility problems may arise from small variances in the HOQ when two or more companies are sharing ideas. This could lead to neglecting important consumer requirements, decreased quality, and even faulty products. These problems could discourage companies from using QFD and the HOQ, or misunderstand the information that it provides.

A standardized format for the House of Quality was considered. It would have provided many advantages in product design and development. Currently there are many problems with the methods used when developing a product's HOQ and its decision matrices. These problems include increased time, costs, and a possible loss of the customer's voice that would yield a product that does not address the customer's needs. The advantages of a standard model included increased interoperability between users, greater robustness, greater efficiency, and less misinterpretation of results.

To achieve a standard model, five different areas in its construction were examined. These areas include the unification of terminology, common and proper use of symbols in the correlation and relationship matrices, a standard system of weights and ranking methods, a standard method of HOQ construction, and the examination of model flexibility for specific user domains. It is believed that these are the key factors that compose the HOQ, and many variations exist when examining various literatures on QFD and HOQ. The purpose for creating a standard model was to control the variations between the different models of the HOQ such that problems with misinterpretation, loss of focus, and increased time would be eliminated. However, after further review it was questionable if standardizing these factors would provide a more efficient model, or if there was need to examine the principles that govern the HOQ itself.

It would not be correct to state that standardizing the aforementioned five factors would have no effect on efficiency. Standardizing these factors would allow for easier development and communication of the HOQ. However, the standardization of some of the factors were deemed less important than others. The factor of standard symbols can be debated since standard symbols would improve interpretation and recognition timing. However, some systems or presentation tools (i.e. computers and specially designed software) may not have the capability for providing the required symbolic characters and therefore must use whatever is available. Furthermore, Hauser and Clausing (1988) recommend that the developer of the HOQ should use symbols that work best for the design group. Therefore the need for standard symbols remains questionable.

The use of weights and ranking methods is also questionable. From the reviewed literature there has been no mention of the importance or the purpose of using existent ranking methods in the HOQ. The methods in question are the 1 to 5 system of ranking used for product comparisons, and the 9-3-1-none and 4-3-2-1 systems used in the relationship matrix of the HOQ. A 1 to 5 system of ranking is used to show how well a design achieves each customer attribute in the competitive analysis. In the relationship matrix, the strength of the relationship between customer attributes and technical requirements are represented using a 9-3-1-none system or a 4-3-2-1 system. Each numbering system represents four levels of relationship strength. The rule is the stronger the relationship, the higher the number assigned. The problem between the two systems listed is that an increase in relationship strength is not always linear with respect to the assigned number. An increase in strength from 3 to 9 in one system is not the same as an increase in strength from 3 to 4 in the other numbering system. Since there was a lack of information provided for these methods, it would be inconceivable to arbitrarily pick one method over the other for the standard model without any explanation or examination.

However, some factors of the HOQ would require a standard format to simplify its implementation. Different terms exist that describe similar components of the HOQ. The different terms can easily confuse the design team or other users of the HOQ, thus increasing time and expense. It is still believed that standard terminology should be applied to the HOQ to improve communication and reduce the chances of misinterpretation.

Even though there are discrepancies with some of the factors identified to create a standard model, it is believed that these are the key areas that could improve the HOQ and its implementation. However, not much has been described in the literature about the principles underlying the HOQ. Therefore, a new problem surfaces since a standard model cannot be created based on methods when there are problems with the HOQ principles itself. The problems of principle must be resolved first since changes to the principles will affect the methods to be used.

The basic principles of the HOQ are to identify the customers needs, and cross-reference them with the technical requirements of the product. These interactions are identified as being favourable or not favourable, thus creating decision variables that helps steer the design team towards a more ideal product from a consumer's point of view. However, when constructing the HOQ, not much is stated on what qualifies as customer attributes or technical characteristics. From the reviewed literature, there are no rules for the management of acceptable requirements for the technical and customer's needs lists. Since these lists are the first step of any HOQ, more attention should be focused on the quality of structure of these lists because of their significant impact on the entire HOQ. Situations do arise where specific customer attributes or technical requirements will conflict, thus one must be sacrificed in order to appease the other. Specific design characteristics resulting from selected technical requirements can have a negative impact on other customer requirements depending on their relationships to each other. Changes must be made to the design such that all customer requirements have been satisfied. Such decision making may become difficult, increasing the time in product development. This increase in time causes increases in costs and delays the product from reaching the market. Furthermore, if an incorrect attribute is chosen, the potential loss may be great.

For this reason, the author proposes to integrate other design theories with the HOQ. By applying these principles from these theories, the author believes that there will be a significant improvement in efficiency in matrix construction and decision making; fewer chances for redundant information; and improved focus on the customer's voice.

The remainder of this dissertation will focus on other design theories, and how they can be used in the HOQ.

II. PROBLEMS WITH THE CURRENT HOUSE OF QUALITY DESIGN

In the original proposal of the author's dissertation, it was discussed that two of the primary problems of the HOQ are excessive development time, and the possibility of losing the customers' input in the design of the product. Excessive development time increases development costs and decreases the ability of the product to attract a large market share. The second problem (referred to as "Loss of the Consumers' Voice" or VOC) often occurs when the design team puts their perceived design requirements over those of the consumers.

1. Problems with Excessive Development Time

The problem of excessive development time has been discussed by Goldense, who identified that only 5 -10% of companies that use the HOQ once, continue using it (Goldense, 1993). He states that most companies do not continually use the HOQ due to increased development time and costs that arise from improper implementation. The problems that lead to excessive development time include coupled consumer attributes that require many iterations to satisfy, poor decision making, and a lack of available data. Due to these problems, time-to-market can increase significantly.

Coupled consumer attributes occur when two or more consumer attributes in the HOQ are directly related, thus the design team must revisit decisions that were made previously. This dependency may cause the design team to make repeated changes to the relationship matrix until the ideal solution has been achieved. An example of this problem is the consumer attributes for a car door. The attribute of having a light door for easier opening and closing may conflict with the attribute of having a sturdy door for safety. This will result in the design team revisiting the ranks and weights developed for these attributes in an attempt to satisfy both of these needs equally (or based on the consumers' preference rankings). The design team may conclude from the competitive ranking in the HOQ that they wish to improve the door's durability to a level equal to that of their competitors. However, to increase the door's durability, additional metal reinforcements must be added. This results in an increase in the door's weight, therefore making the door more difficult to close. The end result is that by adding the metal reinforcements, the company's car door now competes with that of the other companies in terms of durability. However, the company has potentially lost ground to the competitors in the attribute of ease in opening and closing the door. Therefore, after each change the design team must re-evaluate the impact of the change to the other attributes. Even though some of these problems are resolved after one or two visits, much time is required to perform each change and evaluate its effects on the rest of the HOQ.

Poor decision making often occurs when evaluating coupled attributes or when there is a lack of data (in which case, "educated guesses" must be made). Whenever an incorrect or poor decision is made, the design team must revisit the location of the model where the decision was made, then develop and implement another, hopefully correct decision. When implementing the new decision, the design team must re-trace all of the work that was carried out previously, making necessary changes to the HOQ. The length of time required to perform all of these changes varies depending on the effects that they have on the HOQ.

Excessive time caused by unavailable data can lead the design team to make guesses on HOQ decisions. Additional time is required to correct the inaccurate guesses. Furthermore, a lack of data can cause increased development time as designers search for missing information. Overall, unavailable data causes two situations where excessive time can occur. Either the design team must perform iterative changes to the HOQ due to speculation, or the design becomes idle as the team attempts to obtain the missing information.

Excessive development time creates two cost associated problems. The first problem is the increased cost of developing the product. The increased time required to create the product results in increased labour costs for the design teams. Furthermore, if any prototypes or equipment have been developed for the product during the development phase, then those expenses would increase for each change made to the HOQ or the product. Therefore, as development time increases, there is an increase in labour cost, and an increase in material and equipment costs due to changes. The second cost is an opportunity cost. As the development time for the product increases, the chances to deliver the product to the market first decreases. The goal of product development is to develop a product that contains all the designed features that the consumer requires, and ship the product to the market quickly before the competition develops a similar product. Being the first company to sell the product would ensure a large percentage of sales since the product is the only one of its kind, with little to no competition. However, excessive development time gives the competing companies a chance of selling their product first. Even if the company's product is a better design than that of the competitors, the competing companies will still hold a large portion of the market share since its product was offered for sale first.

An example of this problem is as follows. Assume the fictitious companies A and B. Companies A and B are both developing coffee makers. Both companies' coffee makers contain all of the required consumer attributes designed in their product, however company A is attempting to include an automatic turn-on timer. Company B does not intend to include a timer in their product. Company A planned to start selling their product 1-month before company B. However, due to design problems with the automatic timer, their development time has increased by 3 months. This results in company B delivering their product to the market 2 months ahead of company A, allowing them to take an assumed 65% of the market share. Even though company A's coffee maker is a better design, since it arrived at the market 2 months late they only claimed 30% of the market share. If they would not have had excessive development time, they may have captured 85% of the market share. Company A had experienced opportunity cost due to excessive development time.

2. The Problem Involving the Voice of the Customer

The second of the two HOQ primary problems is losing the voice of the customer in the design of the product. The "voice of the customer" refers to the attributes of the product that the consumer finds most important, and should be included or improved in the final design of the product. This is an important part of the HOQ since the model uses customer attributes as a basis for design. The intended goal is to use these attributes to design a product that the consumer wants, and will purchase over its competitors. However, it is possible that the HOQ may not be successful in providing a product that the consumer wants. It is possible that the design team could unintentionally neglect the desires of the consumer in the design of the product.

Loss of the consumer's voice can occur intentionally or accidentally. Intentional neglect occurs less frequently. It usually occurs when the design team puts their own beliefs ahead of that of the consumers, or if there is no technical means to achieve a specified consumer attribute. Since the purpose of the HOQ is to involve consumer input into the product design, it is understandable why intentional neglect seldom occurs.

The accidental loss of the consumer's voice occurs more frequently than intentional losses. The most common cause of the error is during iterative changes of two or more dependent attributes. When the design team attempts to satisfy two or more consumer attributes, judgements may be made against the requirements of the consumer, in order to bring improved results in other dependant consumer attributes. Even though ranking and weight methods have been used in the HOQ by the consumer, sometimes the design team may not properly perceive the importance and priority of the attribute as set by the consumer.

In our example of the car door, the two consumer attributes of a door *easy to close* and *increased durability* can demonstrate how the loss of the customer's voice can occur. Even though the consumer requires both attributes, a higher rank and weight was assigned by the consumer to the door's durability attribute. This may be the case if the consumer has a higher regard for safety than the ease of closing the door. As the design team constructs and evaluates the HOQ, they may have been instructed to keep material costs low. This unintentionally leads them to disregard the attribute of increasing the door's durability since it would require additional material for bracing, thus increasing the cost. Since the design team disregarded the importance of the durability attribute, the customer's requirement for safety is unheeded and the voice of the customer has been lost.

It has been discussed by the author that some of the problems with the HOQ are due to excessive development time and the loss of the customer's voice. Originally it was assumed that a standard model for the HOQ would help eliminate these problems. However, it has been discovered that these two problems are not faults of the model structure, but the principles and methods that the model is founded on. The primary problem is dependency between consumer attributes that leads the design team to spend excessive time manipulating the model, making ad-hoc decisions, and sacrificing the requirements of the consumer. What is required is an evaluation of the methods and principles that would eliminate unnecessary dependency on attributes. This would improve the HOQ since less time is required to evaluate trade-offs between attributes, and the attributes that have the most impact to the product design would not be affected.

III. PROPOSED SOLUTIONS

In the preliminary dissertation, an attempt was made to provide a standard model that would provide a common format for developing the HOQ. The goal of this model was to provide a format, which all users could follow, eliminating increased development times, costs and confusion due to differences in terminology, symbols and calculating weights. The standard model was intended to be used by different departments of an organization, or between organizations such that information loss is minimized.

With further study, however, it became apparent that many difficulties remained. Information on QFD and the HOQ was very limited. Most published books on the subject provided a general description of the purpose of QFD and HOQ, with little information on how they work. Most of the time the available books had minor examples that were incomplete or without proper explanation. W. Eureka and N. Ryan (1988) discuss the use of QFD in design, but do not give detailed explanations on the HOQ and why the illustrated ranking and weight methods were used. Furthermore, information from major commercial organizations was limited. Most organizations could not release such information due to its sensitive nature, and others had not yet adopted QFD. The lack of literature created difficulties when studying the differences in the weight systems (9/3/1/none, 4/3/2/1...) and ranking systems (1 to 5, 1 to 10). Since no reasoning was provided for these different systems, conclusions on their use in a standard model could not be drawn. Further problems occurred when examining the different types of symbols used in the Relationship and Correlation matrices. Between most examples there were differences in the symbols. Some examples used circles and triangles, others checkmarks and X's, and others used numeric values. It became apparent that the choice of symbol used was sometimes not due to the author's preference, but to the limitations of the software or equipment used to construct the HOQ. Some software programs are limited to their character set of symbols, therefore the author must use what's closely related to the symbol.

Hauser and Clausing stated that the use of symbols is not a problem, just as long as the design team uses symbols that works best for the model (Hauser and Clausing, 1988). The reasoning behind this is that a standardized HOQ model may not work in an environment filled with different corporate cultures. Different companies have different design methods and management. A standard HOQ model may hinder the used of these methods. This would create problems and errors in the HOQ model's construction. Hauser and Clausing believe that these companies should use the symbols and ranking methods that work best for them to eliminate confusion and error in the model's construction. Therefore, standard symbols and ranking methods may create more problems instead of improving the HOQ.

Another problem was the lack of information and reasoning, making it difficult to develop criteria for a standard model. Information on the HOQ was difficult to find. From the information that was available, there was no one method that was commonly preferred over the others. Furthermore, it could not be determined if a standard model would provide such improvements in time, cost, and loss of the VOC. However, before improving the model of the HOQ, the principles of the HOQ must be examined and improved upon first. It is believed that the HOQ can be more efficient if changes are made to the principles that it is based upon.

The goal of the HOQ is to develop the most marketable designed product based on consumers input into the design of the product. Tools such as the relationship and correlation matrices achieve this goal. These matrices analyse the relationships between the design characteristics of a product, and the functional requirements set by the consumer to obtain the most practical design. The primary principle or method that allows this is the process of relating "*what* is expected" to "*how* to achieve it". In many cases they adversely effect one another.

