DESIGNING QUALITY ON FLEXIBLE PACKAGING SYSTEMS
USING QFD-AHP

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ABSTRACT

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The main objective of Research and Development (R&D) and Production departments is to be able to produce products that will meet consumer demands while minimizing production cost. Understanding the consumer requirements toward specific products and translating such requirements into engineering characteristics will be a critical exercise. Structuring collaboration between the development and the production team within in a company is important and it is one of the biggest advantages of Quality Function Deployment (QFD). To illustrate the implementation of QFD, the seal component of flexible packaging material will be considered. The seal component is a critical part of the packaging system that assures the safety and shelf life of the content and also the integrity of the package. The application of QFD in the packaging system will involve the participation of different departments within the Product company and also Converter and Suppliers by building the House of Quality (HoQ). Then, the Analytic Hierarchy Process (AHP) will be combined to enhance the multi decision-making process when designing quality within the seal component. The implementation of QFD-AHP enables structured interaction between companies to design quality of the packaging system toward production optimization. Consequently, ideally defined engineering characteristics can assure the quality of the products and QFD-AHP will minimize the need for quality control, product failures, and promote cross-functional team

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KEY TO ABBREVIATIONS

AHP	Analytic Hierarchy Process
B7	Seven Basic Tools
CI	Consistency Index
CR	Consistency Ratio
CTQ	Critical to Quality
CWQC	Company Wide Quality Control
DOE	Design of Experiments
DMAIC	Define-Measure-Analyze-Improve-Control
EC	Engineering Characteristics
FFS	Form-Fill-Seal
FMEA	Failure Mode and Effects Analysis
HoQ	House of Quality
ME-MCDM	Multi Expert-Multiple Criteria Decision Making
N7	Seven New Tools
PDCA	Plan-Do-Check-Act
PR	Product Company Requirements
QFD	Quality Function Deployment
SPC	Statistical Process Control
S/N	Signal to Noise
TQM	Total Quality Management
T.T.P	Temperature, Time, and Pressure
RI	Random Index

KEY TO SYMBOLS

C_i	Importance degree of the *i*th customer requirement
R_{ik}	Quantified relationship between the *i*th customer requirement and the *k*th engineering characteristic
r_{kj}	Quantified relationship between the *k*th engineering characteristic and the *j*th engineering characteristic
R_{ij}^{norm}	Relation coefficient
W_j	Importance degree of the *j*th engineering characteristic

I. INTRODUCTION

High demands from customers and market changes has had an impact on the production process of many companies. Today, the company's goal is to sustain their competitiveness in the world market by collecting the customer requirements and translating such requirements into the engineering characteristics. This approach will enhance their product quality and so the companies' competitiveness while optimizing the production processes.

To accomplish the above-mentioned strategies, the cross-functional team is essential at each stage of product design which requires significant effort and should be done at the early product development phase. In the current work, we are discussing and proposing strategies to reduce product failure through optimization of the production process while minimizing the need of quality control by designing quality within the product.

Quality Function Deployment (QFD) is considered as a tool which translates customer requirements into engineering characteristics with the use of House of Quality (HoQ). QFD was initially applied in manufacturing industries and later on has been widely utilized in research. QFD has shown successful results in various areas such as: service, education, and technical industries (for example, electronics, automobiles, and also construction industries).

The objective of QFD is to design a quality system by analyzing the voice of the customers which will be converted to the engineering characteristics to be included as a design component of the finished product. Furthermore, it will assure the quality to be met in the production line. This methodology is an effective tool to identify not only customer demands but also to define the most critical engineering characteristics to be used to monitor and control the production process.

It is important to emphasize that packaging plays an important role to protect products and safely distribute commodities in processing, manufacturing, and transportation of the products to the end user. Flexible packaging is one of the most popular packaging systems because of its potential to low cost, lightweight, and ease of utilizing space (of empty containers) in a warehouse compared to other packaging systems.

Flexible packaging material utilizes a Form-Fill-Seal (FFS) machinery during the manufacturing of the actual product by forming and sealing packages such as a pouch, bag, and sachet. Specifically, a key component of the FFS package is the seal integrity. Defects in the seal area of the packages can create weakness and open areas (such as channels or pin holes) within the seal area, where the contamination of microorganism, or even impact the internal package atmosphere, reducing the shelf life of the product. The weak seal represents a safety concern, customer dissatisfaction and eventually losses for the company's image.

Since the seal integrity represents a critical quality issue, several quality components should be considered. For instance, sealing range that relates to packaging material characteristics and FFS machinery specifications that require the ability to maintain a constant temperature throughout the production process. As a consequence, such considerations can help to produce an optimum packaging system that will protect the product throughout its shelf life.

The application of QFD-AHP in the sealing requirements of the flexible packaging material which utilizes the FFS machinery will guide companies to develop a reliable sealing process. In order to apply QFD-AHP, we need to have a good understanding of the requirements responsible for an intact sealing process. Subsequent to this, they are ranked in order to identify the most critical engineering characteristic for an optimum seal (an intact package and content).

Finally, the approach carries out in this specific application will serve as a template to design other packaging components. The main advantage of this approach is that it relies on designing quality prior to the production process rather than promoting quality control to assure the product quality.

II. LITERATURE REVIEW

2.1. Background of Quality Management and Definition of Quality Design

As demands from the customer are increased, companies need to adapt and build a product that meets such demands. It is important to know that quality design begins and ends with the customer. Meeting the customer expectations regarding a specific product can be achieved by understanding the characteristics of the product. According to ISO 9000: 2015 (2015) definitions, quality is the "degree to which a set of inherent characteristics of an object fulfills specific requirements" (fundamentals and vocabulary). Quality should provide a safe product meeting the customer requirements during the product design in order to assure the absence of product failure. There have been many 'quality' definitions throughout the years since 1980 and the quality movement includes some techniques such as simple inspection of the product, quality assurance, and furthermore today we discuss the Total Quality Management (TQM) (Weckenmann, Akkasoglu & Werner, 2015).

Quality is the collection of the three spheres which are quality control, quality assurance, and quality management as shown in Figure 1 (Foster, 2012). Quality control indicates a pass-fail assessment which establishes a control chart to analyze the data. Quality assurance identifies the problem from the quality control through statistical techniques. It assesses the quality of products or services after production through failure mode and effect analysis, experimental design, and reliability testing. Quality management involves the activity of building the organizational culture, planning for product improvement, and training for employees.

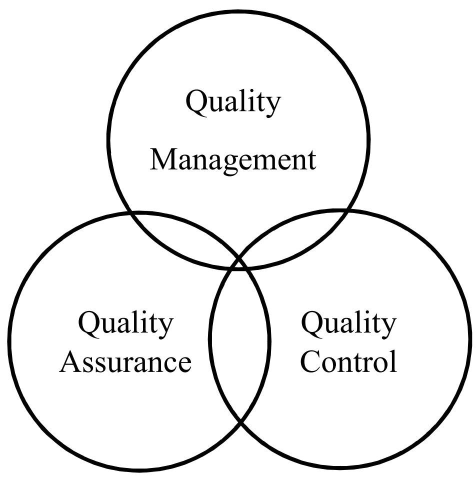


Figure 1. Three spheres of quality

The first iteration of modern Total Quality Management (TQM) concept was derived from Shewart's Statistical Process Control (SPC) chart in the early 1920s in order to inspect quality in mass production manufacturing (Sureshchandar, Rajendran, & Anantharaman, 2001). The concept of quality design, on the other hand, has been led by many such as Deming, Juran, Crosby, Feigenbaum, Ishikawa, and others. Deming (1950) who was influenced by Shewhart's (1924) concept of quality control, developed the process cycle. Deming introduced the Plan-Do-Check-Act (PDCA) cycle at the Japanese Union of Scientists and Engineers seminar in the

1950s, also known as Deming's PDCA cycle (Figure 2). The PDCA cycle should be performed repeatedly in order to achieve continuous improvement and continually reduced variation will support the system in the future capacity (Chiarini, 2011).

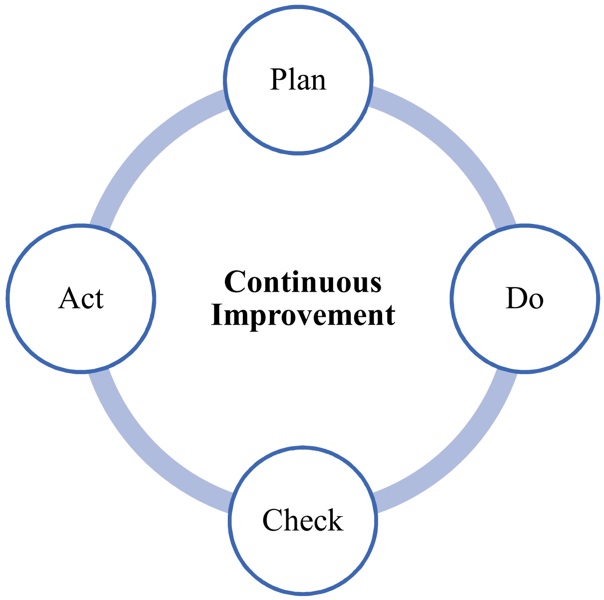


Figure 2. Deming's PDCA cycle

PDCA cycle is based on the four-step model:

Plan:

The scope of the goal will be established by understanding the company's current circumstances.

Do:

Once the plan was determined, define resources and train the employees to enact the plan.

Check:

The result will be measured and analyzed, then compare data to the prediction in order to summarize and review them.

Act:

When the result is not as predicted, restart the cycle of improvement. On the other hand, successful improvements can be standardized as a new change in the operation.

During World War II, the importance of quality improvement increased in America and the application of the control chart to reduce variation was the chosen approach. After World War II, Japanese competitiveness decreased significantly due to the poor quality of their products mainly caused by their manufacturing system. Then, Japan decided to invite Deming to train their employees on how to implement quality into the production process (Essop, 2015).

Toyota Motor Company is one of example of an entity that successfully adapted the quality approach in manufacturing industries with the reflection of Deming's quality concept. This approach helped to develop widely known Lean Manufacturing. The Lean production approach was initially conducted by Henry Ford in a continuous system and revised with the use of TQM and SPC approaches based on Toyota Production System, which was introduced by Ohno (1988). PDCA cycle and standardization processes are the center of the Toyota Production System and Lean Manufacturing (Saier, 2017). The main purpose of quality development in this strategy was related to reducing variation in the production process by designing quality into the product.

In terms of quality design, there was a new approach, which refers to Six Sigma starting in the 1980s-era in America (Watson and DeYong, 2010). Six Sigma began in the manufacturing industry to reduce the variability of production processes and was extended to nonmanufacturing areas as an advanced version of the PDCA cycle in modern society. Motorola initially developed the Six Sigma and it was popularized by General Electric (De Mast, 2004). The purpose of Six Sigma in quality management aims to increase process capability by reducing variation based on the Define-Measure-Analyze-Improve-Control (DMAIC) approach (Figure 3). This approach refers to a data-driven improvement cycle used for improving, optimizing and stabilizing business processes and quality designs.

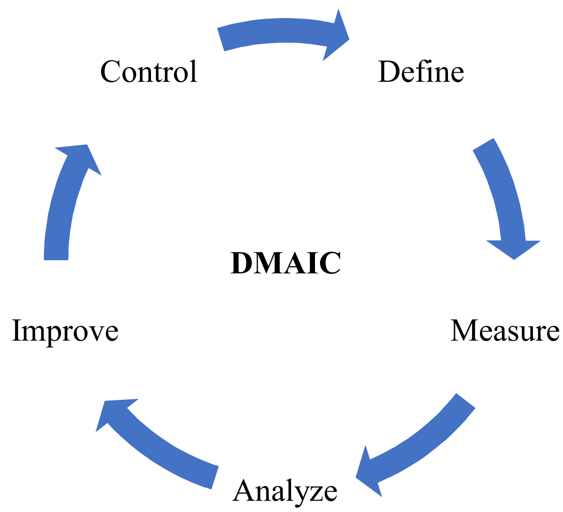


Figure 3. DMAIC process

DMAIC is based on the five-step model:

Define:

The Define phase identifies the scope and objectives of the project. Set goals of the project once the business problem has been clearly discussed, then define the key customers. Afterward, collect the voice of the customer and develop the Critical to Quality (CTQ) which is product characteristics that have a significant impact on the quality of products.