This principle of relating how's and what's is believed to be one of the main factors that leads to excessive development time. Since one design attribute can have various effects on other attributes, the overall target variable for that attribute may vary since it is a function of numeric ranks and weights with respect to the relationships of the other variables. The problem of excessive time occurs when changing one of the attributes leads to a different result in the target variable. Thus different results in the target variable may lead to excess development time. It is believed that if improvements can be made to this principle, then changes in attributes will lead to less variance in target variables therefore reducing development time and costs. In other words, if the method of comparing these relationships were improved, then that ability to achieve the most idealistic design of the product would be reached more quickly.

It is important to note that the design principles used in the HOQ are not unique. Many of the methods and principles used in the HOQ are found in other design theory techniques developed by other authors. The application of the methods may have some variations to the HOQ, however their objectives and final results are somewhat similar. Examining these methods can provide some additional insight on possible solutions to problems in the current methods of the HOQ. The author believes that the current problems in the HOQ will be reduced or eliminated by incorporating some of the other design principles used in design theory. Therefore it is important to review the differences and similarities of these methods and determine if they can offer any improvement to the HOQ.

In the HOQ, the guidelines used when listing customer attributes and technical requirements may contribute to problems in excessive development time. A single customer attribute or technical requirement that contains a grouping of information may lead to confusion if it provides various relationships to another customer attribute (CA) or technical requirement (TR). An example of this situation is the car door example. A functional requirement of the car door is if it is secure when closed. This function has the sub-functions of prevention of airflow between door, and self-locking when closed. To relate the door's security to other requirements would be difficult since the function contains other sub-functions that may have different relationships. However, by decomposing the function into sub-functions, relationship comparison is much easier. Barry Hyman (1998) suggests that in decision making, all features or functions of a product should be broken down into single criteria. He refers to this process as 'reducing to the product's economic values'. Taking a single complex design function and decomposing it into multiple smaller criteria reduces design barriers when comparing between other functional criteria. Reduced barriers allow for an easier comparison between two design functions since judgement can be made on one or two issues that exist between the two functions instead of a larger more complex number of issues. Some examples of the HOQ break complex customer attributes down to several smaller attributes, however most literature reviewed on the HOQ does not provide a detailed discussion on performing this operation including the effects it may have on the resulting product.

It is important to break down CAs and TRs into simpler, single functional criteria since it allows for and easier comparison of these relationships. Even though some models do break down CAs and TRs properly, it is believed that some organizations using the HOQ do not properly break down these attributes, therefore creating further problems when comparing relationships.

This method of functional decomposition is also discussed by Dixon and Poli (1995). In their method of functional decomposition, they state that the design team should identify the sub-functions that only fulfil the overall function of the product. This allows the design team to focus on those functions that serve as the primary purpose of the product. The end result is that the product is more properly designed for its intended use, and less time is required since only the primary functions have been the focus. This differs from the views of Hyman, who places no exceptions or limitations on identifying the sub-functions during decomposition. In the car door example discussed earlier, the additional function of child safety locks may be neglected since it does not provide the end means to the primary function of the ease of closing the door. It is important to note that this method does conflict with current HOQ principles. If specific functions are deemed unnecessary since they have little to no support for the end function, Dixon and Poli's methodology would neglect that function. However in the HOQ, if the consumer places a high ranking for that desired function, then Dixon and Poli's method would be violating the voice of the customer.

The method that Dixon and Poli discuss is referred to as the "Function-First Approach". It requires the design team to think in abstract terms about pure functions and about physical principles and effects. The purpose of this approach is to create the design of a product based only upon its intended functions. This approach requires three steps for implementation. The first step deals only with the functions of the product, where the primary functions for the products end purpose are identified. These functions are also decomposed into sub-functions until the simplest functions are obtained. The second step examines each of the decomposed functions and looks for specific principles and effects that can be implemented to achieve those functions. The final step examines the principles and effects to determine the required mechanics or hardware required that would satisfy those functions.

An example of this method is the design of a space heater. In the first step the functions of the heater are listed and decomposed. The main function of the space heater is to maintain spatial temperatures. This function can be decomposed into five other sub-functions; 1) the conveying of energy to the unit, 2) the control of energy flow, 3) the conversion of electrical energy into thermal energy, 4) the distribution of energy through the room, 5) and an enclosure to support and protect the unit and its parts. These functions are further decomposed until they are in their simplest form.

Once all of the functions have been listed, physical principles and effects are then examined to achieve the functions. In the function of converting electrical energy to thermal energy, two principles can be examined. Conversion can be achieved through either electrical resistance, or mechanical resistance. The function of distribution of the thermal energy can either be done through convection or forcing the circulation of air.

The final step of implementing mechanics to achieve the functions involves determining what mechanical or electrical devices are available that would best perform the function. In the function of energy conversion, electrical resistance can be achieved by running a current through an element to generate heat. For mechanical resistance, a motorized cylinder and brake can also provide heat from friction.

The advantages of this approach are that the product is designed based on the functions required for its end use, where no time is spent on unnecessary functions that do not contribute to the product's end use. This is advantageous since focusing on the primary functions would reduce the development time of the product. Furthermore, this method allows the examination of options that may have not been considered to fulfil the required functions. This method focuses on each individual function, with an added step where the design team must evaluate alternatives for each function. Other methods sometimes lead the design team to quickly select specific principles without much time for consideration.

As mentioned earlier, the function-first method differs from that of the HOQ. The function-first method is based on determining the primary functions required in a product, then evaluating methods to achieve those functions. In contrast the HOQ is based on deriving engineering attributes from the needs of the consumer. The difference is that these consumer needs are "design objectives" in that they represent attributes of the product - what the product has "to be", whereas the product's functions are what the product has "to do". An engineering attribute is required for every consumer need (whether related directly to the product's end purpose or for some other non-purpose-related function i.e. colour, texture...) and its importance is based on the consumer's ranking of the corresponding need. This differs since the function-first method disregards unnecessary functions that have no influence on the product's desired end function. This would result in a loss of the voice of the customer since some consumer desired preferences would be neglected. Furthermore, the function-first method uses a lower level of consumer input into the design of the product compared to the HOQ. Customers' desires are considered, but as only one of many factors and designers may choose to disregard them. However, even with these differences, some of the principles in the function-first method could be applied to the HOQ to help improve product development time. In order for such a system to be implemented, adjustments must be made to the classification of functions in both the CAs and TRs and the ranking systems used in the HOQ. Adjustments are necessary since these are the controlling factors that dictate which functions are most important in the product's design.

Like Poli and Dixon, V. Hubka and W. Eder (1988) also discuss the break down of the functional hierarchy into the simplest functions in their book "Theory of Technical Systems." They state that each function may be assigned to a certain degree of complexity in a hierarchy of complexities. The lowest degree of complexity is occupied by the most elementary functions. These elementary functions are the same as the simplest functions as described by Dixon and Poli. Hubka and Eder refer to this functional hierarchy as the technical system function structure, where the function is a property of the technical system and describes its ability to fulfil a purpose. This method does not seem to differ from the function-first method described earlier. There are many similarities in the fact that the design of the product primarily focuses on the functions it intends to perform, not its attributes. Secondly, this method requires a breakdown of complex functions into simpler functions. The author is unsure if there are any other differences in both principles since Hubka & Eder's work discusses cases of application instead of a detailed description of the theories behind this method.

Another design method discussed earlier was Nam Suh's Axiomatic Design theories (1990). Axiomatic Design (AD) is another method that develops a product based on its intended functions. The principle of designing a product based on functions is similar to the other methods discussed. Furthermore, in AD the functions must also be decomposed into simpler sub-functions that are easier to resolve. However, AD has some differences when compared to the other methods because it takes functional design another step further. Specific rules are placed on the developed solutions to these functions that place limitations in the design.

Suh states that design requirements start with establishing "Functional Requirements" (FR) to satisfy a given set of needs, and ends with the creation of an entity that satisfies the FRs. The entity is based on design parameters (DP) that are derived from the FRs. As stated, this method has similarities to the function first method discussed earlier. However, AD is based on two axioms that govern the selection and use of the FRs and corresponding DPs. The first axiom is the Independence Axiom: all FRs in a design must be mutually independent. Its purpose is to prevent the coupling of FRs when the DPs are changed in the design. If FRs become coupled, it becomes difficult to find a solution that satisfies the coupled FRs. The second axiom is the Information Axiom, the objective of which is to minimize the information content of the design. Its purpose is to use the least information possible to prevent additional constraints to the design. These axioms are the primary difference between AD and the other methods discussed.

An example of how AD works can be illustrated in man's attempt to fly (Suh, 1990). Originally, man developed wing like structures and various machines in an attempt to fly, however all those designs were unsuccessful. The problem was that they considered too many functional requirements in order to achieve flight. Most of these functional requirements were dependent on one another, thus many alternatives where influenced by slight changes in the design of the flying device. The Wright brothers when designing their aircraft only considered three functional requirements; near horizontal take-off, optimal cruising speed, and the ability to change direction. With these three functions they were able to develop the first successful design. Furthermore, the listed functions are independent of each other, which allowed them to develop solutions for each function that would have minimal influence on the other functions. Even though the Wright brothers were not directly using AD, similar principles were considered in their design.

The advantage that AD provides to the HOQ is that CAs can now be properly broken down into individual FRs. Furthermore, these FRs in the HOQ follow a set of principles, the independence and information axioms that assist in the development of the product. The use of these axioms reduces the number of variables in the design, and concentrates the design team to focus on the primary functions that the customer requires the product to perform. The end result is that the product can be designed faster and more efficiently, reducing the excessive decision making time and cost. However, like the function-first method, there is the disadvantage of losing the customers voice in the design of the product. Ensuring function independence could lead to the elimination of specific functions that the consumer requests. Therefore, further discussion is required to provide a solution to this problem.

Reviewing the outlined papers concluded that there are many methods of designing products based on its intended functions. Overall, most of the methods were identical except for some omissions or depth in the method that leads the design team. Suh's AD method provides the most detail on dealing with function design. Like the other papers, it provides principles and methods on how to break down complex function into smaller sub-functions that are easier to work with. However, this method unlike the others provides additional principles that assist in managing the required functions for the design. This creates possibilities in the attempt to reduce excessive development time, or improve current development times, which provides a reduction in development costs. For this reason, this thesis will use the principles and methods of AD and incorporate them with the HOQ in an attempt to reduce development times and costs, thereby making the HOQ more effective.

IV. WHAT IS AXIOMATIC DESIGN AND HOW DOES IT WORK

In the evaluation of other design methods, all of the methods focus on designing the product based on its intended functions. However, most of these functions are complex (since they may serve several purposes) and require decomposition into several smaller sub-functions that are easier to manage. From all of these methods, it was determined that AD provided the best solutions for the problem since it has the ability to break down complex functions, and also provides guidelines for the proper management of these sub-functions. The application of AD into the HOQ allows for a better examination of design relationships since the HOQ now focuses on design functionality instead of an end means to achieve a required customer attribute.

The development for AD starts with the need for a better method of system design. In the past, system design was performed using heuristic and empirical methods due to a lack of formal theoretical framework. Methods such as 'Murphy's Law' and 'keep it simple' emphasize qualitative guidelines which result in a system that requires construction of models and testing to resolve unknown problems that are hidden in the system. Modelling these heuristic systems may lead to increased expense and yield unpredictable results. This leads to making risky decisions due to uncertainty in the performance and the quality of the system.

The development of AD reduces the possibility of these errors by enabling decision making at various levels of the system's design. By examining a system's functional requirements, design parameters, and constraints, decisions can be made with less risk since more detail of the system design is being evaluated at different levels.

Suh best describes the thought process of AD by describing the design activities through four domains. These domains make up the world of design: the customer domain, the functional domain, the physical domain, and the process domain.

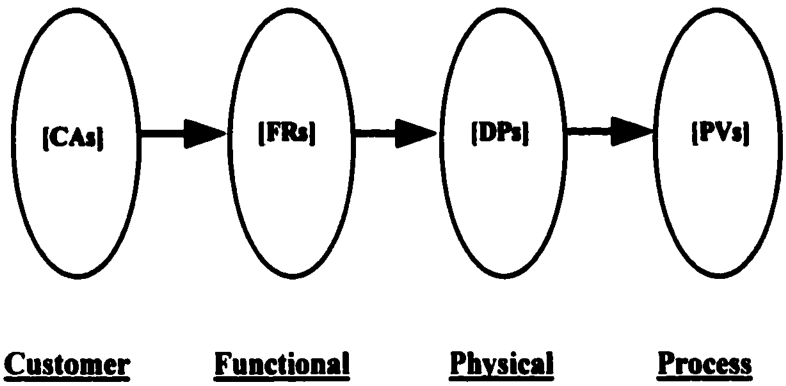


Figure 2 – The Four Domains of Axiomatic Design (Suh, 1998)
This figure shows the process of design from the customer's needs to the manufacturing processes required for the product. The customer's needs are listed in the Customer Attribute Domain. These attributes are translated into functional requirement within the Functional Domain. Design parameters are created to resolve each functional requirement. These design parameters create a physical design within the Physical Domain. Finally, process variables are determined in the Process Domain for the manufacturing of the product.

For each domain, the domain to its left represents the demands or what needs to be achieved, and to its right is the design solution or how demands will be achieved. The first domain is the customer domain. This domain contains all the design requirements that the customer wants in the design of the product or process. The second domain is the functional domain. In this domain the customer needs are transformed into functional requirements and constraints. In the third domain, design parameters are listed that will satisfy each functional requirement. The final domain lists the process variables that will achieve the design parameters. The final step is to produce a process or product derived from the process variables (PVs) in the process domain.

It is important to note that all designs fit into these four domains. Therefore all design activities can be generalized in the terms of the same principles.

The mapping of CAs to FRs between the first two domains can be very difficult. This is because CAs are difficult to define or are vaguely defined. If all CAs have not been properly defined, then it can be extremely difficult to determine their functional requirements. Therefore, it is imperative that consumer attributes in the consumer domain are well defined to minimize the possibility of misinterpretation.

Once the CAs have been listed, the next step is to translate the CAs into functional requirements. A special condition exists in AD for the development of FRs. It is advised that all FRs should be developed in a "solution neutral environment". A solution neutral environment is an environment where previous solutions are blocked out to prevent the development of a pre-existing solution that has been used in a similar case. It is important to develop FRs in a solution neutral environment because a solution neutral environment promotes creativity and innovation by removing biases to previous designs. The neutral environment encourages the design team to develop proper FRs for each CA that would ensure uniqueness in the product's design when compared to similar products.

The translation of CAs to FRs sometimes is difficult depending on the perception of what one believes is a FR. When examining Suh's definition of a FR, the definition itself can be confusing depending on the context. Suh does not purely state what is, or is not acceptable, as a functional requirement. Therefore, many requirements can be argued if they are a FR or not, depending on the context that one perceives it in. For this reason, the author assumes for the remainder of this dissertation, the context of FR will specifically mean, "the requirement on a product's function". This assumption follows that taken by other authors works including "Strategies for Product Design" (Cross, 1994), "Product Design and Development" (Ulrich and Eppinger, 1995), and "Product Design: Fundamentals and Methods" (Roozenberg and Eekels, 1995).

1. The Independence Axiom

When mapping between domains, AD uses the Independence and Information Axioms to assist in making correct design decisions. These two axioms assist the designer by evaluating the alternatives from the mapping process, and reducing these alternatives preventing redundancy and unnecessary information. The independence axiom is used to ensure that the FRs are independent of each other. When several independent FR solutions exist, then the information axiom is used to select the best solution from the alternatives.

The Independence Axiom states that the independence of functional requirements must always be maintained, thus providing the minimal number of FR solutions to attain the design goals. When there are two or more FRs, the design solution must be such that each FR can be satisfied without affecting the other FRs. Therefore it will be important to select the correct set of Design Parameters (DPs) that will satisfy the FRs and maintain their independence.

Just like in the discussion of FRs, there are similar problems with the perception of a DP. Suh's definition of a DP is too vague. A stricter definition of a DP is required to eliminate problems with context. This dissertation will assume that a DP is a design parameter that satisfies a product's functional requirement. This assumption is also identified in the previous citations listed.

Once all the FRs have been identified, the next step is to map the functional domain to the physical domain. It can also be referred to as mapping "what needs to be done" to "how will it be achieved". For each FR in the functional domain, DPs are developed in the process domain. This mapping can be expressed mathematically in terms of vectors. For a given level of design hierarchy, a set of functional requirements to solve a design goal can be represented as a vector in the functional domain {FRs}. The set of design parameters in the physical domain mapping from FRs can be represented as the vector {DPs}. The mathematical relationship between the two is expressed as;

$$\{FRs\} = [A]\,\{DPs\} \qquad \text{(Eq. 1)}$$

where [A] represents a matrix called the design matrix. The design matrix is typically a symmetrical matrix and has the form;

$$[A] = \{Aij\} \qquad \text{(Eq. 2)}$$

The design matrix exists in either of two cases that will satisfy the information axiom. The first case is where all Aij's, except those for which i=j, equals zero. In this case, the matrix [A] is diagonal, thus each FR can be satisfied independently by one DP. This case is called an "uncoupled design".

$$[A] = \begin{bmatrix} A11 & 0 & 0 \\ 0 & A22 & 0 \\ 0 & 0 & A33 \end{bmatrix} \qquad [A] = \begin{bmatrix} A11 & 0 & 0 \\ A21 & A22 & 0 \\ A31 & A32 & A33 \end{bmatrix}$$

<u>Uncoupled Design</u> <u>Decoupled Design</u>

Figure 3 – <u>Uncoupled and Decoupled Design Matrices</u>
The uncoupled matrix is identified by its diagonal values and represents an "ideal" design.
The decoupled matrix is still soluble provided the sequence the variables are solved.

In the second case, the design matrix is triangular. FR independence can only be guaranteed if the DPs are solved in proper sequence. This case is called a "decoupled design".

A set of rules governs the design matrix to ensure FR independence. First, to satisfy a given set of FRs, the number of DPs cannot be less than the number of FRs (Theorem 1). If the number of DPs is less than the number of FRs, then two FRs share one DP and the independence axiom is violated. The second rule is that if the number of FRs equals the number of DPs, then an ideal design exists (Theorem 4). A third case exists for the design matrix where the matrix does not follow a diagonal or triangular pattern. In this case the number of FRs and DPs are arbitrarily interdependent. This is called a "coupled design". If a coupled design exists, then the FRs must be broken down into sub-levels or hierarchies for an attempt to satisfy the new FRs and decouple the design matrix.

2. The Information Axiom

Once a set of FRs has been developed for a design that satisfies the independence axiom, the designer can proceed by using the corresponding DPs. However, different designers may come up with different solutions for the same set of FRs. Each solution presented may be correct, but it can be difficult to determine which solution is the best. The information axiom provides a quantitative means of measuring the merits of a given design. Using the information axiom enables the designer to select the most sufficient solution out of all acceptable solutions.

When completing tasks, information is required to have an understanding on how to complete the task. Information is an item of knowledge that can be applied or referenced to something. Sometimes in a situation, too much information is available. Sometimes the information may have no influence on the task at all. It is important to consider only relevant information and disregard unnecessary information. The sum of information required to complete a task is called information content. In AD, the information content was defined in terms of the probability of being able to satisfy a given FR (Suh, 1989). As the amount of information to the task or FR increases, the probability of satisfying the FR or task decreases. This is because as the quantity of information increases, more likely the task or FR will become sensitive to variations. One goal of AD is to reduce the amount of additional information required to make the system function. If the variance of the system range can be made small, then the bias in the system can be nearly eliminated. Therefore, the information axiom allows a design to be insensitive to variation, thus enabling a robust design.

The information axiom states that the design with the highest probability of success is the best design, and the overall goal is to minimize information content. Therefore, since the information axiom is based on probability, the formula for the independence axiom is;

$$I = \sum_{i=1}^{n} [\log_2 (1/P i)]$$

(Eq. 3)

Where I is defined in terms of the probability of satisfying a given FR, and Pi is the probability of DPi satisfying FRi for a set of n FRs. In most cases, instead of using the logarithm to the base 2, the natural logarithm *ln* (i.e., ln = $\log_e$) can be used.

A general rule for the information axiom is that the design with the smallest I is the best design since it requires the least amount of information to achieve its design goals. If the information content is high, then probability for success is low since much information will be required to satisfy the FR. This situation usually occurs when tolerances for the FRs of a product are tight, requiring additional information to attain a high accuracy. Therefore, a solution that requires minimal information is ideal since there is less variance or bias in the solution, thus making it more robust.

In this dissertation, the author believes that the role of the information axiom is less important than the requirement for the independence axiom. The independence axiom will be required in the new model to assist in resolving dependencies between customer requirements. The removal of these dependencies is believed to improve design time. The need for the information axiom is less of a concern since it is undetermined if its applications will result in a reduction of design time. The information axiom is a necessary principle of AD, however it will not be a primary concern in the application of the new model. Therefore, the need for the information axiom in the new model will be neglected for the time being. In the future, the information axiom should be examined closer to determine if it could provide any benefits to the new model in other areas.

3. System Architecture

When a system design is developed using FRs, DPs and PVs, their relationships can be shown as a series of design equations. These equations constitutes the system's architecture. Using these equations and matrices, modules can be formed that yield the desired FR given the input DP. Thus, the FR and DP hierarchies can be converted into a diagram called the Module Junction Diagram (Suh 98). From the module junction diagram, the system architecture is developed using a flow chart, which will act as a road map for the implementation of the system design.

Consider the following design equations that represent a system's design;

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

$$\begin{Bmatrix} FR11 \\ FR12 \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \end{Bmatrix}$$

$$\begin{Bmatrix} FR21 \\ FR22 \\ FR23 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ O & O & X \end{bmatrix} \begin{Bmatrix} DP21 \\ DP22 \\ DP23 \end{Bmatrix}$$

$$\begin{Bmatrix} FR111 \\ FR112 \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP111 \\ DP112 \end{Bmatrix}$$

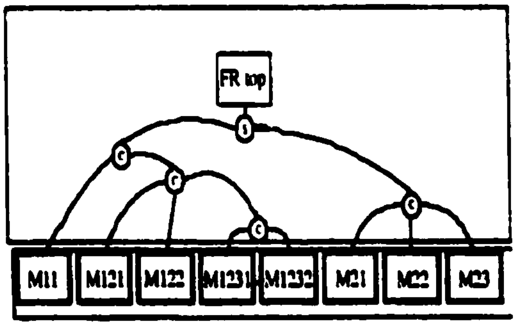


Figure 4 – Design Matrix Equations (Suh,1998)

Figure 5 – Module Diagram (Suh, 1998)

Figure 4 displays the FR and DP relationships in a matrix form for mathematical computations. Figure 5 displays the same relationships in a modular form for easier visualization of each modules relationship and hierarchy. Both methods are used in displaying the system architecture.

The system architecture for the equations in figure 4 is represented in the module diagram shown on figure 5. These figures show how the system would be represented using equations and matrices. The system architecture is made up of modules (M) in the flow diagram. The modules represent the rows of the design matrix. The flow diagram displaying the system architecture is a complete representation of the system, showing how the modules must be connected into the system. It also displays how the system must be operated to obtain the desired performance of the system in terms of the stated FRs.

In the flow diagram, modules that form a junction are cases of uncoupled designs. When there is only one module connecting to a junction, then it represents a decoupled design. Both of these cases satisfies the independence axiom. If there is a feed back mechanism in the module diagram, then this represents a coupled design. Feedback mechanisms in the flow diagram can become unmanageable, because such situations are dependent on their outcome. This dependency leads to the violation of the information axiom. So, it is important to avoid or eliminate feedback mechanisms in the module diagram.

With further examination of the HOQ, it is clear that AD would provide some improvements to the methods used for product design. HOQ's primary problem of dependency between customer requirements has been outlined, where this dependency leads to further problems of increased costs and development time, the making of ad-hoc decisions, and neglecting the voice of the customer. The use of AD provides methods and principles that minimize the dependency problems between customer requirements. This will help resolve most of the sub-sequent problems (discussed above), however problems may still exist with the loss of the customers voice in product design since AD may eliminates some of the customer input. AD uses axioms to reduce the number of variables in a design, and focuses on the primary functions that the customer requires the product to perform. The end result is that the product can be designed more quickly and efficiently, reducing excessive decision making time and cost. Overall, if incorporated into the HOQ, it could create an improvement since less time will be required to evaluate trade-offs between attributes.

The next step of this investigation will be to determine a proper method of merging AD into the HOQ. During HOQ construction, methods of AD will be applied when developing the relationship matrices. The goal is to use AD 's rules and theorems to govern the development of these matrices.

V. COMPARING AXIOMATIC DESIGN AND HOUSE OF QUALITY PRINCIPLES

When examining the methods of HOQ and AD, many similarities exist that will allow for relatively simple combination of the two methods. This section will begin by examining some of the similarities and differences of the HOQ and AD components. The intent is to identify common aspects such as structure and ideology that will allow a combination of both methods. By examining common aspects, the differences can be identified and studied to determine their contributions to an integrated model. Once these similarities have been discussed, a step by step procedure of the new model will be outlined including examples to help explain how the procedure is to be implemented.

There are many similarities between the methods of HOQ and AD that should be examined prior to construction of the new model. Overall, AD can be considered as a more structured, logical, and streamlined version of HOQ that focuses primarily on the design of a product based on function. Similarities exist between HOQ's how's and what's, with AD's use of FRs and DPs. By identifying the similarities and differences, there is a better understanding of how the merged model will function with the most appropriate methods that have been selected.

The purpose of the HOQ is to provide a model for QFD that allows a visual display of the relationships and interactions between customer and technical requirements of a product's design. This visualization is achieved by the model's use of rooms and the interactions between the rooms and the information that they store. The visual relationship allows the design team to investigate product improvements and the effects that changes in the requirements will have on other requirements in the design. The goal is to develop the most marketable design of a product based on consumer input on the design of the product. Involving customer input will improve the design of the product to a point where the customer finds the product superior to its competitors.

The purpose of AD is to develop a defined set of principles which provides a mapping technique between a product's functional requirements and its design parameters to produce a good or ideal design. These principles consist of the information and independence axioms earlier discussed. Using these axioms ensures the mapping process to provide an ideal solution that will satisfy the functional requirements of the design. The goal of AD is to provide information from the design process that is required to create a physical entity with minimal effort and information involved.

One common similarity is to provide a sequential process for design structured on formulated requirements and their resolution (dependent on design parameters). The HOQ uses it's relationship matrix to map these requirements to technical requirements to create a design solution. The sequential process usually involves listing all of the customer requirements first, then identifying the technical requirements, then developing the relationship matrix for analysis. AD also uses a design matrix to map the functional requirements to design parameters, and to display the interactions between all FRs and DPs in the model. AD's sequential process is identical since the first step is to list all FRs, then develop corresponding DPs, then to create the matrix to analyse the relationships. Another similarity is that both models allow comparisons for other design alternatives that may be more feasible. As previously stated, HOQ uses the relationship matrix to evaluate changes to the model to attempt to improve the product's design. The design matrix in AD may also be altered to determine the feasibly of an alternate design, so long as the design axioms are not violated. The differences in the purpose of both models are in the methods used to develop the model structure, and the methods used to examine interactions between alternative designs. HOQ is a physical model with structural rooms (or matrices) that assist the purpose for comparison of alternatives. AD does not rely on mathematical relationships between structural rooms, but only on two principles. The two principles (or Axioms) act as the guiding rules that the design must not violate. HOQ does not have these principles, and in comparison the design rules of AD are constantly violated in the HOQ model, but the violations are identified visually within the structured matrices (or rooms) and it is up to the design team to attempt to resolve these issues.