Measure:

In this phase, CTQs which impact the production processes and meet the performance standards will be measured under the predetermined specification limit. It requires understanding that CTQs align improvement or design efforts with the customer requirements.

Analyze:

The Analyze phase focuses on finding root causes about the products defects, errors or variation during the process. It helps to understand the natural characteristics of products and eliminate the potential failures for further analysis.

Improve:

Once the root causes are identified, the project team will generate a solution to resolve the problem and implement a new strategy in order to improve the production processes.

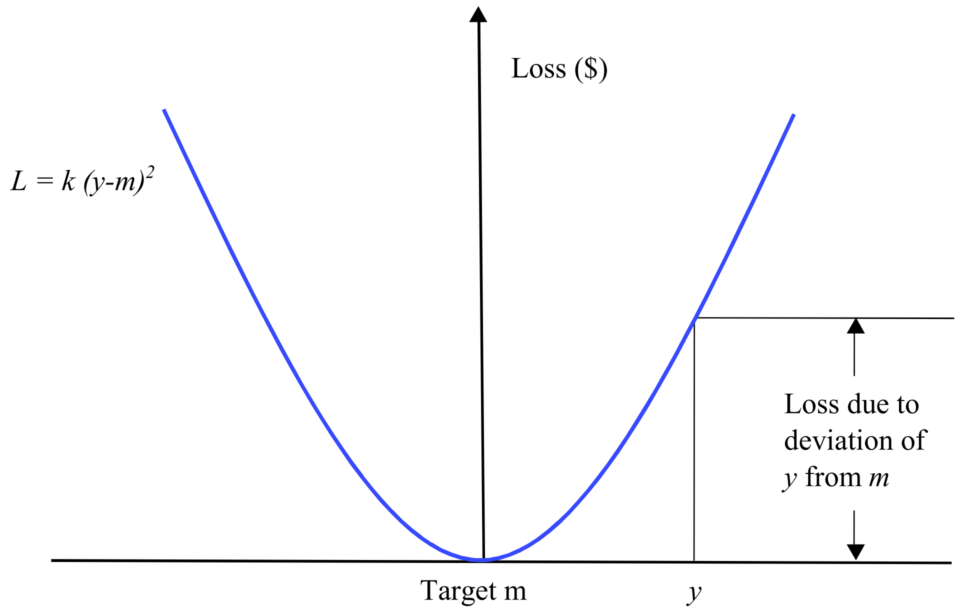
Control:

The Control phase is the final step of the DMAIC, and it aims to sustain the improvements and embed the changes in the process in order to maximize productivity.

The limitation of control charts and the PDCA cycle can be improved with the implementation of Six Sigma (Gupta, 2006). Several quality tools can be used in the DMAIC and "Some examples of techniques are statistical process control (SPC), quality function deployment (QFD; house of quality), failure mode and effects analysis (FMEA) and design of experiments (DOE)" (Uluskan, 2016, p. 410). Each phase of the DMAIC approach can be utilized with these quality tools and the project aims to increase production performance and reduce variation in the process.

As another example, the central goal of quality design and statistical analysis was propagated by Taguchi. Taguchi Method aims to develop a robust design process in order to achieve the lowest cost and minimize variation (Jeyapaul, Shahabudeen, & Krishnaiah, 2005). In this approach, there are two main concepts which are the orthogonal array and signal-to-noise (S/N) ratio. An orthogonal array is a highly fractional factorial design to analyze the experiment. It estimates the most critical interaction between the different process parameters. In terms of S/N ratio, "the term 'signal' represents desirable values and 'noise' represents the undesirable values" (Mehat and Kamaruddin, 2012). Among many noises, uncontrollable factors such as humidity and temperature of the atmosphere is difficult to control. Therefore, the main goal is to select the controllable noise (process parameters) from the production line and reduce variation in order to improve quality with low cost. With this concept, the Taguchi method evaluates the deviation to predict noise from the orthogonal array. As consequence, the highest S/N ratio refers to optimum robust design with minimum variance.

Loss of quality occurs from product characteristics and customer dissatisfaction with defective products (Anthony and Kaye, 2000). A strong system and well-defined parameters with narrow variability are essential to reduce losses due to poor-quality which eventually become a loss to society. Taguchi proposed quality loss function as shown in Figure 4 (Sharma, Cudney, Ragsdell, & Paryani, 2007). According to this theory, losses will increase when variability increases or once the actual value of a specific object deviates from the target value. Attributes falling outside of specifications result in loss of quality, but also losses can occur when the product falls within specification (Cosmin and Ana-Maria, 2012). Thus, Taguchi believed that target value is determined with allowance for variation, so parameter design plays an important role to obtain high quality with the lowest cost by reducing variation in order to have defect-free products.



L = Loss in $

k = Cost coefficient

y = Value of quality characteristic

m = Target value

Figure 4. Taguchi's quality loss function.

To put it concretely, SPC focuses on variance analysis based on sampling for quality improvement; furthermore, TQM extends the meaning of the quality management into all of the functions within an organization including management levels (Grant, Shani, & Krishnan, 1994). TQM is an effective philosophy to produce high productivity and achieve a higher level of quality. In addition, TQM is an integration of all quality management tools such as Quality Function Deployment, Taguchi methods, and Statistical Process Control based on the principle teaching by Deming, Juran, Ishikawa, and Taguchi (Elshennawy, 2004). The quality movement has evolved with new approaches and quality tools by adapting changes with the consideration of the customer demands. Such an approach should be fully supported by higher management in order to bring optimum process in business.

Successful quality implementation can be started with the use of basic quality tools. The practice of quality techniques can provide a decent guideline to facilitate the problem-solving projects in the team processes. There are continuous improvement tools such as basic seven (B7) and new seven (N7) tools to collect information and enhance the quality strategy (Foster, 2012). The seven basic tools include process map, check sheets, histograms, scatter plots, control charts, cause and effect diagrams, and pareto analyses. The seven new tools include an affinity diagram, interrelationship digraph, matrix diagram, tree diagram, prioritization matrices, process decision program chart, and activity network diagram. The use of quality tools can be applied at the level of team projects from defining the process to analyzing the data. The power of B7 and N7 tools are that they are easy to practice, identify the problem, find root causes, and eventually, bring ideas to improve the process as problem-solving tools.

Basic seven (B7) tools are listed and explained in below:

Process map: Create the flow of process map with a set of symbols to identify the process.

Check sheet: Collect data with the use of tables or schematics in a document.

Histogram: Graphical representation of frequency distribution in a bar graph format.

Scatter plot: Collect pairs of data to evaluate the relationship between variables.

Control chart: Collect data and plot into a graph to see any changes to measurable properties over time.

Cause and effect (Ishikawa) diagram: Identify the root causes of the problem with the use of the '5 Whys' to solve the problems.

Pareto analysis: Identify and prioritize the problem with the use of the 80/20 rule; referencing that many trivial problems (roughly 80%) are created by vital few causes (roughly 20%).

New seven (N7) tools are listed and explained in below:

Affinity diagram: Collect data (brainstorm) and organize a number of ideas by its natural relationship.

Interrelationship digraph: Helps to identify major issues from their casual relationships based on the number of arrows received.

Matrix diagram: Collect data to choose an appropriate matrix correlation with a set of symbols.

Tree Diagram: Generate specific ideas under each problem to identify multiple branches

Prioritization matrix: Decision-making process based on multiple criteria by applying weight respectively.

Process decision program chart: Tree chart to develop possible preventative actions of the problem which associates with the feasibility of improvement (Foster, 2012)

Activity network diagram: Identify project's critical path to see the sequential relationships of activities with project timelines.

Improvement of the process capability by applying quality tools is important to achieve the optimum quality of products in order to advance the state of quality competitiveness through the market. In the 1970s, Ishikawa discovered the concept of the Company-Wide Quality Control (CWQC) which emphasizes that all employees within a company from the president to the machine operator should participate together (Elshennawy, 2004). The conversation through all levels of employees can enhance the development process from a variety of perspectives and build the company's culture.

The cross-functional team working and pursuing optimal processes in the production lines require a systematic quality design which is rooted in the customer. Understanding customer requirements and transferring such requirements into the engineering characteristics is important to design quality. Quality Function Deployment is the one approach to obtain these strategies. The ability to design quality is essential to succeed in quality management by integrating systems between multiple departments within an organization. If a producer can select the most critical engineering characteristic to focus on optimizing the process, this quality strategy can lead to cost reduction, high productivity, profitability, and sustainability within a company.

2.2. Quality Function Deployment (QFD) History and Background

Components of quality require two aspects which are quality design and quality conformance to improve overall performance of the product (Figure 5). Quality design should be performed prior to manufacturing of the product including activities to set the design specification. Quality conformance verifies design specifications are met during the manufacturing by achieving quality control and quality assurance.

Figure 5. Components of quality

Many quality approaches were developed to improve quality in the process and organizations in order to improve the production process which is suitable for their business type. Among many approaches, Quality Function Deployment (QFD) methodology has its unique advantage by understanding the transition of the product characteristics from the customer expectations to the component of the products. The main purpose of QFD is process improvement with a quality design and this approach will be implemented in the current study.

Akao (1978) introduced Quality Function Deployment (QFD) to design quality from the customer voices when the product is in the initial design phase prior to the manufacturing. Design of quality requires companies to gather customer requirements and implement how to convert these requirements into the engineering characteristics. The challenge is to identify engineering characteristics and find correlation among different characteristics that influence each other. QFD makes this possible by supporting designers to build up the process parameters but also by showing how such different components are related to each other, and eventually relates to the quality of the final products.

QFD was originally developed in Japan in the late of 1960s in order to improve the competitiveness of Japanese industry and products in the world. In 1972, Nishimura generated the idea of the development process through a quality table with the use of spreadsheets or particular charts at the Kobe Shipyard of Mitsubishi Heavy Industry (Chan and Wu, 2002). In 1978, Akao and Mizuno formulated the very first terminology and procedure of the QFD and published a book with the number of QFD applications. Afterward, QFD began to be introduced in America and Europe in 1983, and at the same time, Akao was invited to give a QFD seminar in Chicago (Abu-Assab, 2012). Originally, the Quality Function Deployment was translated into English as the 'Quality Function Evolution' by Akao and Mizuno. However, when Akao attended the first seminar in America, there was a doubt that evolution was appropriate to express the change in quality. Thus, they started to use the phrase 'Quality Function Deployment'.

The concept of QFD was developed under the Total Quality Control philosophy to identify the priority of customer expectation when designing products that meet such expectations. This approach can be achieved with a cross-functional team representing all areas of the company and its influences are linked with the activity of CWQC phase. This approach has been utilized across a variety of industries in America (automotive, electronic devices etc). In the beginning, the American Supplier Institute conducted a QFD approach on the "big three" automobile manufacturers, and it was successfully administered. The QFD Institute was established in the state of Michigan by Glenn H. Mazur, followed by the approval of Akao in 1994 and more than 1,000 case studies were conducted and published around the world (Akao & Mazur 2003).

The application of QFD provides a structured method to assure the quality of final products in design stage of the product development (Martitan, 2015). It is a customer-oriented method that translates the requests of customers into product components toward quality targets. Understanding the correlation of each component to contribute the performance at facilities can assure the quality of finished products. Since the QFD method requires the involvement of all members to identify quality components, it is time consuming to determine the correlation between customer requirements and engineering characteristics. However, defining the critical key features and the use of a well-organized document will shorten the time of the development process. Understanding the basic principles of QFD is the starting point for quality development and training the participant ahead of time is critical. A commitment to quality within the company that includes upper management can promote a continuous quality improvement activity throughout the company.