Examining the goals of both methods reveals that each method's primary goals are nearly identical. The only difference that appears is when each goal is further defined. For example, defining what is meant by "specific requirements", has two different meanings between each method. HOQ defines requirements as customer requirements, the needs that the customer requires in the product's design such that the customer will purchase the product over the competition. AD on the other hand defines requirements as functional requirements, the requirements that must be designed into the product for it to function as intended for its end means. Another difference between the two methods is the end means of goal achievement. In HOQ, the goal has been achieved when the product's final design involves the consumer's input to provide a more marketable product. However, in AD the goal has been achieved when a final product is designed requiring minimal effort and information. HOQ's method does not make mention of information content or effort, nor does AD's method involve the satisfaction of the consumer's demands. Therefore, the methods' goals are slightly different. Another worthwhile comparison is the definition of the list of requirements. HOQ uses a list of customer requirements also known as WHATs. A WHAT is defined as a customer's need or expectation in HOQ, whereas a FR is defined as the requirement in the design's functional domain that must be satisfied to achieve the design objectives. When comparing the two definitions of requirements, they are similar in the fact that both lists of requirements must be satisfied to achieve the design objectives, however there is one difference between them. The list of FRs consist of a list of requirements that relate only to product function. In HOQ, WHATs are consumer requirements that have no limits to there nature. Consumer requirements can be physical, aesthetic, monetary, and even functional. Therefore, consumer requirements have no limit to what type of requirement they need to be, and most of the time, include functional requirements. To conclude, it will be assumed for the rest of this dissertation that consumer requirements consist of any type of requirement that is needed for the product. FRs are a fraction of customer requirements that are considered in AD. Therefore, both methods of requirements are similar except that AD only used a sub-section of the HOQ's requirements involving functionality.

The corresponding lists that are compared to the requirements are the DPs and technical requirements lists. These lists consist of the solutions that resolve each individual requirement. Technical requirements (TRs), or HOWs, are used in the HOQ.

They are defined as a set of quality characteristics by which the WHATs can be realized. In AD, DPs are defined as a physical embodiment that satisfies the FR. Both of these terms are similar in the fact that they both must satisfy the previously stated requirements for each respective method. The TRs or HOWs must satisfy a given customer requirement in the HOQ, and each DP must satisfy a FR in AD. It was extremely difficult to determine if differences exist between these concepts. In AD, DPs are physical solutions to FRs and belong to the physical domain in the design model. A DP may have some effect on other FRs in the model, however this is valid since the independence axiom has not been violated. Independence must only be maintained between FRs. In the HOQ model, the TRs listed for each customer requirement may also have an effect on other customer requirements in the model. This is evident since there is a need to correlate these effects and measure their impact on the model. Therefore, both DP and TR have similar behaviours in the model. Furthermore, in a majority of HOQ models, TRs are physical in nature. Therefore, because of the consistent similarities of TRs and DPs in definition, domain classification, and behaviour in their respective models, it will be assumed for the rest of this dissertation that there is no difference between TRs and DPs.

There are many differences in the construction methods of the models. Overall there are several steps used to create the HOQ model, and once created, there are several areas that can be adjusted and examined to determine a proper design. The methods used in the AD model are far fewer. When comparing the two models, it is evident that the HOQ model requires more time and effort to construct. This is a result of the need for ranking and weights to help decide upon design issues in the model that are caused by dependencies between customer requirements. In the AD model, the issue of FR dependency is resolved by the independence axiom, therefore less information is required in the model to make decisions. However, the AD model does not perform certain comparisons (competitor comparison) that one finds advantageous in the HOQ model. Therefore, the difference is that the AD model is a smaller and simpler model compared to the HOQ model. Furthermore, the AD model does not provide additional information (or comparisons) that the HOQ model provides. However, both models are similar in structure since both rely on two lists of requirements, and a matrix that compares the relationship of the requirements. AD can almost be considered as a smaller, simplified version of HOQ, which provides a good design based only on the results of the relationship matrix.

From the comparison of the two methods, AD and HOQ are very similar processes. Both methods have a common purpose and almost yield the same type of results. The author concluded however that AD is a fractional component of the HOQ that only deals with product function. The only major difference between AD and HOQ is that its use of the design axioms allows for a reduction in conflicts between functional relationships. AD's use of the independence axiom attempts to eliminate relationship conflicts at the very start of the model, therefore producing an acceptable design in a more efficient manor.

This comparison identifies the similarities between the two models. The next step of this thesis is to determine if AD can be applied to the HOQ in an attempt to improve cost and time efficiencies in the design process.

VI. THE MODIFIED MODEL - Axiomatic House of Quality

The purpose of this section will be to integrate the AD process in to the HOQ to improve development time and cost. As a result, a new model will be formed where AD will be used as the base model, with HOQ components added to perform further product analysis. This new model is named the Axiomatic House of Quality (AHOQ).

The new AHOQ model can be considered both as a model and a tool. The AHOQ is technically a model since it emulates a design from the perspective of functionality, structure, and physical means for design. The AHOQ is a "blue print" of the requirements for the design and how these requirements relate. The AHOQ is also a tool in the sense of its application as a design tool. Design teams will used the AHOQ as a tool to construct a design. Therefore, AHOQ is a design tool that when applied will result in a model of requirements needed for a design. Both as a model and tool, the AHOQ has inputs and outputs. The input into the AHOQ is a design problem in a disorganized state. The output is an organized version of the design problem, and design parameters for the completed model.

For the combination of the two models, the HOQ components being considered include correlation matrix construction, and the competitive analysis functions. Listed below is an overview of the steps required for the new model. Each of these steps will be examined in further detail in the following sections. Included in these discussions will be three different types of examples to provide a more concise understanding of each step. The examples used will include a coffee maker, a car door, and a pen.

A summarized version of the AHOQ is provided in Appendix A. This pamphlet displays the step by step construction of the AHOQ model using the coffee maker design as an example. The pamphlet is intended to act as a quick reference guide on how the AHOQ works and how it can be applied.

Tabie I - Axiomatic House of Quality Model Construction Steps
These are the proposed construction steps for the Axiomatic House of Quality model. These steps will be discussed in detail in the following sections using examples.

Axiomatic House of Quality Model Construction Steps

1. List Customer Attributes
2. Convert Customer Attributes into Functional Requirements
3. Identifying Constraints
4. Formulation of Design Parameters
5. Formulating the Design Matrix and Initial Design
6. Resolving Functional Requirement Dependency
7. Formulate Correlation Matrix
8. Comparison of Competing Products
9. Listing of Constraints
10. Formulation of Process Variables
11. Evaluation of Final Model Results

STEP 1 – Listing of Customer Attributes

The first step of the model is develop and list the customer attributes for the design. The listing of CAs follows the same methods used in either the HOQ or AD (Both approaches & methods of formulating CAs are similar – see Introduction to QFD). It is important to note that the customer domain can consist of a variety of types of customers (the public, a corporation, a department within an organization...). Therefore, the listing of customer attributes will be unique and dependent on the customers and their needs.

The list of customer attributes will dictate what requirements the design must accomplish to satisfy the customer's needs. The CAs provide the problem definition of the design that the model must resolve. The final solution to the CAs is the end design from the model, which satisfies the stated CAs. Therefore, the listing of CAs is the essential first step of the model that defines the design problem.

In AHOQ, the first step of listing CAs will follow that of AD where CAs are listed in the Customer Domain. In our examples, each product has a listing of CAs that the design must achieve.

Table 2 – Step 1 Examples: Identifying Customer Attributes (CAs)

This step is used to display the customers needs in the form of Customer Attributes for the product's design.

Step 1 Examples: Customer Attributes

Example 1. Coffee Maker

1. Make coffee with store purchased coffee grounds
2. Coffee should be served hot.
3. Coffee should not get cold over a few minutes
4. Hold a sufficient amount of coffee (2 to 12 cups)

Example 2. Car Door

1. Easy to open
2. Does not rattle when closed
3. Protection from accidents.
4. Able to view outside.

Example 3. Pen

1. Ability to write using ink
2. Fingers don't get sore from use.
3. Easy to store in a pocket
4. Write for a long time
5. Light weight

STEP 2 – Converting Customer Attributes into Functional Requirements

Once all of the CAs have been identified, the next step is to convert them into functional requirements for the model. FRs are defined as the minimum set of independent requirements that completely satisfy the design objectives for a specific need. The CAs identified by the customer are general descriptive requirements and occasionally do not define functional objectives. Some CAs may have some functional content such as product performance functions, and other CAs may not (colour preference, weight, etc…). The content usually depends on the context in which the CA has been listed. Therefore, each CA must be transformed into functional objectives for the design. If the CA has no functional content, then the CA could be considered as a design constraint or a physical constraint that does not map into the functional domain.

In the list of CAs for the pen, the CA of "fingers don't get sore from use" is a descriptive need of the customer. However, it does not exactly describe the function that the pen must achieve. Therefore the CA must be converted into a functional objective that better describes what the pen's function should be to prevent the customers fingers from getting sore. In this case the fingers may get sore from a poor grip. A FR or design objective could be "a comfortable gripping surface". It is important to note that the terms FRs and design objectives are assumed identical in definition, thus FRs are design objectives. FRs or design objectives are used to describe the functional attributes of the consumer's needs. By converting all CAs into FRs, the CAs have become more functionally descriptive. Therefore all the needs from the consumer are listed in terms of required design functions or objectives (FRs). Solving for each design objective will provide an ideal design solution provided that no axioms have been violated.

As stated earlier, FRs are only a sub-group of the consumer needs used in the HOQ that deals with product functionality. For the new model being proposed, design objectives dealing with product function will only be considered. It is believed that product function is the most important goal that the design should achieve in resolving the consumers needs. By focusing on the design of the product's functions, there will be fewer problems with evaluating trade-offs between requirements thus improving development efficiency. Using AD methods on focusing on design functions is the reason why the second step of converting CAs into FRs is being used for this model.

The conversion of CAs into FRs is a simple process. Each listed CA is examined for what the consumer intends the design to do on a functional basis. This process is the mapping of the required attribute from the customer domain to the functional domain creating a design objective that defines the CA. The functional intention of the CA is identified and is reformed into a design objective or FR that best describes the CA. The biggest key is to make the transformation between the two domains without losing or misinterpreting the functional intent of the original CA. If the CA cannot be transformed into the functional domain, then it is examined to determine if it is a constraint or recommendation. Most constraints are identified as limits. If the CA is expressing a type of limit, then it may be a constraint. Dealing with constraints will be discussed in the next section. Once all of the functionally related CAs have been transferred into the functional

domain, the next step will be to deal with the remaining CAs that do not have functional content.

Table 3 – Step 2 Examples: Identifying Functional Requirements (FRs)

This step displays the transforming of customer attributes into the functional domain for the three examples. In this process, customer attributes with functional content are written in terms of functional requirements. Those attributes that do not have functional content are considered as constraints. It is important to translate customer attributes into functional requirements without misinterpreting the requirements of the customer.

Step 2 Examples: Converting Customer Attributes to Functional Requirements

CAs (Consumer Domain) ⟶	**FRs (Functional Domain)**
Example 1. Coffee Maker	
1. Make Coffee with purchase grounds	Blend coffee using water & coffee grounds
2. Server hot	Heat water to hot temperature
3. Not get cold	Keep coffee warm over period of time
4. Holding 2 – 12 cups	None (Volume Constraint)
Example 2. Car Door	
1. Easy to open	Easy to open
2. Does not rattle	Closes securely
3. Protection in accidents	Durable from impact and elements.
4. Able to view outside from	Allow visibility
Example 3. Pen	
1. Able to write down information	Convey information using a medium.
2. Fingers don't get sore	Comfortable gripping surface
3. Easy to store in pocket	None (Size Constraint)
4. Write for a long time	Long functioning life
5. Light Weight	None (Weight Constraint)

STEP 3 - Identifying Constraints

The identification of constraints is an important part of design in all stages of product development. Design constraints can dictate or partially control the methods that will be applied to the design. Both the HOQ and AD involve the use of constraints in their models, however their application to the model differs. In the revised model proposed, constraints will be used to assist in defining the limits for the product's design.

In the AD model, Suh defines a constraint as "the bounds of an acceptable solution" (Suh,1998), meaning that constraints define a boundary in which a given solution would be considered acceptable. The AD model uses two types of constraints, input constraints and system constraints. Input constraints are constraints on design specifications such as size, weight, material, and costs. System constraints are constraints that are imposed by the system (shape, capacity, and laws of nature). In AD, FRs may be considered as constraints for lower levels of FR hierarchy, and these constraints do not need to follow the independence axiom. In the HOQ model, constraints are used within the relationship matrix. HOQ CAs that can be identified as constraints remain listed in the customer requirements column and are evaluated in the relationship matrix. In the lower level of the house, target values are set for technical requirements. These target values are considered as design constraints that may or may not be achievable.

In the revised model being proposed, constraints are defined as a set of bounds that set the domain of the design environment in which the design is considered as acceptable. Constraints can be defined by the system environment (size, technical capability, etc) or they can be defined by the consumer from CAs. Most CAs can be transferred into the functional domain. Those CAs that cannot map to the functional domain are evaluated to determine if they are a physical constraint.

In other papers examined, many classifications exist for different types of constraints. However, a problem exists where some constraint classifications overlap each other in definition. Since there is a lack of standard taxonomy for the definition on types of constraints, the author has decided to assume a classification for the two types of constraints in the AHOQ model. If the CA imposes some type of limit, then the CA is identified as a *design constraint*. If the CA does not belong to the functional domain, nor defines a limit, then it is identified as a *physical constraint*. Physical constraints usually involve visual aesthetics such as colour or texture and do not have a major impact on the function of the design.

Each constraint identified will be listed in the proposed model. Their importance to the model involves the further definition of an acceptable design. In this step, if a CA is a constraint, it will be identified and used later in the model. When evaluating the design matrix of the model, the design matrix will be compared to the constraints to ensure design validity. In the Pen example, there is a design constraint for the CA requiring the pen to fit in one's pocket. This CA is a constraint since it places a limit on the size of the pen, and does not map into the functional domain. The constraint would be listed as "not exceeding 3/8" in diameter and 6" in length (based on the average size of a shirt pocket). By listing these design constraints, the design can be validated against constraints at the same time when validating the independence axiom.

Table 4 – Step 3 Examples: Identifying Constraints

For the three examples, customer attributes without functional content have been considered as constraints. Here the constraints are identified and determined if they are a design or physical constraint. Furthermore, the bounds of the constraint are listed for the design.

Step 3 Examples: Identifying Constraints

CAs (Consumer Domain) →	FRs (Functional Domain)
Example 1. Coffee Maker	
1. Make Coffee with purchase grounds	Blend coffee using water & coffee grounds
2. Server hot	Heat water to hot temperature
3. Not get cold	Keep coffee warm over period of time
4. Holding 2 to 12 cups	**Volume Constraint = 12 cups max.**
Example 2. Car Door	
1. Easy to open	Easy to open
2. Does not rattle	Closes securely
3. Protection in accidents	Durable from impact and elements.
4. Able to view outside from	Allow visibility
Example 3. Pen	
1. Able to write down information	Convey information using a medium.
2. Fingers don't get sore	Comfortable gripping surface
3. **Easy to store in pocket**	**Size Constraint = 6" long, 3/8" dia max.**
4. Write for a long time	Long functioning life
5. **Light Weight**	**Weight constraint = 1/8 lb. max.**

STEP 4 – Formulation of Design Parameters

Once all of the FRs and constraints have been identified, the next step in the model is to identify the design parameters (DPs). This step is similar to the methods used in the AD model for formulating DPs to resolve FRs. Therefore, the same methods that apply to the AD model will also be applied to this model.

The purpose of the DPs are that they represent the physical elements or variables of the design which satisfies a specific FR. The purpose of this step is to map the customer's requirements from the *functional* domain to the *physical* domain by means of a physical design. This step of the model is where the essence of design actually is performed, where requirements are resolved by the use of creative thinking to formulate a physical solution. By creating a physical design using design parameters, the problem defined by the FRs is practically resolved. It is important to note that steps prior to DP formulation are used to refine the stated problem to a more manageable definition. Subsequent steps are used to evaluate and refine the design. This current step requires the examination of each FR, and to determine the physical element of the required design that can resolve that FR. In this step the final design may not yet be known, but major physical requirements (mechanics, processes, etc....) are identified and will amalgamate together as the design is evaluated and refined.

When formulating DPs in this step, it is important to remember three of the theorems that are used in the AD model. If there are an equal number of DPs and FRs, then an ideal solution exists (Theorem #4). If there are less DPs than FRs, then a coupled solution exists which violates axiom #1 (Theorem #1). If there are more DPs than FRs, then a redundant solution exists (Theorem #3). Therefore, when formulating DPs it is important to have the same number of DPs and FRs. This should be obvious since each DP is formulated to resolve one stated FR.

Table 5 – Step 4 Examples: Formulating Design Parameters

In each example, DPs are created for each FR. The purpose is to translate the design from the functional to the physical domain. The DP is a physical solution for the customer's FR, and the combination of these DPs gives an initial concept of the physical design of the product. It is important to note that all constraints have been removed from the lists to focus attention on FRs and DPs.

Step 4 Examples: Formulating Design Parameters (DPs)

FRs (Functional Domain) →	**DPs (Physical Domain)**
Example 1. Coffee Maker	
1. Blend coffee using water & coffee grounds	Gravity Filtration
2. Heat water to hot temperature	Electrical Resistance Heating
3. Keep coffee warm over period of time	Container material's insulating properties
Example 2. Car Door	
1. Easy to open	lightweight Steels
2. Closes securely	Locking & Seal Integrity
3. Durable from impact	Structural Reinforcement
4. Allow visibility	Glass view hole (Window)
Example 3. Pen	
1. Convey information using a medium.	Medium Permeability
2. Comfortable gripping surface	Grip Surface Contour
3. Long functioning life	Rechargeable Medium

STEP 5 – Formulating the Design Matrix and Initial Design

When the formulation of FRs and DPs are complete, the model is now ready for the creation of the design matrix. The design matrix is used to display the relationships of the DPs and FRs visually and mathematically. The identification of the relationships are necessary to ensure that no violation occurs with the independence axiom. The design matrix follows the same methodology as the AD model, where FRs and DPs can be expressed in vector form, thus allowing a mathematical representation of their relationships. Since the model follows the AD methodology, the detail of vector representation will not be discussed, and it is assumed that all stated facts from AD hold true in this model.

The creation of the Design matrix depends on the number of FRs and DPs listed in the previous step. The total number of FRs dictates how many rows are in the matrix, and the total number of DPs represents the total number of matrix columns. Most of the time the matrix will be square, having the same number of columns and rows. If different, then there may be too many or few DPs. The FRs are listed along the left side of the matrix, one FR for each row. The DPs are listed above the matrix, one DP for each column. This construction is the initial framework of the design matrix as shown below.

	DP(1)	DP(2)	DP(3)...	DP(i)
FR(1)				
FR(2)				
FR(3)...				
FR(i)				

Where i = 1 to n

Figure 6 – A n X n Design Matrix.

The common format for all design matrices. FRs are listed on the left, and DPs are listed above. It is important that each matrix have the same number of FRs and DPs. If the number of FRs exceed the number DPs, then FR dependency will occur. If the number of DPs exceed the number of FRs, then design redundancy has occurred.

Once the design matrix frame has been created, the next step is to complete the relationships within the matrix. There are two methods commonly used to complete these relationships. The first method uses *formulas* to represent the relationships between FRs and DPs. Each relationship is represented by a formula with unknown variables, where values may be substituted for into the variables to determine a solution or the formula is solved to determine an exact value for a variable. The second method of representation is the uses of *1's* and *0's*, where 1 is used to identify a relationship and 0 is used to identify no relationship. This method is the simpler of the two and is most commonly used. For simplicity, in our discussions and examples the 1's and 0's method will be used.

Each relationship in the matrix is examined and assigned a value (or formula). The given DP for a corresponding FR will get a value of 1 for their relationship dependency. Other DPs examined against the FR will receive a 0 unless there is a dependency that exists between the FR and DP. If a dependency does exist, there is a possibility that the independence axiom has been violated.

	DP(1)	DP(2)	DP(3)...	DP(i)
FR(1)	1	0	0	0
FR(2)	0	1	0	0
FR(3)...	0	1	1	0
FR(i)	0	0	0	1

For i = 1 to n

Figure 7 – Methods of Identifying Relationships in a Design Matrix
The most common method used for identifying relationships is the 1 and 0 method where 1's indicate a relationship, and 0's indicate no relationship. Another method of displaying relationships is the use of equations when trying to determine an unknown variable.

Once the relationships within the design matrix have been identified, the next step is to analyse the results of the matrix. Each FR and DP relationship is examined to determine if the independence axiom has been violated. If a violation of the independence axiom has occurred, then the design and relationships must be adjusted to prevent problems that lead to excessive design time.

Three types of design matrices can result from the examined relationships. The first type is the *Ideal Design* where the matrix is represented as a diagonal or identity matrix. In this case, there is no violation of the independence axiom and therefore the design of the product is acceptable.

	DP(1)	DP(2)	DP(3)...	DP(i)
FR(1)	1	0	0	0
FR(2)	0	1	0	0
FR(3)...	0	0	1	0
FR(i)	0	0	0	1

For i = 1 to n

Figure 8 – An Ideal Design Matrix

An Ideal Design Matrix is easily identified by a diagonal pattern of relationships in the design matrix. This identifies that each FR is associated to only one individual DP. Therefore, functional independence has been satisfied.

The second type is the *Coupled Design* matrix. In this case, DP(3) affects several FRs on the left. Since there are dependencies from other FRs for both DP(2) and DP(3), this matrix fails the independence axiom. To resolve this situation, there must be a change made to the physical design that would uncouple the dependencies of the FRs to one DP each. When a physical change has been made to the design, the design matrix should be re-constructed and examined to ensure that the new changes do not violate the independence axiom.

	DP(1)	DP(2)	DP(3)...	DP(i)
FR(1)	1	0	1	0
FR(2)	0	1	1	0
FR(3)...	1	1	1	0
FR(i)	0	0	0	1

For i = 1 to n

Figure 9 – A Coupled Design Matrix
In a coupled matrix, there may be relationships between one or more DPs and FRs. This can be determined by counting the total number of 1's in any FR row. If the total number is greater than one, then more than one DP satisfies the FR, thus violating the Independence Axiom. The result is a dependent design where a change in a DP will affect the whole design.

The final type of matrix is called the *Decoupled* or *Quasi-coupled* matrix. In this situation, DP(3) is dependent on one or more FR. However, the DPs can be solved in such an order to that would not violate the independence axiom. In this case DP(1) should be solve first, then used to solve DP(2) and so on. In this case the physical design is acceptable and the design team may proceed.

	DP(1)	DP(2)	DP(3)...	DP(i)
FR(1)	1	0	0	0
FR(2)	1	1	0	0
FR(3)...	1	1	1	0
FR(i)	1	1	1	1

For i = 1 to n

Figure 10 – A Decoupled Design Matrix

A decoupled design matrix is not an ideal matrix, however a valid solution can exist. In this situation, the Independence Axiom has been violated. However, the FRs can be solved in a sequential order that will provide a valid solution.

As the design matrix is being created and examined, a conceptualisation of the physical design of the product should be formed. An initial physical design can be derived from the listed FRs, DPs, and constraints. At this point no final design solution can be agreed upon, however an initial design is required to help examine the relationships and independence of the FRs and DPs. Violations of the independence axiom will required some changes to be made to the physical design to ensure FR independence. At this point the design team will have to examine both the physical design and the design matrix and make necessary modifications. When the analysis of the matrix is complete and acceptable, then the conceptual design also is deemed acceptable and the design team can continue to the next step, where the physical design will be further refined to ensure that it satisfies customer requirements.

Step 5 Examples: Formulating the Design Matrix and Initial Design

<u>Example 1. Coffee Maker</u>

In this example, the FRs and DPs were used to define the initial design of the coffee maker. From DP(1) it is was decided that the coffee would be blended using a gravity filtration method. Therefore the design of the coffee maker would include a mixing chamber were water enters from the top to mix with the coffee grounds, then separated using filter paper to allow the coffee mixture to exit at the bottom of the chamber. DP(2) required electrical resistance heating to heat the water. It was decided that the water would be transported from its holding tank to the top of the mixing chamber though a tube. At the bottom of the water holding tank the water would be heated using electrical resistance, forcing the hot water up the tube and to the top of the mixing chamber. DP(3) involved the coffee container's thermal capabilities. A glass coffee-pot will be designed to hold the coffee and keep it warm. The glass will conduct heat from an electric base plate located at the bottom.

FRs/DPs	1. Filter	2. Heat	3. [illegible]
1. [illegible]	1	0	0
2. Heat Type	0	1	1
3. Warmer	0	1	1

Figure 11 - Coffee Maker Design Matrix

This matrix is the design matrix for the coffee maker design. From the design matrix, a DP may affect more than one FR. Therefore, the design matrix displays a coupled design.

The coffee maker's design matrix shows that the gravity filter DP(1) only affects the blended coffee FR(1), and is independent of the heated water FR(2) and to keep the coffee warm FR(3). The electrical resistance heating DP(2) also satisfies FR(2) but is dependent of FR(3). This is because the insulating properties of the glass pot releases heat, causing a required variance in the heat source to compensate for the heat loss. This also occurs with the container's insulating property DP(3) since it has an effect on FR(2) and FR(3). The additional need for a heated base plate on the bottom to heat the glass pot has a direct relationship with the requirements of heating the coffee. Even though the coupling of these FRs do not negatively effect each other (both ensure the coffee remains warm), their dependencies could create problems later in the design. An example would be determining the amount of current or heat energy is needed at both sources to keep the coffee warm. A common current may not be attainable for both heat sources. Since some of the design's FRs have dependencies, the design matrix identifies a coupled design. Therefore, the design team must uncouple the FRs before continuing with the design.

Example 2. Car Door

In this example, the initial design of the car door will use a thin gauge lightweight steel for its construction (DP(1)). A typical car door latch will be located at the end of the door to securely fasten the door with the car frame when the door is closed. Also a rubber seal will outline the outer perimeter of the door to provide a seal from the outside elements (DP(2)). Across the centre of the door an additional metal bracket will be welded to increase the impact strength of the door (DP(3)). Finally the upper half of the door will have an opening to install a window (DP(4)).

FRs/DPs	1. Steel	2. Lock	3. Reinf.	4. Window
1. Easy Open	1	1	0	0
2. Close Sec.	0	1	0	0
3. Durability	0	0	1	1
4. Visibility	0	0	0	1

Figure 12 - Car Door Design Matrix
In the car door design matrix, some DPs are dependent on more than one FR. However, a valid solution is still available provided on the sequence that the FRs are resolved. This design matrix displays a decoupled design.

When examining the design matrix, we can conclude that FR(2) and FR(4) are independent since DP(2) and DP(4) only effects its corresponding FRs. However, FR(1) and FR(3) are not independent. FR(1) (door easy to open) is also affects by FR(2) (closes securely). The reason is that the door latch function will also effect how easy the door can be opened or closed. A similar problem exists between FR(3) (durable from impact) and

FR(4) (allow visibility). The durability from impact is also effected by the function of visibility since the design requires an opening in the door for a window. This hole in the door does reduce the structural integrity of the door therefore causing a FR dependency.

The conditions above would normally cause a violation of the independence axiom since dependencies exist between FRs. The design of the car door would become difficult because modifications to the door's design would have possible negative effects on all other required functions of the door. Changes to the latch design may make the door more difficult to open, or the size of the window can make the door less durable to impact. However, in this example, the dependencies that occur in FR(1) and FR(3) have been decoupled by FR(2) and FR(4). FR independence can be achieved if the design first resolves the two independent FRs, and then uses their results into the design to decouple the two dependent FRs. If the design of the door latch is resolved first, then the solution to this design should be incorporated into the design of the lightweight steel door to ensure that it opens easy. The design matrix for the car door is termed as a decoupled design, and satisfies the independence axiom. Therefore the car door design is acceptable.

Example 3. Pen

The design of the pen examines and incorporates the three derived DPs from the stated FRs. DP(1) (medium permeability) is a relatively easy DP to resolve since like most pens, a permanent ink base will be used as a medium. DP(2) (grip surface contour) will dictate part of the shape of the pen's body. The body will be of typical diameter like most pens (3/8"). However, at the tip of the pen where the fingers hold the body there will be a variable change in the pen's diameter to match the contour of the finger. This allows for more of a contact surface between the pen body and finger allowing for better control, and a greater distribution of pressure across the finger to reduce the fingers fatigue. The pen will also be designed as an assembly where replaceable ink cartridges can be used to satisfy DP(3) (rechargeable medium).

FRs/DPs	1. Perm.	2. Cont.	3. Refill
1. Medium	1	0	0
2. Grip	0	1	0
3. Life	0	0	1

Figure 13 - Pen Design Matrix
In this example, the relationships between the FRs and DPs are all independent. Since the independence axiom has not been violated, and ideal solution exists. This design matrix displays an Ideal Design.

The design matrix of the pen is an ideal matrix, satisfying the independence axiom. The type of medium (DP(1)) has no effect on the shape of the pen or its long functioning life. The shape of the pen is also independent of the pen's functional life. Since the design satisfies the independence axiom, the design team may continue to the next step of the design knowing that modifications will not effect the desired function of the pen.