2.3. House of Quality (HoQ)

The approach to initiate QFD starts with the construction of a relationship matrix that will involve various departments such as marketing, quality, purchasing, engineering, and research and development. Employees from various departments are necessary to organize a QFD team to analyze the "voice of customer" and identify the most critical product requirements that need to be tracked to assure quality. For example, the customer requirements which is a qualitative measurement such as "easy to open packages, product freshness, intact seal, nice appearance, etc." will be translated into quantitative measurement such as "seal strength, permeability to moisture, ink viscosity, etc". Based on the customer requirement, the QFD process could be implemented with the 4 Phases: 1) House of Quality, 2) Parts Deployments, 3) Process Planning, and 4) Production Planning as presented in Figure 6.

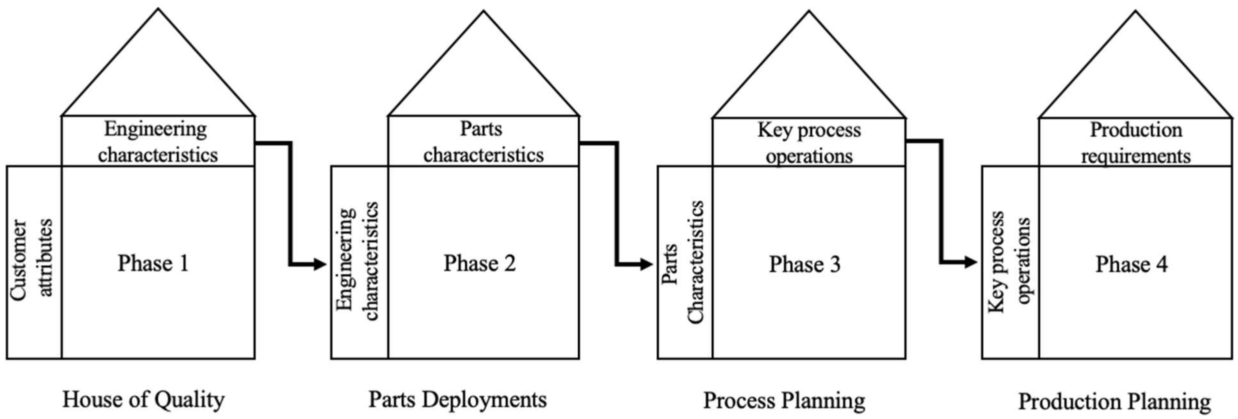


Figure 6. Four phases of the QFD process

Figure 6 indicates each phase of QFD approach by completing the whole cycle of the product development system. Each of 4 Phases will be discussed and explained below not only in the content of each Phase but also how they are interrelated:

1) Phase 1

Phase 1 is widely known as the House of Quality (HoQ) but also called product planning. It is the first approach to translate *Customer attributes* (referred to as customer requirements) into *Engineering Characteristics*. Engineering characteristics represent the important parts of the product (such as 'barrier properties').

2) Phase 2

Phase 2 is known as Parts Deployments. The translated Engineering characteristics from Phase 1 will be a starting point to analyze *Part characteristics* in Phase 2. It identifies appropriate parts characteristics of the product for the production of the proper parts of the product (such as ‘no moisture loss or gain’).

3) Phase 3

Phase 3 is known as Process Planning. The translated Part characteristics from Phase 2 will be a starting point to analyze *Key process operations* which are also known as process parameters for manufacturing (such as ‘polymer formulation’).

4) Phase 4

Phase 4 is known as Production Planning that generates *production requirements* to monitor the production process through maintenance schedule, work plan, and inspection.

Many US companies only use Phase 1 of the HoQ for the implementation of QFD with a clear interrelationship (Martitan, 2015). The House of Quality (HoQ) is a conceptual map of product development and an excellent tool to integrate several departments’ perspective and ideas into one diagram. As a starting point, the organization clearly defines the scope and objective of the project and identifies key customers.

HoQ approach will be outlined by 6 steps to build up the interrelationship between customer requirements and engineering characteristics under the umbrella of the HoQ which is shown in Figure 7.

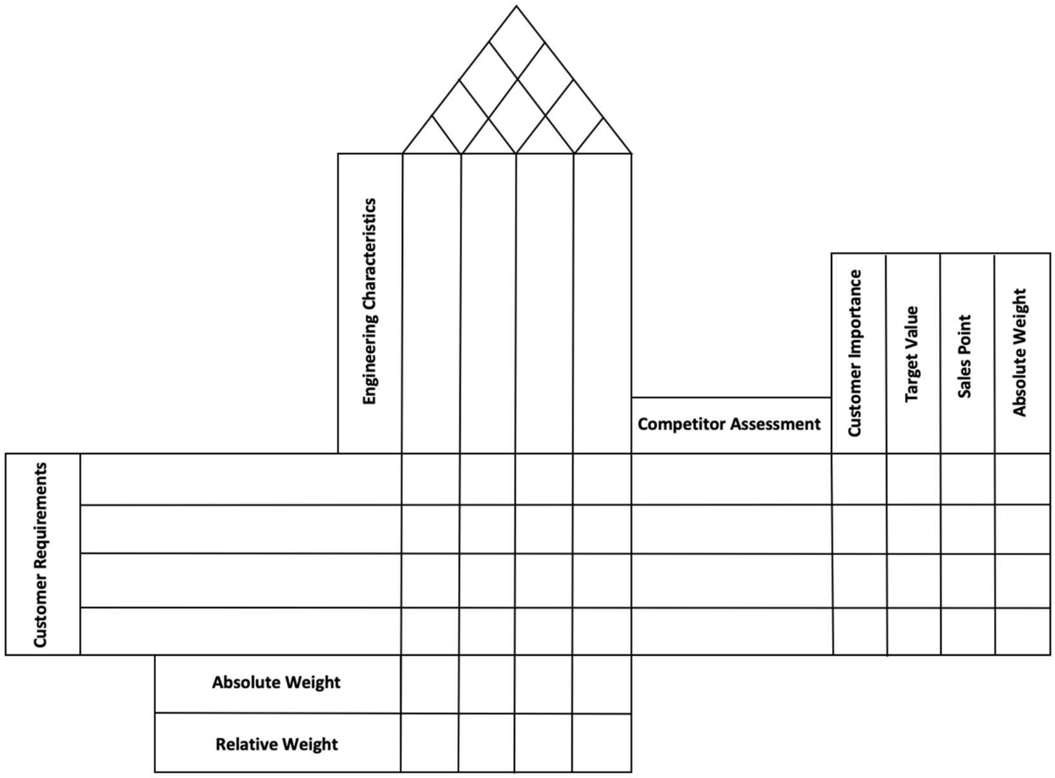


Figure 7. House of Quality (HoQ) diagram

The following discussion will describe the different steps necessary for the implementation of the House of Quality (HoQ) in Figure 7.

1) <u>Identify customer requirements</u>

Customer requirements represent the customers preferred characteristics and such characteristics need to be met for the product to be chosen by the customer. Customer requirements will be collected by using several methods such as interview, survey, and focus group. Then analyze information through the affinity diagram. The list of customer requirements is placed on the left of the HoQ. Conversion of engineering characteristics should start from the understanding customer needs and expectation toward the product or specific process parameters that the product should be met.

2) Identify engineering characteristics

Engineering characteristics are measurable process parameters that can be monitored or controlled during the production process. Engineering characteristics will be identified by expert knowledge, experience, and research. The basic seven (B7) tools and new seven (N7) tools (previously mentioned in the Literature Review, page 11-12) can be used to promote discussion and suggest clear guidelines. The list of engineering characteristics is placed at the top horizontal axis of the HoQ. The team should be aware that one customer requirement can impact several engineering characteristics.

3) Construct a relationship matrix between customer requirements and engineering characteristics

A *relationship matrix* between customer requirements and engineering characteristics is depicted in the main body of the HoQ. Subject assessment will be used to construct the relationship matrix based on the team discussion. The associated interaction will be assigned through a set of numbers (1, 3, and 9). The value within a scale denotes the strength or weakness of such correlation (1 – weak relationship, 3 – moderate relationship, 9 – strong relationship). From this process, the team can understand how the customer requirements are related to the engineering characteristics.

4) Construct a correlation matrix between engineering characteristics

A *correlation matrix* between engineering characteristics is located in the roof of the HoQ. This matrix describes whether those engineering characteristics are negatively or positively correlated.

5) <u>Conduct a competitor assessment</u>

A *competitor assessment* is closely related to benchmarking and is located on the right of the HoQ. The assessment is performed on a scale of 1 to 5 (1-low and 5-high). As related to the customer requirements, the company will evaluate their product by comparing with competitor's products in order to have an objective observation where the company stands in the market.

6) <u>Prioritize customer requirements</u>

Overall prioritized customer requirements are placed in the far-right wall of the HoQ. It includes four categories which are customer importance rating, target value, sales point, and absolute weight (Foster, 2012).

The *customer importance rating* is determined by a focus group on a scale from 1 to 10 (1-low to 10-high), a subjective assessment.

Target value will be assigned on a 5-point scale and it indicates whether the quality design team should improve the product compared to the competition (1-no necessary to change and 5-Improve the product relative to competitors).

Sales point indicates how the customer requirements are significantly related to the market point of sales with a scale of 2-point (1-low effect on sales and 2-high effect on sales).

Once the team analyzed the information, finally, the *absolute weight* of customer requirements will be calculated by multiplying the customer importance rating, target value, and sales point.

7) Prioritize engineering characteristics

Prioritized engineering characteristics will be located at the bottom of the HoQ through absolute weight and relative weight. The calculation process will be illustrated below.

a) Calculate the *absolute weight* of engineering characteristics

   a-1) Multiply the *customer importance rate* from the Step 6 by the *relationship matrix* value from the Step 3.

   a-2) Add all the calculated relationship matrix, then write the results in the *absolute weight* of the engineering characteristics.

b) Calculate the *relative weight* of engineering characteristics

   b-1) Multiply the *absolute weight* from the Step 6 by the *relationship matrix* value from the Step 3.

   b-2) Add all the calculated relationship matrix, then write the results in the *relative weight* of the engineering characteristics. Since *relative weight* considers target value and sales point of the customer requirements, this value is more precise than the *absolute weight*.

8) Evaluation

Based on the calculation from Step 7, each column of engineering characteristics will be added and prioritized. Control all of engineering characteristics at once is time consuming and costly. Therefore, the QFD team will select the most critical engineering characteristic and decide which engineering characteristic should be tracked first for optimum improvement.

2.4. Overcome the Weakness of QFD with Prioritization Methodology

The QFD promotes the interaction of different departments by fostering a systematic approach. As a consequence, the QFD will influence the idiosyncrasy of the company's culture rooted in the interaction between departments. The use of QFD approach could generate a set of documents that will depict a roadmap for quality design. The final product design will result by the proper interrelationship of product's quality, functionality, processing parameters in order to obtain a highly sustainable product. There is a significant investment in developing a process by the implementation of the QFD. Ultimately, it will assure a great investment on the design process and how it relates to the production process resulting in a product with minimal failure, waste, and quality control.

Although the conventional QFD is an efficient approach to prioritize the engineering characteristics, there are two weakness associated with it: 1) The method to determine the degree of importance of the customer requirements is inconsistent, 2) Dependency level between the engineering characteristics is not considered. Therefore, QFD approach had been implemented in several studies in combination with other tools such as:

- Lee, Ru, Yeung, Choy, and Ip (2015) integrated Fuzzy Logic with QFD in order to avoid inaccurate and imprecise expressions from the customers when applying decision-making process in the healthcare service. In this study, the Fuzzy Logic aims to translate the subjective customer requirements as specific as possible with the set of five-linguistic labels (e.g. very poor, poor, neutral, good, and very good) through triangular fuzzy numbers.

- Fiorenzo, Maurizio, Domenico, and Luca (2017) combined Multi Expert-Multiple Criteria Decision Making (ME-MCDM) technique in the developing the climbing safety harness in order to overcome two controversial assumptions: 1) Customer requirements (expressed on ordinal scale) are artificially converted into a cardinal scale, 2) Traditional QFD uses independent scoring method in prioritization of the engineering characteristics. Fiorenzo et al (2017) compared the importance of engineering characteristics with different numerical levels (e.g. 3, 5, 10-level scale) to assign an ordinal scale both on the customer requirements and engineering characteristics to overcome above-mentioned assumptions.
- Dai and Blackhurst (2012) used the Analytic Hierarchy Process (AHP) in supplier assessment in order to evaluate sustainability perspective such as economic, social, and environmental performance. Bhattacharya, Sarkar, and Mukherjee (2005) integrated AHP approach as a decision support technique in the selection of robot for the performance enhancement.