STEP 6 – Resolving Functional Requirement Dependency

This next step discusses with how to resolve FR dependencies in the physical design and design matrix. When the design matrix has been completed, and an ideal design has been achieved, then there is no need to proceed with this step and the design team should continue to the next step to construct the correlation matrix. However, if the design matrix has produced a coupled design, then this step will be required to decouple the FRs in the design thus satisfying the independence axiom.

In a coupled design, a DP has effects on two or more stated FRs creating more than one dependency. The result is that changes to the physical design will affect more than one of the stated requirements. Therefore, design changes become more difficult, resulting in a possible loss of the functional requirements desired by the customer and excessive design time.

To resolve the problems associated with a coupled design, the FRs must become independent in order to decouple the design. There are two possible methods in decoupling the design. The first method requires the designer to examine the physical design and determine if modifications to the design could uncouple the FRs. The dependency problem can be pinpointed by examining the design matrix to find which DP effects more than one FR. From there, the designer must determine if there is another option in the physical design that is acceptable by the DP and will only have dependency to one FR. If so, the modification to the physical design would result in the decoupling of the design matrix, and satisfy the independence axiom. Suh provides an example of this method when designing a refrigerator freezer. The vertical hung door creates a dependency between the two FRs (to provide access for food and to minimize energy loss). As the door opens, energy is lost as heat enters. His solution to the problem required that the door open horizontally. Therefore, food can be accessed and far less heat could enter the system. The physical change to the design has decoupled the FRs.

A second method for decoupling is to identify the coupled FRs and determine if physical separation of the design will achieve functional independence. As in the first method, the coupled FRs must be identified. Once identified, the design parameters must be examined to determine if a physical separation of the design will eliminate dependencies between the coupled FRs. An example of this method can be found in some remote controlled vehicle systems. Some systems use a main power source to control velocity, acceleration, and direction. However, problems occur when the power source is nearly drained. When the power source is near empty, the velocity of the vehicle may remain constant, but there is not enough energy for the direction control systems to respond. The end result is that the vehicle continues in one direction at a constant velocity, not responding to the remote control system until the power source is fully dead. To decouple the system, the power source is separated for the two systems. An additional power source is created to power the directional controls, leaving the main power source to supply the energy needed for velocity. Therefore, as the main power source drains, the directional controls of the remote unit are still active due to the separate power source.

It is important to note that if a design team is having problems resolving the FR dependency issue, then the step of creating the correlation matrix may provide additional information about the model's dependencies that could assist in decision making.

Therefore, it would be acceptable in difficult cases to complete the correlation matrix in step 7 to better identify all the relationships in the model, then return to step 6 using this additional information to attempt to resolve the independence axiom.

STEP 7 – Correlation of Design Parameters

In the HOQ, the correlation matrix is used to display the relationships between the technical requirements in the model. These relationships are used to assist in making trade-off changes in the product's design. These relationships have either positive or negative influence on each other. This technique could also be used in the AHOQ in analyzing the relationships between DPs.

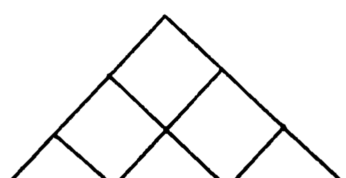
The purpose of using the correlation matrix is to determine the existing relationships between DPs. It is important to determine if any DP depends on other DPs. If there is a dependency, it is important to determine if this is a positive or negative dependency, such that the design team is aware of what impacts design changes could have to the model. Normally the AD methodology would dictate that independence should be maintained for DPs as it is done for FRs. This is so that the next step -- determining process variables (PVs) -- can be conducted using the design matrix. However, in Suh's work the issue of DP independence is sometimes unclear, and in most models DPs are usually independent as a result of FR independence. Therefore, in the AHOQ, it is assumed that in most cases there will be no relationships in the correlation matrix due to FR independence. If DP dependencies are found, their relationships will be identified and used as a tool to make necessary changes to the design. It is important to note that this approach may be incorrect, and future work on incorporating PVs into the model may change these assumptions.

The procedure of creating the correlation matrix for this model is like that of the HOQ. A grid will be created above the listed DPs. The relationships between each DP will be examined and recorded. If there is no relationship, no value will be entered in the grid. If a relationship exists and there is a positive influence between the DPs, then a (+) sign is entered. A negative influence will result in a (-) sign entered.

Step 7 Examples: Creating the Correlation Matrix

Example 1. Coffee Maker

In this example, there was a positive relationship in the correlation matrix between the glass insulator and electric heating. To uncouple the FRs, the physical design was changed for the insulating property DP. Instead of using a glass coffee-pot, it was decided to use a thermos type of coffee-pot to keep the contents warm inside. Therefore, an electric base plate for heating the contents is no longer necessary. This design change eliminates the dependency between FR(2) and FR(3). Electrical resistance heating, gravity filtration, and the thermal properties of the container are now all independent from each other. Therefore, the design matrix now represents an ideal matrix and the design may continue.

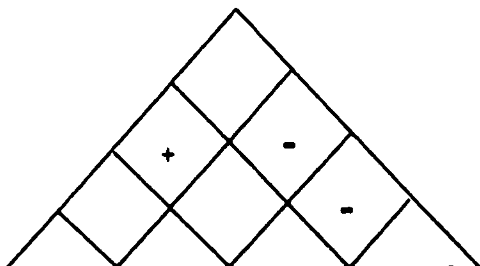


FRs/DPs	1. Filter [illegible]	2. [illegible]	3. [illegible]
1. [illegible]	1	0	0
2. [illegible]	0	1	0
3. Warmer	0	0	1

Figure 14a – Coffee Maker Correlation Matrix
In this example, there are no DP dependencies in the Correlation Matrix.

Example 2. Car Door

In this example, a negative relationship exists between the door's locking and seal integrity, and the glass window. A second negative relationship exists between the structural re-enforcement and the glass window. There is a positive relationship between structural re-enforcement and lightweight steels as stronger lightweight steels can improve the doors structural integrity.

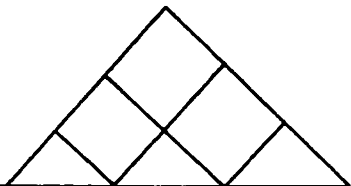


FRs/DPs	1. Steel	2. Lock	3. Reinf.	4. Window
1. Easy Open	1	1	0	0
2. Close Sea.	0	1	0	0
3. Durability	0	0	1	1
4. Visibility	0	0	0	1

Figure 14b – Car Door Correlation Matrix
A positive relationship exists between lightweight steels, and steel reinforcement DPs. Negative relationships exist between the locking mechanism and the window, and the steel reinforcement and the window DPs.

Example 3. Pen

In the pen example, all DPs are independent of each other. Therefore, all the correlation cells are blank.



FRs/DPs	1. Perm.	2. Cont.	3. Refill
1. [illegible]	1	0	0
2. Grip	0	1	0
3. Life	0	0	1

Figure 14c – Pen Correlation Matrix
There is no correlation of DPs in this example.

STEP 8 – Comparison of Competing Products

The next step of the model involves the comparison of competing products. This step will be somewhat similar to the process used in the HOQ for comparing different product designs. The purpose of this step is to compare the competing product's design to the design derived by this model. The goal is to determine design criteria of the model that excel or lag to that of the competitor's designs, such that design changes can be made to improve the product against it's competitors.

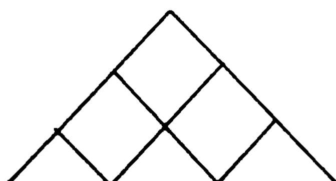
Unlike the methods used in the HOQ that compare design *features* against the competition, the AHOQ will compare the *functionality* of the design. The goal is to identify and evaluate the methods used to achieve the functional objectives by the competitor's design. The evaluation will determine if the methods used by the competition provide a better solution in achieving design functionality. Identifying better alternative methods can then be incorporated into the current design if it is believed that they will achieve improved functionality in the design, and do not validate any of the AD axioms.

The development of this comparison in the model consists of two sections. The first section is used to identify the different methods used to achieve the stated FRs. To the right of the design matrix, a column is created for each competing product being examined. For each FR in the model and each competing product, a verbal description is written in the column describing the process or DPs used to satisfy the given FR. The brief description of the competitor's DP is recorded and is evaluated for use in the current proposed design. The second section consists of the evaluation of the competitor's design criteria and the criteria being developed in the model. The evaluation method proposed is similar to that of the HOQ. Placing the rankings in one section allows for an easier comprehension of how the competing products rate against each other. Therefore, the user does not have to visually wander around the model remembering the rank for each method to be examined. The evaluation is performed using a 1 (worst) to 5 (best) ranking method where for each FR, a rank is given for the model and each of the competitors. Different symbols can be used to distinguish between the rankings of each competing product's design methods. This ranking is usually done from an outside source independent of the design team to limit the error in the rankings. The rankings provide the information to determine if there are more feasible methods in solving FRs that the competition has implemented.

Step 8 Examples: Comparison of Competing Products

Example 1. Coffee Maker

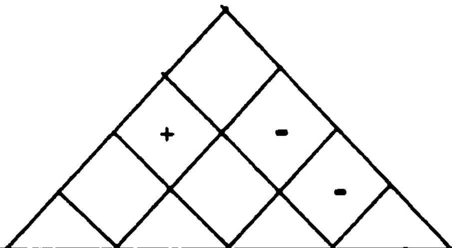
Competitive assessment is located on the right of the main matrix. The two competing products are a French Press coffee maker (Product A), and a traditional coffee drip type maker (Product B). The ranking for the model's current design is expressed as the bold number.



FRs/DPs	1. Filter	2. Elect	3. Insulate	Product A	Product B	Ranking
1. Blender	1	0	0	Uses Strainer	Same method for blending	1 2 3 4 $\boxed{5}$
2. Heat Type	0	1	0	Pre boiled water	Same method for heating	1 2 3 4 $\boxed{5}$
3. Warmer	0	0	1	None	Uses base plate for heat	1 2 3 $\boxed{4}$ 5

Figure 15a – Coffee Maker Competitive Analysis
The competitive analysis for the coffee maker displays two competing products. Their DPs are listed in the first section. Then their DPs are ranked with the current designs DPs in the second section.

Example 2. Car Door

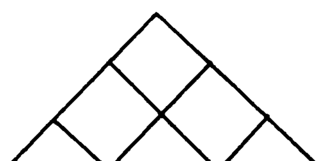


FRs/DPs	1. Steel	2. Lock	3. Reinf.	4. Window	Product A	Product B	Ranking
1. Easy Open	1	1	0	0	Same method	Dual Door	1 2 3 4 5
2. Close Sec.	0	1	0	0	Same method	Same method	1 2 3 4 5
3. Durability	0	0	1	1	Thicker steel	Same method	1 2 3 4 5
4. Visibility	0	0	0	1	Same method	Same method	1 2 3 4 5

Figure 15b – Car Door Competitive Analysis
The competitive analysis for the car door displays two competing products. Their DPs are listed in the first section. Then their DPs are ranked with the current designs DPs in the second section.

Example 3. Pen

Product A is the conventional ballpoint pen, Product B is a fountain pen.



FRs/DPs	1. Perm.	2. Cont.	3. Refill	Product A	Product B	Ranking
1. Medium	1	0	0	Same medium	Wet medium	1 2 3 4 5
2. Grip	0	1	0	Tubular body	Tubular body	1 2 3 4 5
3. Life	0	0	1	Disposable	Refill constantly	1 2 3 4 5

Figure 15c – Pen Competitive Analysis
The competitive analysis for the pen displays two competing products. Their DPs are listed in the first section. Then their DPs are ranked with the current designs DPs in the second section.

STEP 9 – Listing of Constraints

In the previous steps of the model, customer requirements that were not functionally related were identified as design constraints and were temporarily put aside. In this step the constraints will be added to the model. These customer requirements had no effect on the design's functionality or any FR in the model. Other customer requirements that are considered constraints can be added to fine-tune the design to achieve all of the customers needs.

In AHOQ the constraints are listed at the base below the lists of FRs. For each constraint, it is examined against each DP to ensure that the constraints do not interfere with the functionality of the design. These constraints are also compared to that of the competition to identify if there are other opportunities to improve the design.

Step 9 Examples: Listing of Constraints

Example 1. Coffee Maker

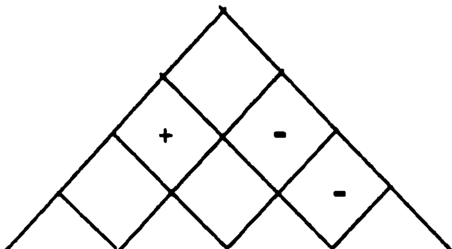
In example 1, the only constraint is that the maximum holding capacity of the pot is 12 cups. This constraint has no effect on DP(1) and DP(2). The constraint may have some influence on DP(3) but it is acceptable. DP(3) uses a thermos type of pot to hold coffee. The constraint effects DP(3) in that the thermos must be large enough to hold 12 cups max.

FRs/DPs	1. Filter	2. Elec	3. [illegible]	Product A	Product B	Ranking
1. Blender	1	0	0	Uses Strainer	Same method for blending	1 2 3 4 5
2. Heat Type	0	1	0	Pre boiled water	Same method for heating	1 2 3 4 5
3. Warmer	0	0	1	None	Uses base plate for heat	1 2 3 4 5
Constraints						
Vol =12 cups	None	None	OK	Holds 3 cups	Holds 10 cups max.	1 2 3 4 5

Figure 16a – Coffee Maker Listing of Constraints
The constraints of the coffee maker are listed below. The volume constraint effects only one DP and therefore will set the bounds for that DP. Furthermore, the constraint is ranked against the constraints of the competing products.

Example 2. Car Door

There were no constraints listed for the car door example. Therefore this step would not apply.

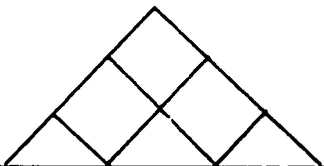


FRs/DPs	1. Steel	2. Lock	3. Reinf	4. Window	Product A	Product B	Ranking
1. Easy Open	1	1	0	0	Same method	Dual Door	1 2 3 4 5
2. Close Sec.	0	1	0	0	Same method	Same method	1 2 3 4 5
3. Durability	0	0	1	1	Thicker steel	Same method	1 2 3 4 5
4. Visibility	0	0	0	1	Same method	Same method	1 2 3 4 5

Figure 16b – Car Door Listing of Constraints
In this example there were no constraints listed.

Example 3. Pen

In example 3, there were 3 constraints (length, diameter, and weight). The only effect that a constraint may have is the diameter constraint on DP(2) (grip surface). However, since the design of the grip surface is needed only at one end of the pen, the constraint does not interfere with DP(2) and is acceptable.



FRs/DPs	1. Perm.	2. Cont.	3. New	Product A	Product B	Ranking
1. Medium	1	0	0	Same medium	Wet medium	1 2 3 4 5
2. Grip	0	1	0	Tubular body	Tubular body	1 2 3 4 5
3. Life	0	0	1	Disposable	Refill constantly	1 2 3 4 5
Constraints						
Size = 6" lng	None	OK	None	6.5" long	7" long	1 2 3 4 5
Dia = 3/8" max.	None	OK	None	Dia = 3/8"	Dia = ½"	1 2 3 4 5
Wt = 1/8 lbs.	None	None	None	Less than 1/8 lbs	Less than 1/8 lbs	1 2 3 4 5

Figure 16c – Pen Example Listing of Constraints

In the pen example there are three constraints. Two of the constraints dictating size only effect the contour DP and therefore will set the bounds for the design of the DP. The constraint bounds of the competing designs are also listed and ranked for analysis.

STEP 10 – Formulation of Process Variables

In AD, the next step after developing the FR - DP design matrix is to develop the process variables needed for the process domain. Process variables (PVs) are the variables that dictate the manufacturing process that will satisfy the derived DPs in the model. Like the FR and DP relationships, the DP and PV relationships use the same axioms. Therefore, the PVs must satisfy the independence axiom and information axiom when relating back to the DPs.

In AHOQ, the DP – PV relationships can also be included into the model. This can be achieved by placing another design matrix at the bottom of the model (below the listing of constraints). The PVs can be listed in a column on the left and can be examined against the derived DPs from the model. Since the DP – PV relationships follow the same design axioms, steps 4 to 6 and 8 can be repeated to develop the design matrix.

The value that the process variables give to the model is that it allows the design process to go a step further using the same integrated tool. The conventional HOQ focuses only on the design of the product to customer requirements. Including PVs allows the design process to extend into the means of manufacturing or manufacturability.

It would be a valuable step to include PVs into the model. However, this outline is only a rough version of its application in the model for simplicity. Further examination must be performed to fully include the design matrix for DPs and PVs into this model. Since the primary focus of this dissertation is product design, and due to the complexity that follows with adding PVs to the model, this step of adding the PVs will be excluded from the dissertation. A detailed examination of this step should be followed up in future work.

FRs/DPs	1. Filter	2. Elect	3. Insulate	Product A	Product B	Ranking
1. Blender	1	0	0	Uses Strainer	Same method for blending	1 2 3 4 5
2. Heat Type	0	1	0	Pre boiled water	Same method for heating	1 2 3 4 5
3. Warmer	0	0	1	None	Uses base plate for heat	1 2 3 4 5
Constraints						
Vol=12 cups	None	None	OK	Holds 3 cups max	Holds 10 cups max.	1 2 3 4 5
Process Variable Design Matrix						
PV(1)	1	0	0	Company A PV(1)	Company B PV(1)	1 2 3 4 5
PV(n)	0	1	0	Company A PV(n)	Company B PV(n)	1 2 3 4 5

Figure 17 – Step 10 Example: Formulation of Process Variables (PVs)

Process Variables are used to determine the means of manufacturing the specific DPs. The listing of PVs is located below the constraints. A second design matrix is constructed to determine the relationships between the PVs and DPs.

STEP 11 – Evaluation of Final Model Results

With the completion of steps 1 through 9 (step 10 being optional), the design of the modified HOQ model is complete. The completed model provides design requirements for the product, based on satisfying customer requirements in the functional domain. The model also provides information on competing products, where comparisons can be performed on all of the competing designs. The final step of the model is to analyze the data the model provides to determine if there are any improvements needed to the design, or missed consumer requirements that the design should incorporate.

The first area of model examination is the design matrix. The design matrix contains the base criteria that will compose the physical design. It consists of the consumer demands of the product that have been translated in terms of functional requirements to corresponding design parameters. First, the design matrix should be examined to ensure that functional independence has not been violated. The design team should verify that each DP is dependent on only one individual FR. If there are dependency problems with DPs and FRs, the dependency should be resolved before proceeding further. Secondly, from the design matrix the physical definition of the product's design is derived. The preliminary physical design of the product has started in this phase. The design team should check that the physical means selected (dictated by the DPs) address all of the consumer's functional needs. If some of the consumer's functional requirements have not been achieved, the design team should revise the design matrix to include the missing functional requirements. If there are no axiomatic violations in the design matrix, and all consumer requirements have been addressed, then the design matrix has provided an ideal design. Therefore, the physical design derived from the design matrix is an acceptable design.

The second area for examination is the constraints listed at the bottom of the model. The constraints listed are used to address non-functional requirements of the customer, therefore further defining the physical design. It is important for the design team to check the constraints to ensure that they have been addressed in the design of the product, and that they do not interfere with the functional requirements of the design. These constraints must be incorporated into the design of the product so that the design can achieve optimum consumer satisfaction.

The third area of examination is the correlation matrix. The correlation matrix is used to display the relationships between the DPs listed in the model. The matrix does not provide information that directly leads to changes in the physical design. However, the design team should be aware of the DP relationships so that they can fully understand the implications that a change in the design will have on other DPs in the model.

The final area for examination is the competitive assessment. The competitive assessment is used to compare the model's resulting design to the design of the competing products. There are two items to look for in the competitive assessment.

The first is the existence of possible sales points. Possible sales points are FRs and constraints that the model's design (and the competing product's designs) fail to meet customer expectations. These areas should receive the greatest amount of effort for design modification since they represent the greatest potential pay-off. The model should be examined to find an improved solution for the FR or constraint that will improve the product's marketability to the customer, and improve it above the designs of the competing products.

The second item is to look for possibilities of incorporating DPs where the competing product excels. Analyzing the competitive assessment can identify areas where the competition rates high, and the model's design rates low. The methods (DPs) used by the competition to achieve a more desirable solution to FRs could be incorporated into the model's design. This saves a great deal of design time and expense. However, before incorporating the competitor's methods (DPs) into the design, the DPs should be placed into the model's design matrix to ensure that the design changes do not violate the independence axiom.

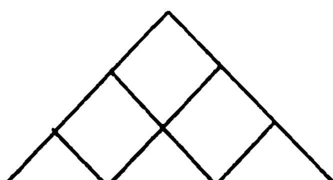
Once the model examination is complete, and all required modifications have been verified and completed, the final design of the product is complete. The model has provided the necessary information to complete the product's design that will make it superior to that of the competition. The model has isolated the functional requirements dictated by the consumer, and has provided the best design parameters to achieve those requirements. The constraints further define the physical design, and the competitive assessment allows further possible design changes to make the product more marketable. The next step is to complete the development of the physical product using the model's information as its design guidelines.

A simplified completed version of the AHOQ can be found in Appendix A. The appendix contains a pamphlet of the construction steps of the AHOQ using the coffee maker design as an example.

Step 11 Examples: Evaluation of Final Model Results

Example 1. Coffee Maker

Examining the design matrix shows that FR independence is achieved. Therefore the design of the coffee maker is a good design. To achieve customer requirements, the functional design will include gravity filtration for mixing, electric resistance heating to heat the water, and a thermos container to keep the coffee hot. The container will be designed to hold 12 cups as defined by the constraints. The competitive assessment lists the different functional methods used by the competition. There are no sales point opportunities or functions that the competition is doing better. Therefore, no changes to the proposed design (outlined by the design matrix) are needed to improve our design.

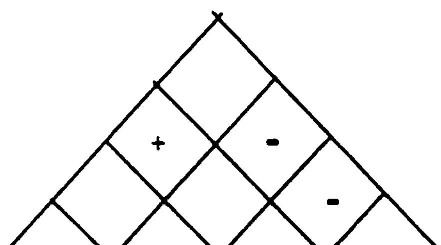


FRs/DPs	1. Filter	2. Elect	3. Insulate	Product A	Product B	Ranking
1. Blender	1	0	0	Uses Strainer	Same method for blending	1 2 3 4 $\boxed{5}$
2. Heat Type	0	1	0	Pre boiled water	Same method for heating	1 2 3 4 $\boxed{5}$
3. Warmer	0	0	1	None	Uses base plate for heat	1 2 3 $\boxed{4}$ 5
Constraints						
Vol=12 cups	None	None	OK	Holds 3 cups	Holds 10 cups	1 2 3 $\boxed{4}$ 5

Figure 18a – Step 11 Example: Evaluation of Model Results for the Coffee Maker Design
The final AHOQ model for the coffee maker design.

Example 2. Car Door

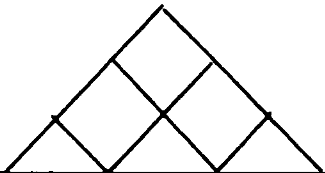
Examining the design matrix shows that FR independence is achieved through decoupling. Therefore the design of the car door is a good design. To achieve customer requirements, the functional design will include light weight steels so the door can open easily, a special locking mechanism and seal to prevent door rattle, inner steel reinforcement to improve door durability from impact, and a glass window to look out the door. There are no listed constraints on the door's design from the customer. The competitive assessment lists the different functional methods used by the competition. FR(1), FR(2), and FR(4) are possible sales point opportunities. This is due to the competition using the same methods to achieve functional requirements. Alternative design parameters should be examined to improve the model's design, making it superior to that of the competition. Therefore, changes to the proposed design should be conducted to improve our design.



FRs/DPs	1. Steel	2. Lock	3. Reinf.	4. Window	Product A	Product B	Ranking
1. Easy Open	1	1	0	0	Same method	Dual Door	1 2 3 4 5
2. Close Sec.	0	1	0	0	Same method	Same method	1 2 3 4 5
3. Durability	0	0	1	1	Thicker steel	Same method	1 2 3 4 5
4. Visibility	0	0	0	1	Same method	Same method	1 2 3 4 5

Figure 18b - Step 11 Example: Evaluation of Model Results for the Car Door Design

Example 3. Pen



FRs/DPs	1. Perm	2. Cont.	3. Rew	Product A	Product B	Ranking
1. Medium	1	0	0	Same medium	Wet medium	1 2 3 4 5
2. Grip	0	1	0	Tubular body	Tubular body	1 2 3 4 5
3. Life	0	0	1	Disposable	Refill constantly	1 2 3 4 5
Constraints						
Size = 6" lng	None	OK	None	6.5" long	7" long	1 2 3 4 5
Dia = 3/8" max.	None	OK	None	Dia = 3/8"	Dia = ½"	1 2 3 4 5
Wt = 1/8 lbs.	None	None	None	Less than 1/8 lbs	Less than 1/8 lbs	1 2 3 4 5

Figure 18c – Step 11 Example: Evaluation of Model Results for the Pen Design
Final AHOQ model of the pen redesign.

Examining the design matrix shows that FR independence is achieved. Therefore the proposed design of the pen is a good design. To achieve customer requirements, the functional design will include an ink medium for permeability, a contoured body for the fingers for a better gripping surface, and a rechargeable medium for a long useful life. The dimensions of the pen are 6" long, 3/8" diameter, and less than 1/8 lbs. in weight as defined in the constraints. The competitive assessment lists the different functional methods used by the competition. A possible sales point opportunity is to examine another type of writing medium. Functional methods that the competition is doing better include the long functional life of the pen. The model should examine making the design of the pen disposable instead of rechargeable since the customer prefers a throw away item. Also the diameter constraint should be reduced under 3/8".

VII. MODEL DISCUSSION

Some problems in the conventional HOQ model have been identified that prevent a design team from reaching their goals. The two primary problems are design conflicts causing increased product development time, and the possible loss of the customer's voice. The problem of increased time also tends to lead to increased cost, and the potential loss of customers or opportunity costs. The problem of the loss of the customer's voice is a result of the design team's inability to correctly understand the customer's needs, and from making ad-hoc decisions.

It was originally believed that the problems were due to a lack of standards in the HOQ framework. Differences in terminology, procedure, and symbols were believed to cause miscommunication between users of HOQ and the customer. However, after further examination it was found that changes needed to be made to the principles that the HOQ model is founded upon.

The creation of the AHOQ has addressed problems of design time and costs. By merging the principles of the HOQ with AD, there is an improvement in efficiency and time. Furthermore, a more robust model has been created that should allow for the development of a marketable product with minimal effort and cost compared to the HOQ. This model is less likely to have problems of misinterpretation by the design team.

Most companies who first used the HOQ do not continue to use it because of problems with design time, confusion, expenses, and the ability to use the design tool properly. The AHOQ has been specifically created to resolve these problems. One of the primary problems with the HOQ principles is that there are no guidelines that dictate what qualifies as a CA (customer attribute) or a TR (technical requirement). Any consumer request can be listed as a CA, whether or not it is functional, or physical, or a constraint. Therefore, some CAs may have no effect on the overall design of the product, and some CAs may realistically be unachievable. Furthermore, other HOQ principle problems include dependencies between CAs. These CAs either complement or contradict each other. The problem is that dependent CAs in the HOQ cause confusion and lost time. The design team will spend much time trying to find a balance between depended CAs that will still satisfy the model. Sometimes this equilibrium is incorrectly attained in situations where decisions are made with a lack of proper information. It is important to note that reviewing decisions will occur in any model and is not the issue at fault. The problem lies with the amount of work put into the model from the result of the decision. The problem with the HOQ is that decisions are made half way through the model, and are not evaluated until the model is complete. A change in a decision in the relationship matrix or correlation matrix will require the model to be either re-examined or reconstructed from the mid-point on. Therefore, the dependencies of CAs leads to a continuous reviewing of decisions that increased the development time and cost of the product.