Analytic Hierarchy Process (Saaty, 1970) and Normalization (Wasserman, 1993) are the tools chosen in the current study in order to overcome the weaknesses of the traditional QFD as mentioned earlier (page 23). Dai and Blackhurst (2012) combined the Analytic Hierarchy Process and Normalization to create the QFD-AHP approach. Ultimately, QFD-AHP will help to determine the most important engineering characteristics in the designing process and it will be implemented in the current study in Part V.

The following discussion will describe the application of QFD-AHP.

1) <u>Have a consistent evaluation in customer requirements with the use of Analytic Hierarchy Process (AHP)</u>

Analytic Hierarchy Process (AHP) is widely utilized with QFD as a multi-criteria decision method and it was developed by Saaty in 1970s. The AHP uses the paired comparisons between the criteria and it identifies the one that is more important over another by ranking them. Evaluating the individual alternatives is necessary and establishing the overall weights for the criteria will help to select the best one (Alonso and Lamata, 2006). AHP can reduce the complex decision with a clear rationale and ensures the consistency of the paired comparisons.

In order to conduct the calculation of paired comparisons in AHP, Saaty's matrix will be considered. It indicates the degree of importance for two alternatives criteria by using the scale range from 1 to 9 as shown in Table 1. For example, 1 indicates that two selected criteria are equally important and 9 indicates the first criterion is extremely preferred over the others. The numerical value of 2, 4, 6, and 8 expresses the intermediate degree of the importance of the adjacent values.

Table 1. Satty's scale matrix to define the degree of importance for two alternatives criteria

Degree of Importance	*Numerical Values(s)*
Equal importance between two criteria	1
Moderate importance of one over another	3
Strong importance one over another	5
Very strong importance of one over another	7
Extreme importance of one over another	9
For compromise between the adjacent values	2,4,6,8

The paired comparisons process will be calculated through Matrix A, B, and C and the calculation process of each Matrix will be explained in the following steps:

1-a) <u>Matrix A</u>

The paired criteria will be scored in a square *Matrix A* and it makes a reciprocal matrix. The reciprocal means that when multiplying the two numbers, it makes 1. For example, the numerical value of (criterion 1, criterion 2) is 3 followed by Table 1. Then, the score of (criterion 2, criterion 1) will be $\frac{1}{3}$, because the reciprocal of 3 is $\frac{1}{3}$ by flipping over the fraction to make 1. Diagonal in a square Matrix A indicates to compare the criterion itself, therefore, the score of the diagonal is always 1.

1-b) <u>Matrix B</u>

Matrix B will be created by summing each column of Matrix A and each value in a column will be divided by summation.

1-c) <u>Matrix C</u>

Matrix C will be created by summing each row of Matrix B. Then Matrix C will be averaged across the rows. Eventually, Matrix C indicates the importance weight of each criterion and it helps to identify the most important criteria.

Once the paired comparison is conducted, the *Consistency Ratio (CR)* should be calculated in order to ensure whether the consistency of paired comparisons is acceptable or not. The degree of consistency level will be obtained through *Consistency Index (CI)* and *Random Index (RI)*, and their calculation processes are explained in the following steps:

1-d) <u>Understand the *Consistency Ratio (CR)* equation</u>

The *Consistency Ratio (CR)* will be obtained from the *Consistency Index (CI)* divided by *Random Index (RI)* which is shown in Equation (1). *CI* refers to the index of the consistency judgments for entire paired comparisons. In order to calculate *CI*, *Consistency Measure (CM)* should be calculated first as follow in step 1-5.

$$\text{Consistency Ratio (CR)} = \frac{\text{Consistency Index (CI)}}{\text{Random Index (RI)}} \qquad \text{(Eq. 1)}$$

1-e) <u>Calculate the *Consistency Measure (CM)*</u>

In order to obtain the *Consistency Index (CI*), *Consistency Measure (CM)* should be calculated. It can be calculated by multiplying *Matrix A* and *Matrix C* and dividing them by respective degree of importance from *Matrix C* (note that we will use Matrix C inputs before they are averaged). Then, the *Consistency Measure (CM)* will be averaged and Equation (2) will be used to calculate the *Consistency Index (CI)* (note that *N* indicates the number of criteria for the paired comparison judgment).

$$\text{Consistency Index (CI)} = \frac{\text{Average of Consistency Measure (CM)} - \text{N}}{\text{N} - 1} \qquad \text{(Eq. 2)}$$

1-f) <u>Calculate the *Consistency Ratio (CR)* with a given *Random Index (RI)* table</u>

The *Random Index (RI)* is given by AHP which is shown in Table 2. *RI* refers to the average value of *CI* for a randomly generated reciprocal matrix. Finally, *Consistency Ratio (CR)* will be calculated through the Equation (1) and it is important that the result should be less than 0.10 in order to obtain satisfactory consistency. According to Saaty

(1994), “A consistency ratio of 0.10 or less is positive evidence for informed judgment” (p.42). If the *CR* is greater than 0.10, it requires to revise the subjective paired comparisons judgment.

Table 2. Random Index (RI) values(s) given by Saaty’s AHP

Number of criteria	*RI*
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

2) <u>Consider dependency among the engineering characteristics with the use of Normalization</u>

Once the customer requirements had been evaluated with their consistency assessment, Normalization model (Wasserman, 1993) will be used. Traditional prioritization of QFD did not consider dependency when calculating the degree of relationship intensity of the engineering characteristics. Therefore, Wasserman proposed the normalized relationship by assuming that the engineering characteristics are mutually dependent (Chen and Chen, 2014). Chen and Chen pointed out that if the quality characteristics are mutually interdependent, the QFD team can follow the original formulation, and however, this does not happen in reality because everything is dependent on each other.

The user of QFD-AHP should construct two matrixes in order to normalize the engineering characteristics. The two matrixes include; 1) correlation between engineering characteristics and customer requirements (body of the HoQ), 2) correlation among the engineering characteristics themselves (roof of the HoQ).

In terms of first correlation (body of the HoQ), conventional scale of 1-3-9 (weak, moderate, strong) is utilized with a set of symbols to indicate the interrelationship. The weight for conversion from ordinal evaluation (three symbols) to cardinal scale (1, 3, 9) is most used, although alternative systems can be used (1, 2, 4, or 1, 3, 5) (Franceschini, 2002).

On the other hand, the second correlation (roof of the HoQ) should maintain the scale levels between 0 and 1 (Franceschini, 2002). Therefore, a set of symbols assigns the value 0.1-0.3-0.9 which indicates a weak, moderate, and strong association.

After that, two correlations are normalized in relation coefficient (R_{ij}^{norm}) to determine the degree of relationship intensity by adjusting their interrelationships.

The calculation process of the Normalization model combined with AHP is below:

2-a) Normalize two correlation matrixes in *relation coefficient (*R_{ij}^{norm})

Relation coefficient (R_{ij}^{norm}) will be calculated by adjusting two correlations through Equation (3). The two correlations are; 1) quantified relationship between the *i*th customer requirement and the *k*th engineering characteristic (R_{ik}), 2) quantified relationship between the *k*th engineering characteristic and the *j*th engineering characteristic (r_{kj}).

$$R_{ij}^{norm} = \frac{\sum_{k=1}^{n} R_{ik} r_{kj}}{\sum_{j=1}^{n} \sum_{k=1}^{n} R_{ik} r_{kj}}, \quad \text{(Eq. 3)}$$

where

R_{ij}^{norm}	Normalized relationship between ith customer requirement and the jth engineering characteristic (i = 1,2, . . . , m; j = 1,2, . . . , n);
R_{ik}	Quantified relationship between the ith customer requirement and the kth engineering characteristic (i = 1,2, . . . , m; k = 1,2, . . . , n);
r_{kj}	Quantified relationship between the kth engineering characteristic and jth engineering characteristic (k, j = 1,2, . . . , n).

2-b) <u>Calculate the importance degree of engineering characteristics (W_j) corresponding to the importance degree of the customer requirements (C_i)</u>

Importance degree of the *i*th customer requirement (C_i) from the Step 1-c will be combined with relation coefficient (R_{ij}^{norm}) in order to determine the importance degree of the *j*th engineering characteristic (W_j). The Equation (4) will be used and it helps to identify the most critical engineering characteristic by prioritizing them.

$$W_j = \sum_{i=1}^{m} R_{ij}^{norm} C_i \quad \text{(Eq. 4)}$$

where

W_j	Importance degree of the jth engineering characteristic (j = 1,2, . . . , n)
R_{ij}^{norm}	Normalized relationship between the ith customer requirement and the jth engineering characteristic (i = 1,2, . . . , m; j = 1,2, . . . , n);
C_i	Importance degree of the ith customer requirement (i = 1,2, . . . , m).

2-c) <u>Evaluation</u>

Consequently, the calculation process of the Normalization model combined with AHP will integrate all factors from the HoQ: 1) the importance degree of customer requirement (left of the HoQ), 2) the correlation between customer requirements and engineering characteristics (body of HoQ), 3) the correlation between engineering characteristics (roof of the HoQ). As a result of the calculation process, the QFD team can select the most significant engineering characteristic to achieve the optimum production process that will fulfill customer expectations.

III. FLEXIBLE PACKAGING INDUSTRY AND THE IMPORTANCE OF SEALING

3.1. The Significance of Quality in the Packaging Industry

Packaging plays an important role when delivering products: including accurate and reliable information regarding the shelf life, expiration dates, nutritional value of the content. In addition, packaging can securely protect products and transfer through the supply chain to the end users by meeting the specific quality characteristics (Lindh, Olsson, & Williams, 2016). There are several functions of packaging to be considered; containment, protection, convenience, and communication (Robertson, 2006).

The Packaging has several functions:

<u>Containment</u>: All products must be contained in a system that allows its distribution and handling throughout the supply chain.

<u>Protection</u>: Protect the products from the damage such as environmental effects or handling issue during distribution in order to assure its shelf life.

<u>Convenience</u>: Provide packaging with desirable consumer size, easy-handling, dispensing, and easy-opening, and end of life scenarios.

<u>Communication</u>: Provide correct information through labeling such as product recognition, content composition, instructions for opening, shelf life information to the potential end users.

The protection function is the one that has the greatest impact in assuring the product quality remains through different environmental conditions (e.g. oxygen, moisture, ingress of microorganism) and preventing distribution damages due to excess of vibration, shock, and compressive forces. The protection function and enhanced sustainability of the final products are closely related to the returns that are the result of quality loss from damage, misplaced commodities due to labeling, and spoilage of products during transportation (Olsson, Petterson, & Jönson, 2004). In order to deliver a product efficiently and safely using the supply chain, conducting quality control is necessary to reduce product failures. However, quality control in the packaging industry is hard to perform on every product due to the type of production lines (extrusion, printing, etc.) and it is difficult to sample material during production without creating waste. For example, consider flexible packaging that starts with a roll of film in order to form the container (usually a pouch). It is impossible to check the quality of the film in the middle of the roll without disrupting production. Frequent machine shutdowns inspection result in lost energy, decreases in cycle time, and a waste of packaging material necessary to properly align the printing, laminating, co-extrusion, etc. Therefore, properly designed and managed packaging processes are required in order to reduce the cost of damage or fail product during manufacturing.

The QFD is a significant approach in the quality development process and it is well known that many industries have positively implemented this approach. Although the application of QFD has shown successful results, it had not been widely applied to the packaging industry. In this paper, the application of QFD-AHP will be considered in the packaging industry. Optimizing quality condition during manufacturing plays an important role to produce packages due to the complexity of the quality control process. Packaging systems are very complex, for instance, the flexible packaging industry requires the understanding of the manufacturing of raw materials such as resin, additives, films, inks, or adhesives to be able to produce final products that meet the consumer requirements.