The corrections to the HOQ problems involve the use of AD's independence axiom. Establishing independence at the start of the model in the design phase is an important step that will prevent the continuous reviewing of decisions. In the AHOQ, FR dependence is examined and resolved early in the model. The advantage is that prior to the model proceeding, all dependencies have been resolved, thus addressing many of the manufacturing issues that may occur. The need to go back and examine decisions, or the need to find a balanced solution is significantly reduced. Unlike the HOQ, the AHOQ allows the design team to identify the results of decisions during each step of the construction. This helps promote concurrent engineering practices. The most crucial decisions involve the FRs and DPs, and these decisions are evaluated in the same step using the design matrix. Thus, decision making follows a structured and informed approach resulting in less time on reviewing decisions and making changes. Secondly, the design of the product relies primarily on the functional requirements identified by the consumer. This new design tool has not been used in real world problems, and to do so would have exceeded the bounds of this dissertation. However, since the AHOQ was developed to resolve HOQ problems, it is believed that the AHOQ will provide improvements in terms of time and cost savings compared to the HOQ. Unlike the HOQ, the AHOQ examines and segregates the CAs into different design classifications. CAs that are identified as functional requirements will be the bases for the product's design. Other CAs will act as constraints or physical requirements that can be added to the design as long as they do not interfere with the functional requirements.

As for the issues with the voice of the customer, the AHOQ only provides a small improvement on ensuring that the requests of the customer are designed into the product. With the segregation of the CAs it is believed that there is less chance of misinterpretation of what the consumer requires. The segregation allows the design team to understand what the product must perform, and to what limit it must perform. All FRs, constraints, and requests by the consumer are captured and included into the design. However, like the HOQ the possibility of losing the VOC can still happen. VOC can be lost if CAs are not clearly defined by the customer, or if there exist conflicting CAs in the design and one of them must be omitted. Therefore, the AHOQ does not provide a significant improvement on the issue of the loss of the VOC.

Overall it is believed that these changes to the principles of the HOQ will result in an improved development time and lower costs. The principles set by the AHOQ will help improve development time as CAs can be segregated and the product can be properly designed on functionality. Furthermore, conflicts between CAs are easily resolved using the independence axiom thus saving time. As performed in the examples, conflicts are handled at each step in the model rather than at the completion of the model. This eliminates the need to constantly modify a model in order to find a good solution. It is believed that the changes in the AHOQ will improve the product's design and efficiency over the development stages.

VIII. CONCLUDING REMARKS

During the research of this dissertation, the author encountered difficulties when trying to find examples where HOQ had been successfully implemented. Most literature on the HOQ had very few examples of its use. This makes it difficult to compare the benefits that the AHOQ could provide over the HOQ. Considering this problem, the author believes that more of a comparison study is needed to quantify the benefits of AHOQ over just HOQ.

The purpose of this work has been to merge Axiomatic Design and the House of Quality to provide an integrated tool for upstream design. This purpose has been achieved with the development of AHOQ. AHOQ uses the combined methodology of AD and the HOQ provide a more efficient design tool for the design or redesign of products for consumer use. AHOQ incorporates the use of the design matrix and design axioms from AD, is structured in the HOQ format, and uses competitive assessment and rankings like that in the HOQ. The combination of both methods is evident in the examples uses in this dissertation. Through the steps of each AHOQ example, methodologies from both methods can be depicted, improving the design process of each product. Therefore, the purpose has been achieved with the combination of AD and HOQ methodologies to form the new AHOQ design tool.

The stated goal of this dissertation was to provide a more structured and usable form of the HOQ that incorporates the relationships between various functional requirements. This has been achieved with the inclusion of AD and design axioms in the AHOQ model. AD and design axioms allows the AHOQ model to focus primarily on the desired functions of the product set by the consumer. These functional requirements are used as the base criteria for the product's design. As in the examples, FRs are derived from the attributes desired by the consumer, where independent DPs are developed to resolve the stated FRs. Therefore, the design of the product will satisfy the specified functional needs set by the customer. Furthermore, the logical methods used by the design matrix strengthens the structure of the model. The use of the independence axiom prevents continuous changes to the model in an attempt to find an ideal design by eliminating all FR dependencies. Therefore, the design can be developed more efficiently due to the improved structure of the AHOQ model.

In the reported work, three objectives were also outlined for the creation of the new model. The first objective was to provide principles that govern the functional requirements set by the customer via customer attributes. Most of these principles are found in the first four steps of the AHOQ model. The principles involve identifying the consumers needs (CAs), then determining the functional requirements of the consumers needs, then identifying model constraints, and finally developing design parameters to resolve the stated functional requirements. In the following steps creating the design matrix, the principles of independence are addressed using the independence axiom. Therefore, the AHOQ model has the ability to govern functional requirements set by the customer in a most efficient method.

The second objective was to provide a method using AD that reduces development time and costs. The new AHOQ model includes the used of AD's design axioms allowing functional independence to be achieved in the design. Since there are no functional dependencies, there are fewer occurrences to modify the design as dependencies begin to appear. Therefore, there is less of a chance of performing iterative steps when a change to the design is forced due to a dependency. Since there is a reduction in design time, there is also a reduction in costs. Therefore the objective of a reduction of time and costs has been achieved.

The final objective was to provide a method of design based on function, without losing focus of the customer's requirements. In the AHOQ model, the primary criteria for design involve the functional requirements defined by the consumer. The product design occurs primarily in the design matrix where DPs are defined from the FRs. Since the FRs result from CAs, then the customer's requirements have been addressed. However, error may still exist when trying to maintain the voice of the customer. Error can occur if the design team misinterprets what FRs are being requested by the customer. Therefore, AHOQ has achieved this objective, however there is still chance for error.

With the completion of the goals and objectives, a quick reference pamphlet of the AHOQ was created. The purpose of the pamphlet is to act as a quick reference sheet on how the AHOQ can be applied in real world problems. The pamphlet contains a simplified version of the construction steps of the AHOQ using the coffee maker design as an example. This pamphlet is included in this dissertation in Appendix A.

In the discussion of error, no model is completely perfect in preventing errors. The new AHOQ model itself has two problems that could occur during the design. The first problem as discussed earlier is the potential loss of customer requirements or the 'voice of the customer'. If the requirements believed to be most important by the consumer are not of functional nature, then there is a possibility that they will not be completely fulfilled. The AHOQ model is based on design by function first. Non-functional requirements or constraints may be altered or only partially achieved if the design requires it in order to satisfy all functional requirements in the design matrix. Therefore, the most important needs of the consumer may be partially addressed or neglected in order to satisfy functional independence.

The second problem involves situations where the design involves only one or no functional requirements at all. In a single function design, a 1 X 1 design matrix is created where only one FR and DP exist. In this situation there is no need to proceed with determining FR independence since it will always be achieved. As for a non-functional design, there is no need to develop a design matrix and determine model independence since no FRs exist. Both of these situations are unique, however the AHOQ model still can be applied to evaluate the final design. The steps involving non-functional requirements, constraints, and competitive assessment can still be completed to determine an ideal design.

IX. FUTURE WORK

As discussed earlier in the dissertation, there is potential for future improvement to this model. This model is only in its infancy and through further time and application other steps or principles can be added to further improve on its design. An additional step not completely discussed is the uses of adding process variables to the model. PVs can be uses in a similar method with the design matrix where DPs and PVs are analyzed for independence. Determining a design's PVs is the next step required for the manufacturing of the product, or the facilitating of a system.

A second item that could be examined it the use of AHOQ for system design. In this model and most examples used AHOQ was primarily intended for product design. However, it is believed that AHOQ will have a significant effect on improvement of systems if applied. Systems such as the methodologies used in banking, hospitals, the business sectors, or information management could all be designed more efficient if AHOQ is applied as a design tool. This is because systems like products have functions that they must perform, and the design parameters are the processes how these function are executed. It is believed that AHOQ applied to systems would provide improvement and eliminate many unforeseen errors. Other future work could also include the development of a software program of the AHOQ that could possible be used on the web. This would ensure proper structure of the model and act as a guide for the design teams.

The role of the information axiom to the AHOQ model also should be examined in future work. Currently the information axiom is neglected in the model since it is undetermined if it would provide any cost savings. The information axiom may improve the AHOQ in other areas of the model not discussed in this dissertation. Therefore, the information axiom should be examined further to determine if it would provide any benefit to the AHOQ model.

Another possibility for future work is to examine the use of AHOQ as a diagnostics tool. Since AHOQ has the ability to develop a design for a new product, it could also be uses to examine the design of current products. Applying AHOQ to current products could identify faults in the product's design where the manufacturer can make immediate design changes. It is possible that AHOQ can easily be used as a diagnostic tool, however future studies are required to determine unforeseen problems that may occur.

In conclusion the new AHOQ model has provided many benefits that both HOQ and AD were unable to provide. The new AHOQ model has improved design efficiency and time over that of the HOQ. Previously in HOQ, design modifications were determined at the end during the evaluation of the model. If any changes were required, the HOQ must be updated to determine the effects of change. With the inclusion of AD's design axioms and design matrix, problems with design are determined earlier and are resolved prior to the completion of the model. This falls in line with concurrent engineering practices since design issues are handled prior to model completion. Furthermore, AHOQ enables a reduction in cost in the design process. Since less time for design is expected, the reduction in time will result in less cost in labour and modifications. Furthermore, AHOQ can be considered as a robust model since it not only can be applied to product design, but systems design, and can even be used as a systems diagnostics tool. In the initial study of HOQ and its principles, it was determined that much time and effort was required to complete the model. Furthermore, there was a potential loss of the consumer's requirements and other design information. However, with the combination of the principles and methods of both AD and HOQ to develop the new AHOQ model, an improved design can be created and completed more efficiently and effectively.

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APPENDIX A - CONDENSED AXIOMATIC HOUSE OF QUALITY MODEL

The Coffee Maker Example

The following sheet is a one-page synopsis of the AHOQ model. This example can be used as a "pocket guide" for the step-by-step design or redesign of any product. The sheet illustrates the application of AHOQ using the coffee maker example discussed in this dissertation. The purpose of the "pocket guide" is to provide a condensed version of the AHOQ model that will allow users to easily store and reference when applying AHOQ for design.

STEP 1 – List Customer Attributes

List the requirements of the customer in terms of customer attributes

1 Make coffee with store purchased coffee grounds
2 Coffee should be served hot
3 Coffee should not get cold over a few minutes
4 Hold a sufficient amount of coffee (2 to 12 cups)

STEP 2 – Convert CAs into FRs

Convert the customer attributes into functional requirements

CAs (Consumer Domain) ⟶	FRs (Functional Domain)
1 Make Coffee with purchase grounds	Blend coffee using water & coffee grounds
2 Server hot	Heat water to hot temperature
3 Not get cold	Keep coffee warm over period of time
4 Holding 2 – 12 cups	None (Volume Constraint)

STEP 3 - Identify Constraints

Identify requirements that are not functionally related, and determine if they are a design constraint (highlighted in bold)

CAs (Consumer Domain) ⟶	FRs (Functional Domain)
1 Make Coffee with purchase grounds	Blend coffee using water & coffee grounds
2 Server hot	Heat water to hot temperature
3 Not get cold	Keep coffee warm over period of time
4. Holding 2 to 12 cups	**Volume Constraint = 12 cups max.**

STEP 4 – Formulate Design Parameters

Concerning only the listed functional requirements, determine design parameters that will resolve each corresponding functional requirement

FRs (Functional Domain) ⟶	DPs (Physical Domain)
1 Blend coffee using water & coffee grounds	Gravity Filtration
2 Heat water to hot temperature	Electrical Resistance Heating
3 Keep coffee warm over period of time	Container's insulating properties

STEP 5 – Formulate the Design Matrix and Initial Design

Construct the design matrix base on the formulated FRs and DPs.

FRs/DPs	1. Filter	2. Elect	3. Insulate
1. Blender	1	0	0
2. Heat Type	0	1	1
3. Warmer	0	1	1

STEP 6 – Resolving FR Dependency (Decoupling FRs)

Perform modifications to the design to remove any FR dependencies. This may require adding or breaking down FRs to decouple the design, or determining other design parameters available to achieve each FR. This step is complete once an ideal solution has been found.

STEP 7 – Correlation of Design Parameters

Determine if there is any correlation or dependencies between design parameters

FRs/DPs	1. Filter	2. Elect	3. Insulate
1. Blender	1	0	0
2. Heat Type	0	1	0
3. Warmer	0	0	1

STEP 8 – Comparison of Competing Products

Competitive assessment is located on the right. The two competing products are a French Press coffee maker (product A), and a traditional coffee drip type maker (product B). The ranking for the model's current design is expressed as the bold number

FRs/DPs	1. Filter	2. Elect	3. Insulate	Product A	Product B	Ranking
1. Blender	1	0	0	Uses Strainer	Same method for blending	1 2 3 4 5
2. Heat Type	0	1	0	Pre boiled water	Same method for heating	1 2 3 4 5
3. Warmer	0	0	1	None	Uses base plate for heat	1 2 3 4 5

STEP 9 – Listing of Constraints

List all constraints in the model and evaluate their effects on the design

FRs/DPs	1. Filter	2. Elect	3. Insulate	Product A	Product B	Ranking
1. Blender	1	0	0	Uses Strainer	Same method for blending	1 2 3 4 5
2. Heat Type	0	1	0	Pre boiled water	Same method for heating	1 2 3 4 5
3. Warmer	0	0	1	None	Uses base plate for heat	1 2 3 4 5
Constraints						
Vol =12 cups	None	None	OK	Holds 3 cups	Holds 10 cups max	1 2 3 4 5

STEP 10 – Formulation of Process Variables

Determine the process variables required for each DP

FRs/DPs	1. Filter	2. Elect	3. Insulate	Product A	Product B	Ranking
1. Blender	1	0	0	Uses Strainer	Same method for blending	1 2 3 4 5
2. Heat Type	0	1	0	Pre boiled water	Same method for heating	1 2 3 4 5
3. Warmer	0	0	1	None	Uses base plate for heat	1 2 3 4 5
Constraints						
Vol=12 cups	None	None	OK	Holds 3 cups max	Holds 10 cups max	1 2 3 4 5
Process Variable Design Matrix						
PV(1)	1	0	0	Company A PV(1)	Company B PV(1)	1 2 3 4 5
PV(n)	0	1	0	Company A PV(n)	Company B PV(n)	1 2 3 4 5

STEP 11 – Evaluation of Final Model Results

Perform a final analysis on the model to determine if any design modifications are required. The model should be evaluated to determine if FR independence has been achieved, and the proposed design satisfies all requirements and constraints set by the consumer. Furthermore, the competitive assessment should be reviewed to determine if there are any opportunities that the design may incorporate in which the competition has provided a superior solution.

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