Therefore, a company should carefully ponder and develop packaging specifications not only for packaging material but also on packaging machinery types (such as fillers, sealer, etc). In addition, a company should consider how the packaging specification, material and filling machinery are interrelated. The application of QFD-AHP can facilitate to design quality and select the critical engineering characteristics with minimal quality control. This approach will assure that the packaging material will have optimal performance at the Product company (such as food or cosmetic company).

3.2. Flexible Packaging Industry and the Development of Flexible Packaging Material

A company should consider the type of packaging material depending on the characteristics of the products in order to have an effective package. Effective packaging materials will maintain the shelf life of the products for an expected time, provide easy-opening, and recyclability. While developing the packaging system for specific content, it is important to focus on productivity, cost savings while maximizing customer values.

There are many types of packaging materials, specifically, when considering the flexible packaging, it is easily adaptable to meet the requirements of the products, distribution, and cost. For that reason, flexible packaging is widely utilized in the world market. According to Soroka, flexible packages are a “package or container made of flexible or easily yielding materials that, when filled and closed, can be readily changed in shape” (Soroka, 2009). As a non-rigid packaging structure, it produces a monolayer of flexible packaging which includes one layer of material, but also the multilayers of packaging materials could be considered for specific application. Flexible packaging could be manufactured from the integration of different layers such as polymeric, paper, and aluminum in various forms such as wraps, bags, pouches, and sachets.

The use of flexible packaging has become a trend due to its affordability, lower weight, flexibility for printing, and other customizable properties (Kliopova-Galickaja and Kliaugaite, 2018). Flexible packaging represents an important component of the total packaging volume consumptions in the food industry. In the food industry, the direct cost of packages takes up a large amount of total cost of the product, thus, the use of flexible packaging material helps to reduce cost during the product design process. Flexible packaging is a very versatile packaging system and it is possible to develop a package that is tailored for a specific application. This may have a significant impact on the cost of the final product since we are not over or under packaging. So, the cost will be minimized because the product is not over-packed (paying a high price for packaging) or under pack that may result in failure.

The sustainability of flexible packaging is an important characteristic when considering the economic and environmental implications of the final product with the ability to recycle, reuse, and energy efficiency that relates to the converting process, specific to the production of packaging materials. In addition, flexible packaging encourages use of minimal packaging material to pack products and it requires less energy and fuel consumption during the production and transportation. Developing an environmentally responsible material is an essential task and requires not only selecting the proper material and production process, but also the reduction of waste during packaging production. Therefore, eliminating the unavoidable waste packaging material need to be designed and it can be maximized during the QFD process.

The development of the flexible packaging material needs to be carried out with the collaboration of different departments within the company (purchasing, production, engineering, etc…) and also the participation of partners (including Converters and Converter's suppliers of the raw materials). The flexible packaging is manufactured by considering packaging raw materials (such as additives, resins, adhesives, inks, and coats) in the production of roll of the films that could be co-extruded or laminated. The responsibility of the Converter is to produce packaging materials that will have optimal performance on the specific Form-Fill-Seal (FFS) machinery at each Product company. The company can enhance the quality of the finished product from the full understanding of the FFS machinery specification and packaging material that will adapt to the specific FFS machine.

Consumers who buy a product in the market are part of a larger consumer-product relationship. Product company who uses the flexible packaging can be the customer for the Converter and the Converter can be the customer for the Suppliers. Therefore, it is important to understand the customer requirements and transfer the voice of the customer into the product design. Therefore, communication between the Converter, Converter's raw material Suppliers and the Product company that will use the packages for their specific food or chemical product is important. In addition, the flow of information should be exchanged among the companies and their feedback, comments, suggestions need to be added into the HoQ. All these companies will participate to design quality of the flexible packaging system. In the current study, Product company is a driver to design the quality. The Product company will identify their requirements and related key engineering characteristics for the roll of films under consideration to be used in a specific Form-Fill-Seal machine.

In order to illustrate the implementation of QFD-AHP in the manufacturing process, as mentioned earlier, this study will use only one component of the flexible packaging system that is the sealing component. It is important to emphasize that there are many other quality components that need to be developed with the same approach. Seal area is one of the most critical parts of packages because it is greatly responsible for the shelf life of the products.

3.3. Sealing Characteristics and the Importance of Having a Consistent Sealing

In terms of flexible packaging performance, one important component is seal integrity and it requires the ability to seal under different conditions (different FFS machines, temperature variations, or contaminated environments, etc). For example, if the content is a liquid that may contaminate the sealing area, the packaging material should be formulated in a way that the material will seal under contaminated conditions. As such, the seal components of the flexible packages are what will be considered as an example of the implementation of QFD-AHP.

Flexible pouches are widely used as primary packaging for many different products: solid, liquid, and powders. Each product will have specific characteristics that could impact the sealing process. A good understanding of the product characteristics is necessary for the design of the sealing process and an intact seal will go along way to assuring the quality of products and enhance their shelf life (Kim and Ustunol, 2001). The FFS machinery, which is a part of the automated assembly line, is commonly used to produce pouches in order to fulfill the fast speed of the production process. The FFS machinery generates pouches from the roll of plastic films while filling such pouches with varied product types (liquids, solids, or powders). Since the seal areas are bonded by the application of heat, good understanding of the sealing process is important in order to prevent the failure (Moghimi, Sagib, & Park, 2018).

There are different types of sealing processes and thermal sealing is the one that is widely used with the FFS machine. The thermal sealing technique consists of two sealing bars to compress the films that can achieve the molten state to bond the films together. Acceptable bonding in a seal area can be achieved under a certain range of the temperature, a sufficient period of time, and pressure (T.T.P) by providing a constant seal. T.T.P are the important sealing parameters to qualify heat sealing process. (Meka and Stehlinc, 1994). In order to prevent damage such as deformation and packaging material delamination, it is important to maintain a consistent temperature throughout the sealing bars (Oliveirat and Faria, 1996). Also, the heat transfer rate of the sealing bar is very closely related to the type of sealing bars and the number of thermocouples.

In order to have a constant seal in designing quality process, polymer resins and additives should be carefully formulated by considering specific applications, for example, material properties (such as hot tack and seal strength), material compatibility with the product, and FFS machinery. The distribution of T.T.P throughout the sealing bar is important because each FFS machine will have a different range of T.T.P. In addition, web tension of rolled film should be monitored during the production process in order to avoid any wrinkles on seal areas. Last but not least, the thickness of the films will impact on seal areas because the variations in gauge will lead to having inconsistent seals.

The seal must have sufficient strength to hold the product while the seal is still hot during the filling process. It usually refers as a hot-tack of the material and it is related to the polymeric formulation of the packaging material. A good hot tack assures a finished product that is an optimum product process. In addition, the consistent seal should be maintained after the seal of finished products is being cooled, which is referred to seal strength. Another characteristic that needs to be assessed is the temperature variability of the FFS machine during the production process. This is related to the specific FFS machine construction, for example, the more thermocouples or how well the FFS machine maintains the temperature will impact on the integrity of the seal. The packaging material will have to be formulated in a way that materials seal in a wide temperature range. If the FFS machinery has good temperature control during the sealing process, the packaging material could be formulated with fewer additives.

Once the several key components which are related to creating good seals are identified, the next step is to ponder what are the specific engineering characteristics. The engineering characteristics need to be met in order to have a final product that will meet the expectation of optimum performance. It is important to understand how much each of the different engineering characteristics is responsible for generating the performance, in our case, the optimum seal. Assessing the information as a team (within the company such as QC, R&D, purchasing, engineering, etc… as well as partners such as suppliers of raw material, machinery company, etc…) will contribute to the identification of the optimum processing conditions and packaging formulations that will assure a reliable sealing process.

IV. DESIGNING QUALITY FOCUSING ON SEAL COMPONENTS

Our current application of quality design is to implement the QFD-AHP into the package system before it comes to the actual production process. The collaboration between Suppliers, Converters, and the Product company should be carefully considered. As mentioned above, it is important to have a good understanding of Consumer expectations and have a definition on how such requirements are going to be met by the packaging material. The packaging material will be designed to meet specific functions; therefore, this will assure the optimum final performance of the package system. As consequences, it will minimize the need of quality control process throughout production lines and prevent product failures.

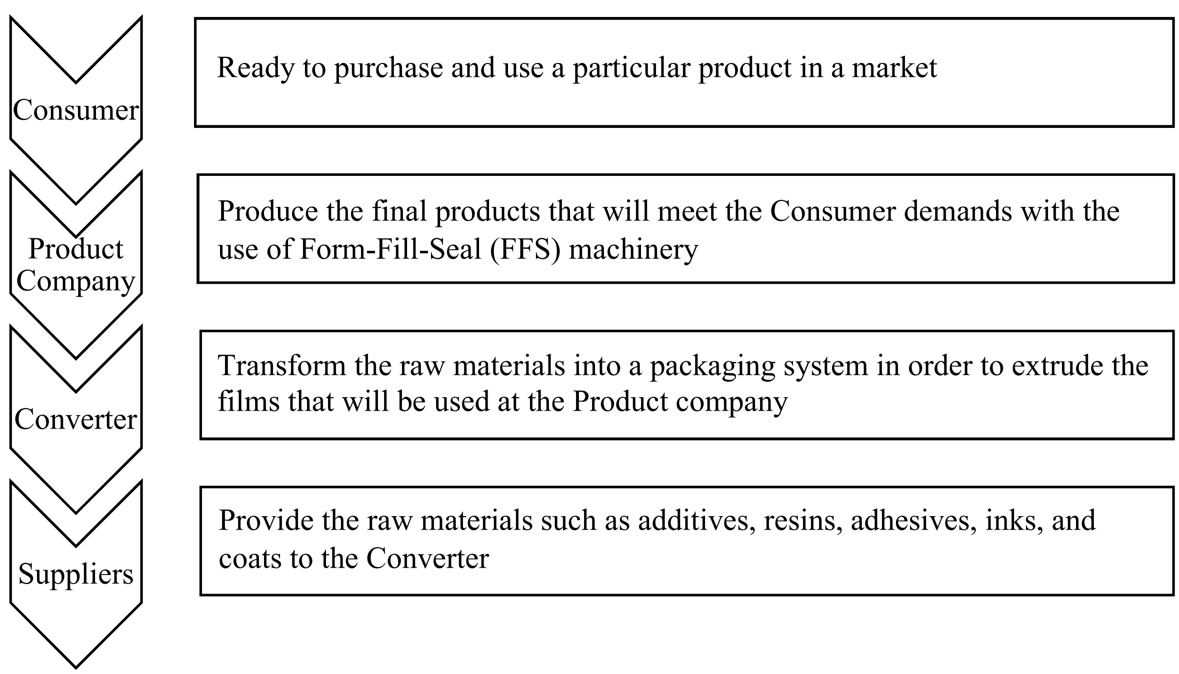


Figure 8. Diagram of quality designing how the information flow

In order to understand how to design quality on the seal components, the relationship between Consumer, Product company, Converter, and Suppliers needs flow as illustrated in Figure 8. The question is how to manage the design of engineering characteristics and answer is given below.

4.1. Identify the Consumer Demands

Consumer demands for the specific product will be critical and will be the driving force of the development process. Therefore, it is vital to identify the Consumer demands clearly before we start designing quality.

Consumer demands will be collected from the marketing department in the forms of complaints, requests, market research, or human factors studies. In addition, interview the customer or develop a survey will be considered to collect data in regard to the package system of the finished products. Some of the expectations that we foresee from the Consumer could be an easy to open package system, undamaged seal, and intact printed instruction. Then, the demands such as easy opening, undamaged seals, and intact print can be designed and monitored by the Product company in collaboration with the Converter and Suppliers of raw materials.

4.2. Identify the Product Company Requirements

As mentioned in the House of Quality (Figure 7, page 19), we need to identify: 1) Product company requirements which are located in the left of the HoQ, 2) Engineering characteristics which are located in the top horizontal axis of the HoQ. In this section, we are starting with the Product company requirements.

Based on the Consumer demands identified above, the Product company requirements will be defined. First, the Product company needs to understand the technical specifications in regard to product, machinery, and material at their facilities that will need to be adjusted in designing a product. The Supplier and Converter should ask specific questions to identify what attributes of the packaging system will assure Consumer expectations are met. Furthermore, the Product company personnel need to be in contact with the Supplier and Converter and they all need to clarify which process parameters need to be adjusted in later.

Some examples of question Converter and Product company may discuss:

- What type of product will be packed on pouch? (e.g. power, liquid, or solid)
- What type of packaging material will be used in regard to product characteristics?
- What type of FFS machinery will be used to manufacture the final products?
- What type of sealing method will be used with the FFS machinery?
- What is the specification of FFS machinery? (e.g. range of temperature, pressure, time and number of thermocouples)

Once the information is collected and analyzed, the Product company requirements will be identified that assures an intact seal within the packaging system. It is important that this set of requirements refers to specific machinery (e.g. FFS machine within the Product company) and respective company (e.g. Converter to extrude the films through laminates or co-extrusion). The sealing needs to be optimized through the collaboration of both companies and by a constructive exchange of ideas and expectation.

Some of the expectations from the Product company regarding the packaging material are: 1) It should withstand the weight of product while the seal is hot, 2) Have an intact seal while the seal is cool down, 3) Have a consistent seal throughout the operation, 4) Have the ability to seal in a wide range of temperature, 5) Printing is intact in a seal area.

4.3. Identify the Engineering Characteristics

In order to define the Engineering characteristics with regard to the above Product company requirements, it is important to understand the relationship between polymer formulation and the films as it relates to T.T.P in the FFS machine. A good understanding from the Supplier and Converter of the polymer properties and how it relates to specific engineering characteristics that meet the Product company's requirements will bring minimal waste and optimum running time. Different polymers have different heat seal properties. For instance, the formulation of polymers may impact the temperature range in hot tack and/or seal strength of the package system. The polymer needs to be properly formulated to seal the packages in a wide temperature range which can be efficiently utilized with the FFS machine.

In the heat-sealing process, the films interface is molten under the T.T.P of the FFS machine. Once the sealing bar is released, the sealed area will be cooled and solidified (Miyata, Ozama, Nishioka, Koda, & Murasawa, 2014). There are many different parameters responsible for an intact seal and one of such parameters is the percent of crystallinity. We will consider this parameter for this discussion that impacts the temperature range for sealing (but it is important to include all key parameters responsible for the assessment of seal integrity). If the percent of crystallinity is high, a higher temperature (more energy) is required as compared to a more amorphous polymer. Heat sealing properties can be influenced by the molecular structure based on molecular weight and molecular weight distribution. In addition, molecular entanglement impacts on heat sealing process by minimizing the interface and producing homogeneous layer (Selke and Culter, 2013). Last but not least, the Supplier should provide a heat resistant ink in order to maintain intact printing. Consequently, the examples of engineering characteristics are:

1) molecular weight, 2) molecular weight distribution, 3) molecular entanglement, 4) percent of crystallinity, 5) heat resistant ink, 6) hot tack strength, 7) seal strength, 8) ink viscosity. Therefore, it is important to emphasize that the choice of polymer formulation and processing conditions of the FFS machine need to be carefully tracked.

4.4. Understanding How the Converter and Supplier Relate to Each Other and Influence Engineering Characteristics

Once the Product company requirements and related engineering characteristics are identified, the Product company shares this information with the Converter and Suppliers of raw materials. The Converter will evaluate the engineering characteristics by designing packaging materials that will provide protection to the product and also meet the specific requirements of the FFS machine at each Product company. Their discussion should consider the formulations of packaging films with optimum hot tack, seal strength, low static, and best rheology that brings a minimum deformation during the sealing process (Najarzadeh, Tabasi, & Ajii, 2014).

The Converter should also work with the Suppliers of raw materials such as additives, adhesives, and inks to design the packaging material. For example, when designing pouches for liquids or low-density powders, additives need to be included in order to improve hot tack that will facilitate sealing under contaminated conditions. Blended resins with additives are widely used. Additives for blends include: antioxidants, heat stabilizers, and antistatic agents to enhance the polymer properties. These additives aim to prevent the polymer from oxidative degradation, resist heat, reduce friction, and static electricity. Minimizing static and developing a strong seal is necessary, in order for the material to run smoothly without sticking in different parts of the

FFS machinery. In addition, Antistatic agents or slip agents can help to prevent the attachment of the product, for example, powders which can potentially disturb the sealing process.

Adhesives are another important raw material to be considered when designing packaging films. Adhesives are used in the lamination of different layers; the appropriate choice of the adhesives can help to resist delamination throughout that shelf life. Adhesives help to enhance the packaging material by bonding layers such as plastic and paper. Therefore, the selection of adhesives is critical depending on the end use.

Printed packaging material requires inks that are compatible with specific packaging systems under consideration in order to prevent the issue of migration of additives from inks. Sometimes, additives are formulated to be released at high temperatures to facilitate the release of packaging materials from the sealing bar. Also, ink hardeners can be added to minimize inks' tendency to stick to the sealing bars (Dunn, 2014). Therefore, the use of heat-resistant ink is useful to ensure intact print in the package system in order to deliver readable instructions. In the printing process, careful consideration of selecting inks is critical due to the issue of migration if it is a solvent based ink.

Once the necessary raw materials are collected, then the Converter extrudes films by integrating the composition of raw materials. There are many methods of extruding films and especially, blown film process is widely used in the production of flexible packaging material. Blown film is generated from the extrusion of molten polymer through a rotating or circular die. The molten polymer is blown to form a thin bubble, then the bubble is cooled and collapsed forming a flat film. Thickness variation can occur when uneven cooling takes place. In blown film, winding web tension and thickness variation has an important impact on the quality of the sealing area. If an uneven thickness of the film is utilized in the FFS machinery, thicker spots will require longer dwell time or higher temperature to transfer heat, then thinner spots will be exposed its above limitation, eventually, resulting in inconsistent seal or seal failures.

Surface treatment through corona treating systems of the films is important to promote good performance of printing, coating, and laminating packaging material. Corona treatment is utilized right after extruding the films and before the printing or coating the films. This treatment helps to increase the wettability and adhesion of the films by oxidizing the surface and creating spots which allow the interaction of inks, adhesives, or additives (Dunn, 2014). The surface treatment decays with time, so storage of the packaging material should be kept to a minimal amount, and under specific environmental conditions. Excessive treatment can detrimental for the packaging material and storing the packaging material for a long time can disrupt sealing.

Once the film is being extruded and treated under the corona treatment, coating, lamination, and printing processes are taken to strengthen barrier properties. Coating processes require molten plastic to be applied as a coating. The coating thickness is critical because failure to bond substrates will lead to delamination. In addition, heat seal coatings can increase seal strength by applying a coating on the films that include a plasticizer. The laminating process integrates multilayers of flexible packaging material such as plastic, aluminum foil, or paper to promote heat resistance, barrier properties, or seal strength. The Converter produces a single layer or multilayer laminate structures depending on its necessity and it requires an adhesive lamination to combine the two monolayers. In the printing process, the careful consideration of selecting inks is critical. Usually, nitrocellulose is used in solvent-based flexographic inks in the seal area since they are more heat resistant (Leach, 1988) Then eventually, the Product company combine the product content and the printed roll of films in order to manufacture the packages with the use of FFS machinery.

V. APPLICATION OF QFD-AHP ON THE SEAL OF PACKAGING

For this application, a Vertical-Form-Fill-Seal (FFS) machinery located at the Product company facilities and a roll of a single layer of flexible packaging material will be considered. The steps necessary for the implementation of the QFD-AHP at the Product company is outlined.

5.1. Identify Product Company Requirements and Engineering Characteristics

1) Analyze the list of requirements and engineering characteristics

As described in Part IV (page 42 – 44), product company requirements and engineering characteristics is abbreviated with PRs and ECs as described in Table 3 and Table 4.

Table 3. Product company requirements with the illustrative example

Product company requirements (PRs)	*Definition*
PR 1	Withstand the weight of product while the seal is hot
PR 2	Have an intact seal while the seal is cool down
PR 3	Have a consistent seal throughout the operation
PR 4	Have the ability to seal in a wide range of temperature
PR 5	Printing is intact in a seal area

Table 4. Engineering characteristics with the illustrative example

Engineering Characteristics (ECs)	*Definition*
EC 1	Molecular weight
EC 2	Molecular weight distribution
EC 3	Molecular entanglement
EC 4	Percent of crystallinity
EC 5	Heat resistant ink
EC 6	Hot tack strength
EC 7	Seal strength
EC 8	Ink viscosity

2) <u>Develop a reciprocal Matrix A</u>

Product company requirements (PRs) are scored through paired comparisons following Saaty's scale matrix (Table 1, page 25). In the current study, we assumed that the VFFS machinery has a good control of T.T.P operation during the production process. The result of paired comparisons may vary based on machinery specification, therefore, it is important first to understand the technical specifications at facilities.

Then, the inputs of paired comparisons will make a square Matrix A. For example, PR 1 is strongly more important than PR 5 and we can assign the numerical value 5 in the (1, 5) or first-row, fifth-column position. The reciprocal value of 5 is $\frac{1}{5}$ and it will be automatically inserted in the (5, 1) or fifth-row, first-column position. Similarly, corresponding to moderate importance (numerical value is 3), is assigned to PR 1 over PR 4 in the (1, 4) position. The outcome of the entire paired comparisons is conducted and developed in a reciprocal Matrix A which is shown in Table 4. A detail illustration to fill up Matrix A is described in the Appendix.

Table 5. Paired comparisons judgment of the product company requirements (Matrix A)

$$\begin{array}{c c}
 & \begin{array}{ccccc} PR1 & PR2 & PR3 & PR4 & PR5 \end{array} \\
\begin{array}{c} PR1 \\ PR2 \\ PR3 \\ PR4 \\ PR5 \end{array} &
\begin{bmatrix} 1 & 1 & 1/3 & 3 & 5 \\ 1 & 1 & 1/3 & 3 & 5 \\ 3 & 3 & 1 & 3 & 3 \\ 1/3 & 1/3 & 1/3 & 1 & 3 \\ 1/5 & 1/5 & 1/3 & 1/3 & 1 \end{bmatrix}
\end{array}$$

3) <u>Calculate the degree of importance of each product company requirement (PRs)</u>

In order to determine the degree of importance of PRs, the AHP calculation process is used as described in Part II (2.4. Overcome the Weakness of QFD with Prioritization Methodology, page 25 - 26).

The calculation process is outlined below:

Each column of Matrix A is added. Then, each value in a column is divided by the summation to generate Matrix B as below.

$$B = \begin{bmatrix} 0.18 & 0.18 & 0.14 & 0.29 & 0.29 \\ 0.18 & 0.18 & 0.14 & 0.29 & 0.29 \\ 0.54 & 0.54 & 0.43 & 0.29 & 0.18 \\ 0.06 & 0.06 & 0.14 & 0.10 & 0.18 \\ 0.04 & 0.04 & 0.14 & 0.03 & 0.06 \end{bmatrix}$$

Each row of Matrix B is added and averaged across the rows to obtain Matrix C as below.

$$C = \begin{bmatrix} 0.22 \\ 0.22 \\ 0.40 \\ 0.11 \\ 0.06 \end{bmatrix}$$

Then, the column vector (Matrix C) can be computed in C^T, where C^T is the transpose of column vector (Dai and Blackhurst, 2012).

$$C^T = \begin{bmatrix} 0.22 & 0.22 & 0.40 & 0.11 & 0.06 \end{bmatrix}$$

4) <u>Determine the level of consistency of the paired comparisons judgment</u>

In order to prove the level of consistency, the Consistency Ratio (CR) is calculated as described in Part II (2.4. Overcome the Weakness of QFD with Prioritization Methodology, page 26-28).

The calculation process is outlined below:

Consistency Measure (CM) is calculated by multiplying Matrix A and Matrix C and dividing them by Matrix C (note we will use Matrix C inputs before they are averaged).

$$\begin{array}{c}\text{Consistency Measure}\\ \text{(CM)}\end{array} = \begin{bmatrix} 5.49 & 5.49 & 5.58 & 5.29 & 5.16 \end{bmatrix}$$

The Consistency Measure (CM) is averaged and calculated in 5.40. Then, the Consistency Index (CI) is calculated by using Equation (2) as described on page 27.

$$\begin{array}{c}\text{Consistency Index}\\ \text{(CI)}\end{array} = \frac{5.40-5}{5} = 0.101$$

The Consistency Ratio (CR) is calculated by using Equation (1) as described on page 27. The Random Index (RI) is 1.12 (N=5) as given by Table 2 (page 28).

$$\begin{array}{c}\text{Consistency Ratio}\\ \text{(CR)}\end{array} = \frac{0.101}{1.12} = 0.09$$

It concludes that Consistency Ratio (CR) is 0.09. According to Franceschini (2002), “An empirical rule supplied by Saaty states that the CR of 0.10 or less is considered acceptable” (p. 68). Therefore, consistency level of paired comparisons judgment in the current study is acceptable.

5.2. Construct Two Matrixes in the House of Quality

1) <u>Relationship matrix between product company requirements (PRs) and engineering characteristics (ECs)</u>

Each product company requirement (PR) is correlated to each engineering characteristic (EC) and the result is shown in the body of the HoQ in Figure 9. The correlation is done using a conventional scale of 1-3-9 which indicates a weak, moderate, and strong relationship. Symbols are going to be assigned to each category as shown in Figure 9.

2) <u>Relationship matrix among the engineering characteristics (ECs)</u>

In the traditional QFD, engineering characteristics were considered independent but later found to be dependent on each other. Therefore, dependency among the engineering characteristics should be considered. Engineering characteristic (EC) is correlated to themselves and the obtained matrix is shown on the roof of the HoQ in Figure 9.

The correlation is done using the scale of 0.1-0.3-0.9 which indicates a weak, moderate, and strong relationship. Symbols are going to be assigned to each category as shown in Figure 9.

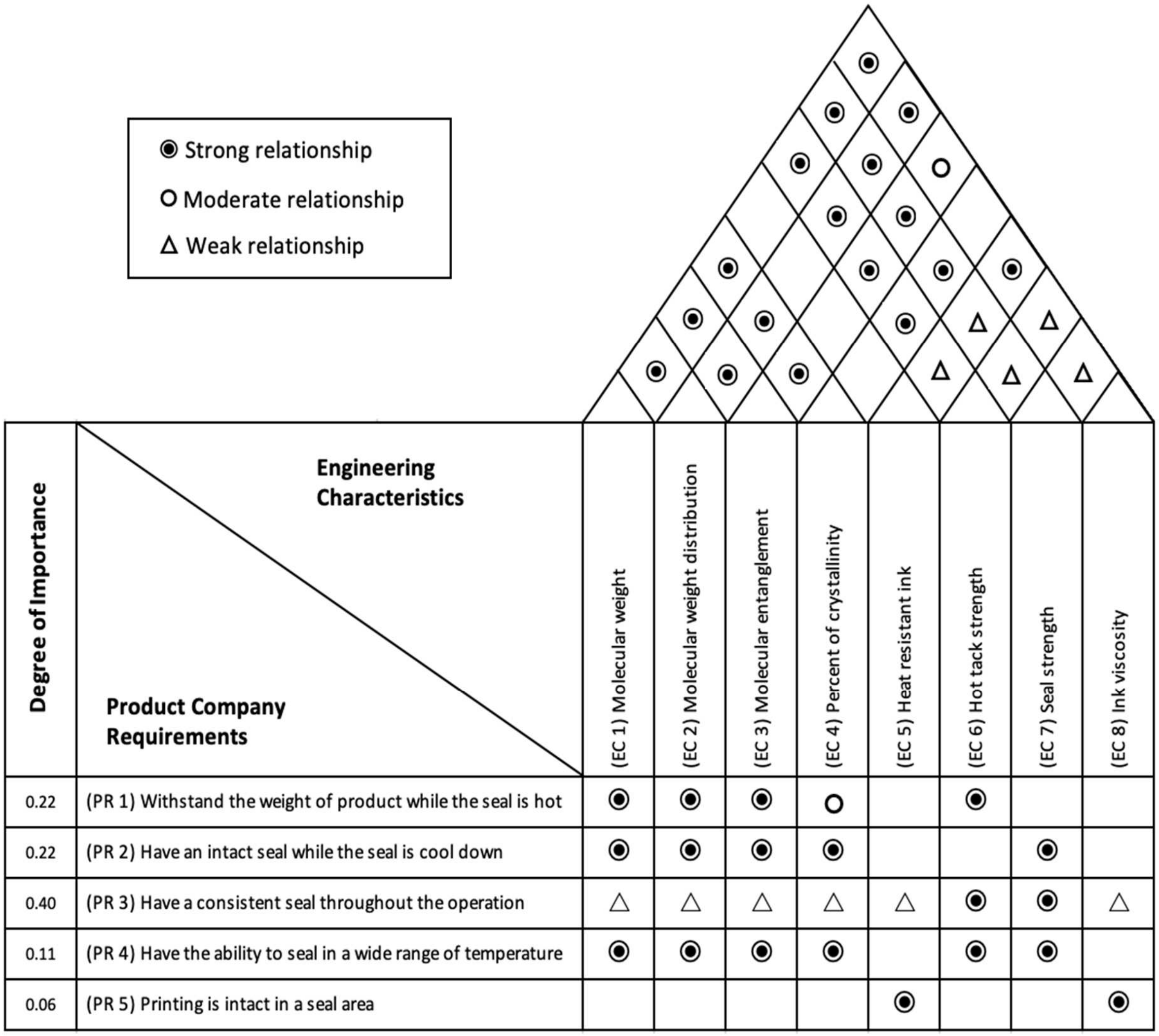


Figure 9. House of Quality (HoQ) between product company requirements (left of the HoQ) and engineering characteristics (top horizontal axis of the HoQ).

5.3. Identification of the Most Significant Engineering Characteristics

1) <u>Normalize two correlation matrixes in relation coefficient (R_{ij}^{norm})</u>

Two correlation matrixes (roof and body of the HoQ) will be normalized through the Normalization method as described in Part II (2.4. Overcome the Weakness of QFD with Prioritization Methodology, page 29-30).

An example is outlined to calculate the relation coefficient $R_{1,6}^{norm}$ (PR 1 and EC 6) based on Figure 9:

Simplify, R_{ik} indicates correlation in the body of the HoQ (*i*th product company requirements and *k*th engineering characteristics). r_{kj} indicates correlation in the roof of the HoQ (*k*th engineering characteristics and *j*th engineering characteristics). In addition, if k=j, $r_{kj} = 1$.

The relation coefficient $R_{1,6}^{norm}$ is used an Equation (3) on page 30 and calculated in the following manner:

$$R_{1,6}^{norm} = \frac{\sum_{k=1}^{8}(R_{1,k}r_{k,6})}{\sum_{j=1}^{8}\sum_{k=1}^{8}(R_{1,j}r_{j,k})}$$

1-1) Denominator is calculated below:

1-1-a) Consider ($R_{1,1}$)

Add all values from ($r_{1,1}$), ($r_{1,2}$), ($r_{1,3}$), ($r_{1,4}$), ($r_{1,5}$), ($r_{1,6}$), ($r_{1,7}$), and ($r_{1,8}$) in the roof of the HoQ. Then, summation is multiplied by ($R_{1,1}$) in the body of the HoQ. The calculation is shown below:

$$(1 + 0.9 + 0.9 + 0.9 + 0 + 0.9 + 0.9 + 0.9) \text{ x } 9$$

1-1-b) Consider ($R_{1,2}$)

Add all values from ($r_{2,1}$), ($r_{2,2}$), ($r_{2,3}$), ($r_{2,4}$), ($r_{2,5}$), ($r_{2,6}$), ($r_{2,7}$), and ($r_{2,8}$) in the roof of the HoQ. Then, summation is multiplied by ($R_{1,2}$) in the body of the HoQ. The calculation is shown below:

$$(0.9 + 1 + 0.9 + 0.9 + 0 + 0.9 + 0.9 + 0.9) \text{ x } 9$$

1-1-c) Consider ($R_{1,3}$)

Add all values from ($r_{3,1}$), ($r_{3,2}$), ($r_{3,3}$), ($r_{3,4}$), ($r_{3,5}$), ($r_{3,6}$), ($r_{3,7}$), and ($r_{3,8}$) in the roof of the HoQ. Then, summation is multiplied by ($R_{1,3}$) in the body of the HoQ. The calculation is shown below:

$$(0.9 + 0.9 + 1 + 0.9 + 0 + 0.9 + 0.9 + 0.3) \text{ x } 9$$

1-1-d) Consider ($R_{1,4}$)

Add all values from ($r_{4,1}$), ($r_{4,2}$), ($r_{4,3}$), ($r_{4,4}$), ($r_{4,5}$), ($r_{4,6}$), ($r_{4,7}$), and ($r_{4,8}$) in the roof of the HoQ. Then, summation is multiplied by ($R_{1,4}$) in the body of the HoQ. The calculation is shown below:

$$(0.9 + 0.9 + 0.9 + 1 + 0 + 0.9 + 0.9 + 0) \text{ x } 3$$

1-1-e) Consider ($R_{1,5}$)

Add all values from ($r_{5,1}$), ($r_{5,2}$), ($r_{5,3}$), ($r_{5,4}$), ($r_{5,5}$), ($r_{5,6}$), ($r_{5,7}$), and ($r_{5,8}$) in the roof of the HoQ. Then, summation is multiplied by ($R_{1,5}$) in the body of the HoQ. The calculation is shown below:

$$(0 + 0 + 0 + 0 + 1 + 0.1 + 0.1 + 0.9) \text{ x } 0$$

1-1-f) Consider ($R_{1,6}$)

Add all values from ($r_{6,1}$), ($r_{6,2}$), ($r_{6,3}$), ($r_{6,4}$), ($r_{6,5}$), ($r_{6,6}$), ($r_{6,7}$), and ($r_{6,8}$) in the roof of the HoQ. Then, summation is multiplied by ($R_{1,6}$) in the body of the HoQ. The calculation is shown below:

$$(0.9 + 0.9 + 0.9 + 0.9 + 0.1 + 1 + 0.1 + 0.1) \text{ x } 9$$

1-1-g) Consider ($R_{1,7}$)

Add all values from ($r_{7,1}$), ($r_{7,2}$), ($r_{7,3}$), ($r_{7,4}$), ($r_{7,5}$), ($r_{7,6}$), ($r_{7,7}$), and ($r_{7,8}$) in the roof of the HoQ. Then, summation is multiplied by ($R_{1,7}$) in the body of the HoQ. The calculation is shown below:

$$(0.9 + 0.9 + 0.9 + 0.9 + 0.1 + 0.1 + 1 + 0.1) \text{ x } 0$$

1-1-h) Consider ($R_{1,8}$)

Add all values from ($r_{8,1}$), ($r_{8,2}$), ($r_{8,3}$), ($r_{8,4}$), ($r_{8,5}$), ($r_{8,6}$), ($r_{8,7}$), and ($r_{8,8}$) in the roof of the HoQ. Then, summation is multiplied by ($R_{1,8}$) in the body of the HoQ. The calculation is shown below:

$$(0.9 + 0.9 + 0.3 + 0 + 0.9 + 0.1 + 0.1 + 1) \text{ x } 0$$

1-1-i) Finally, add all of the values from step (1-1-a) to step (1-1-h) in order to obtain the denominator:

$$9(6.4) + 9(6.4) + 9(5.8) + 3(5.5) + 0(2.1) + 9(4.9) + 0(4.9) + 0(4.2)$$
$$= 228$$

1-2) Numerator is calculated in the following manner:

Since we are calculating relation coefficient $R_{1,6}^{norm}$, only EC 6 is considered. As mentioned earlier, R_{ik} indicates correlation in the body of the HoQ and r_{kj} indicates correlation in the roof of the HoQ.

The numerator is calculated below.

$$R_{1,1}r_{1,6} + R_{1,2}r_{2,6} + R_{1,3}r_{3,6} + R_{1,4}r_{4,6} + R_{1,5}r_{5,6} + R_{1,6}r_{6,6} + R_{1,7}r_{7,6} + R_{1,8}r_{8,6}$$

$$= 9(0.9) + 9(0.9) + 9(0.9) + 3(0.9) + 0(0.1) + 9(1) + 0(0.1) + 0(0.1) = 36$$

As a consequence, calculation process of relation coefficient $R_{1,6}^{norm}$ is summarized below:

$$= \frac{R_{1,1}r_{1,6} + R_{1,2}r_{2,6} + R_{1,3}r_{3,6} + R_{1,4}r_{4,6} + R_{1,5}r_{5,6} + R_{1,6}r_{6,6} + R_{1,7}r_{7,6} + R_{1,8}r_{8,6}}{R_{1,1}(r_{1,1} + \cdots + r_{1,8}) + R_{1,2}(r_{2,1} + \cdots + r_{2,8}) + \cdots + R_{1,7}(r_{7,1} + \cdots + r_{7,8}) + R_{1,8}(r_{8,1} + \cdots + r_{8,8})}$$

$$= \frac{9(0.9) + 9(0.9) + 9(0.9) + 3(0.9) + 0(0.1) + 9(1) + 0(0.1) + 0(0.1)}{9(6.4) + 9(6.4) + 9(5.8) + 3(5.5) + 0(2.1) + 9(4.9) + 0(4.9) + 0(4.2)}$$

$$R_{1,6}^{norm} = \frac{36}{228} \cong 0.16 \text{ (as shown in Figure 10)}$$

As another example, calculate the relation coefficient $R_{1,8}^{norm}$ (PR 1 and EC 8). Denominator is same with $R_{1,6}^{norm}$ and only numerator is changed as described in below:

$$= \frac{R_{1,1}r_{1,8} + R_{1,2}r_{2,8} + R_{1,3}r_{3,8} + R_{1,4}r_{4,8} + R_{1,5}r_{5,8} + R_{1,6}r_{6,8} + R_{1,7}r_{7,8} + R_{1,8}r_{8,8}}{R_{1,1}(r_{1,1} + \cdots + r_{1,8}) + R_{1,2}(r_{2,1} + \cdots + r_{2,8}) + \cdots + R_{1,7}(r_{7,1} + \cdots + r_{7,8}) + R_{1,8}(r_{8,1} + \cdots + r_{8,8})}$$

$$= \frac{9(0.9) + 9(0.9) + 9(0.3) + 3(0) + 0(0.9) + 9(0.1) + 0(0.1) + 0(1)}{9(6.4) + 9(6.4) + 9(5.8) + 3(5.5) + 0(2.1) + 9(4.9) + 0(4.9) + 0(4.2)}$$

$$R_{1,8}^{norm} = \frac{19.8}{228} \cong 0.09 \text{ (as shown in Figure 10)}$$

All calculation processes follow the same way and the result is shown in Figure 10.

Degree of Importance	Engineering Characteristics / Product Company Requirements	(EC 1) Molecular weight	(EC 2) Molecular weight distribution	(EC 3) Molecular entanglement	(EC 4) Percent of crystallinity	(EC 5) Heat resistant ink	(EC 6) Hot tack strength	(EC 7) Seal strength	(EC 8) Ink viscosity
0.22	(PR 1) Withstand the weight of product while the seal is hot	0.16	0.16	0.16	0.16	0.00	**0.16**	0.12	**0.09**
0.22	(PR 2) Have an intact seal while the seal is cool down	0.16	0.16	0.16	0.16	0.00	0.13	0.16	0.08
0.40	(PR 3) Have a consistent seal throughout the operation	0.18	0.18	0.17	0.17	0.03	0.12	0.12	0.05
0.11	(PR 4) Have the ability to seal in a wide range of temperature	0.16	0.16	0.16	0.16	0.01	0.14	0.14	0.07
0.06	(PR 5) Printing is intact in a seal area	0.14	0.14	0.05	0.00	0.3	0.03	0.03	0.30

Figure 10. Relation coefficient (R_{ij}^{norm}) between the product company requirements (PRs) and the engineering characteristics (ECs)

2) <u>Prioritize and select the most critical engineering characteristics</u>

Once the relation coefficient (R_{ij}^{norm}) is calculated, the degree of importance of *i*th product company requirements (C_i) is combined to determine the importance degree of *j*th engineering characteristic (W_j). Equation (4) is used as described in Part II (2.4. Overcome the Weakness of QFD with Prioritization Methodology, page 30).

By considering the example discussed above and using Figure 10, the importance degree of EC 6 (W_6) corresponding to PR 1 is calculated below:

$$W_6 = R_{1,6}^{norm} \text{ x } C_1$$

$$= 0.16 \text{ x } 0.22$$

$$= 0.03 \text{ (as shown in Figure 11)}$$

All calculations follow the same steps and the result is shown in Figure 11.

Product Company Requirements \ Engineering Characteristics	(EC 1) Molecular weight	(EC 2) Molecular weight distribution	(EC 3) Molecular entanglement	(EC 4) Percent of crystallinity	(EC 5) Heat resistant ink	(EC 6) Hot tack strength	(EC 7) Seal strength	(EC 8) Ink viscosity
(PR 1) Withstand the weight of product while a seal is hot	0.03	0.03	0.03	0.03	0.00	**0.03**	0.03	0.02
(PR 2) Have an intact seal while seal is cool down	0.03	0.03	0.03	0.03	0.00	0.03	0.03	0.02
(PR 3) Have a consistent seal throughout the operation	0.07	0.07	0.07	0.07	0.01	0.05	0.05	0.02
(PR 4) Have the ability to seal in a wide range of temperature	0.02	0.02	0.02	0.02	0.00	0.01	0.01	0.01
(PR 5) Printing is intact in a seal area	0.01	0.01	0.00	0.00	0.02	0.00	0.00	0.02
Technnical Importance	0.16	0.16	0.16	0.15	0.03	0.12	0.12	0.08
Relative Importance	16.5%	16.5%	15.7%	15.2%	3.3%	12.5%	12.4%	8.1%

Figure 11. Importance degree of jth engineering characteristic (W_j)

In order to prioritize the engineering characteristics, technical importance is calculated by adding each column of the importance degree of jth engineering characteristic (W_j). The relative importance is used to illustrate the priority of the engineering characteristics in percentage form.

As a result, the engineering characteristic with higher technical and relative importance (as shown in Figure 11) needs to be closely tracked.

We can conclude that EC 1, EC 2, EC 3, EC 4 are the most critical engineering characteristics and these characteristics should be considered first to optimize the production process by controlling and assessing.

VI. CONCLUSION

The development of flexible packaging requires different functions of the business to participate together including the interrelationship between Consumer, Product company, Converter, and the Suppliers (resins, inks, additives, adhesives, etc) in order to manufacture the final products. It is important that each of the businesses outlined above should coordinate with each other and encourage partnerships in order to facilitate the flow of information. QFD provides a structure to support the interactions among the different companies and plays a critical role in identifying packaging requirements and critical engineering characteristics.

The use of HoQ helps to define each of the participants' expectations that sometime are overlooked. Conducting quality control on every individual product is costly and a waste of time. Therefore, it is important to design quality as part of the development process in order to reduce the need of quality control and at the same time assure good quality. The QFD-AHP approach helps to precisely define what engineering characteristics should be considered and prioritize them to achieve the optimum production process. Eventually, it will enhance the quality of products that will bring in company profit and lead to maximizing Consumer satisfaction.

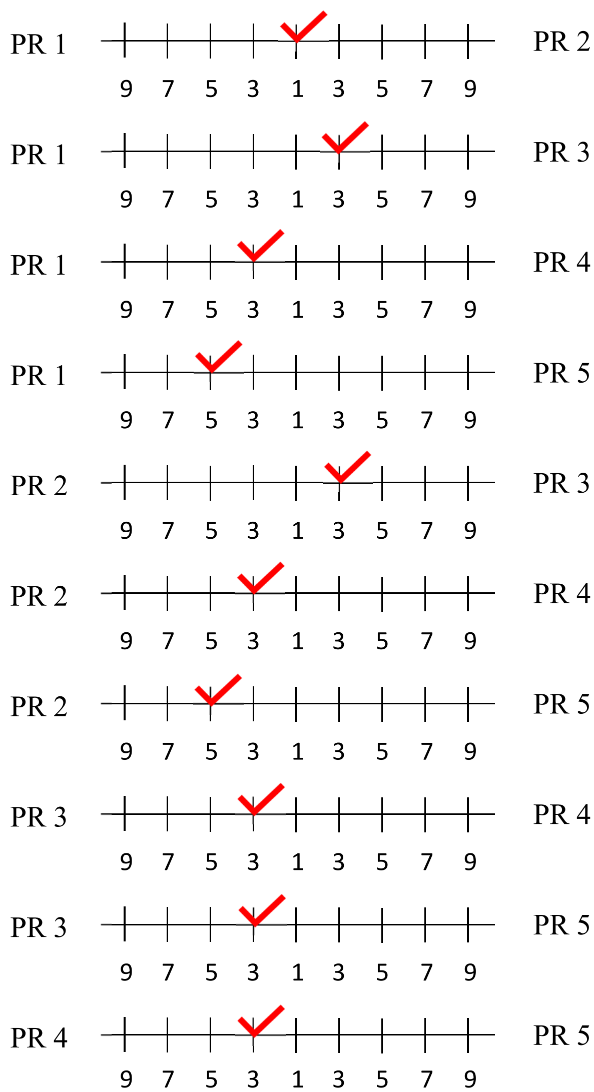
The application of QFD-AHP can be extrapolated into other packaging components such as type of container (rigid or flexible) and material properties (barrier or strength). For example, in the medical device packaging industry, package integrity is one of the most important components when considering the sterility of the products. The Horizontal FFS machinery is widely used, and the sterilization process is necessary to assure the sterility of the medical devices once it reaches the consumer. With regard to the sterilization process, some of the examples of the engineering characteristics are material compatibility, sufficient seal strength to withstand the sterilization, and the porosity of the packaging material. Furthermore, packaging components such as impact strength and barrier properties are other important characteristics that could be considered with the QFD-AHP methodology in the future.

APPENDIX

An Example to Make a Reciprocal Matrix through Paired Comparisons

1) Determine the paired comparisons

- PR 1 Withstand the weight of product while the seal is hot
- PR 2 Have an intact seal while the seal is cool down
- PR 3 Have a consistent seal throughout the operation
- PR 4 Have the ability to seal in a wide range of temperature
- PR 5 Printing is intact in a seal area



We can make a Matrix from the 5 comparisons above, therefore, we have 5 by 5 Matrix. The diagonal inputs of the Matrix are always 1 because it compares itself.

2) Fill the upper triangular Matrix (portion of upper diagonal).

2-a) If the value is located on the left side of 1, enter the actual value in a Matrix.

2-b) If the value is located on the right side of 1, enter the reciprocal value in a Matrix.

For example, judgment value of paired comparison between PR 1 and PR 5 is located in the left side of 1. Then, value 5 will be assigned in the (1, 5) position. As another example, judgment value of paired comparison between PR 1 and PR 3 is located in the right side of 1. Then, the reciprocal value $\frac{1}{3}$ will be assigned in the (1, 3) position.

(3) Fill the lower triangular Matrix (portion of lower diagonal)

In order to fill the lower triangular Matrix, the reciprocal values of the upper triangular Matrix is used. Transpose positions of the upper triangular Matrix will be filled in lower triangular Matrix. If a_{ij} (row *i,* column *j*) in upper triangular, below formula is used in lower triangular:

$$a_{ji} = \frac{1}{a_{ij}}$$

Based on above steps, we have complete reciprocal Matrix.

$$\begin{array}{c} \\ PR1 \\ PR2 \\ PR3 \\ PR4 \\ PR5 \end{array} \begin{array}{c} \begin{array}{ccccc} PR1 & PR2 & PR3 & PR4 & PR5 \end{array} \\ \begin{bmatrix} 1 & 1 & 1/3 & 3 & 5 \\ 1 & 1 & 1/3 & 3 & 5 \\ 3 & 3 & 1 & 3 & 3 \\ 1/3 & 1/3 & 1/3 & 1 & 3 \\ 1/5 & 1/5 & 1/3 & 1/3 & 1 \end{bmatrix} \end{array}$$

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