An Integration of Fuzzy-Analytic Hierarchy Process and Quality Function Deployment in Lean Concept Selection: A Case Study

Ahmad R Sarfaraz
California State University, Northridge, USA

Hamid Pourmohammadi*
California State University, Carson, USA

Joana E. Perez
California State University, Northridge, USA

This paper aims to demonstrate the application of Fuzzy-AHP and QFD methodologies in Lean concept selection in manufacturing industries. Since the application of Fuzzy-AHP and QFD in Lean concept selection are fairly new, research materials are limited to AHP applications. In this study, the Fuzzy-AHP methodology and its integration with QFD are applied to investigate the selection of Lean concept. In our suggested model we first, design the Fuzzy-AHP hierarchy structure for Lean concept selection which is converted to numerical pairwise comparison matrix. Then, five Lean manufacturing concepts are evaluated using five criteria that are set by management and, finally based on the results, top two Lean concepts are selected. Using a case study, the integrated Fuzzy-AHP and QFD approach and analysis of results are discussed. Our proposed model helps to establish a more in-depth research and analysis in the Lean concept selection that includes more hierarchy levels to work with.

* Corresponding Author. E-mail address: hamid@csudh.edu

I. INTRODUCTION

The evolution of manufacturing has been an incremental process since the start of the industrial revolution. Large machines have been invented and developed over the years to cater to the needs of humans. In this modern era, we are not only facing dilemmas in the design of equipment but also in the human interface with the systems. Efficiency, productivity, and profitability have been the major focus in designing a system that can function within specified manufacturing parameters such as delivery time, cost, pricing, and quality. It is critical for a company to maintain a balance between cost, quantity, and quality especially when it involves various product families. In order to address issues in mass production, significant changes in the simple Lean concept from the early 1800's were made by Henry Ford. He designed a fabrication process which incorporates the idea of flow production. His ingenuity emerged when he improved the manufacturing of machine components by introducing interchangeable parts to the assembly line. The problem in Henry Ford's company was not the inventory turnover but the inability to provide variety of products (Lean Enterprise Institute, 2009).

As the world progressed and demanded diverse products, Lean concept also changed over time. Other competitors of Ford have addressed the issues with the low product diversity and offered different choices for consumers. However, a serious problem has emerged in companies that tried to keep more inventory than what was actually needed. To solve this issue, Toyota introduced the Toyota Production System (Lean Enterprise Institute, 2009). The team in Toyota, led by Kiichiro Toyoda and Taiichi Ohno, changed the production system and only produced parts or products when they are needed based on customer demand, which is also known as Just-In-Time (JIT). (Lean Enterprise Institute, 2009; Earley, T., 2012). They only used machines that can produce the right amount of products which minimized overproduction, delays, and costs.

Both manufacturing and service companies today have adopted some of the Lean concepts in their processes. To maximize the company's full potentials, it is essential to choose the appropriate Lean concept. This paper aims to formulate, analyze, and discuss results of Fuzzy-AHP and its integration with QFD in selecting Lean concepts particularly in a manufacturing company. Vinodh, Shivraman, and Viswesh (2011) presented a case study on Lean concept selection using AHP approach. We present the application of our suggested methodology (Fuzzy-AHP and QFD) on this case study. This paper also aims to provide answers to the main management question: What type of Lean concept or concepts should a manufacturing company adopt?

1.1. Literature Review, Lean Manufacturing Concept Definition and Selection

Lean concepts have been accepted and practiced by almost all successful manufacturing companies. Hasty delivery schedules, escalating increase in downtimes and delays, skyrocketing overhead and operating costs, and other issues have driven an organization to implement a Lean system in their work environment. It has been observed that a shift from batch and queue or mass production to one-piece flow or pull production contributed to the success of manufacturing companies. In simpler terms, batch and queue is the process of producing products in groups while a one-piece flow production is a process of assembling products one at a time in a linear fashion ("Batch Production", 2012).

Various Lean concepts have been introduced over time. A study by Ross & Associates Environmental Consulting, Ltd. (2004) showed that major Lean concepts are appealing to the most companies. Experts in Lean manufacturing were interviewed to give their inputs about which Lean concepts helped them develop an efficient, eco-friendly, and economical system. According to the study, there are eight core Lean methods that organizations implement. The eight Lean concepts mentioned in the study are as follows:

1. *The Kaizen Rapid Improvement Process* - The goals of any organization must be to maximize profit, reduce costs, minimize wastes, ensure quality, and satisfy all stakeholders. Without adapting Kaizen, or continuous improvement, the mentioned goals may not be fully satisfied. Kaizen is considered to be the "building block" of Lean systems and should be implemented and supported by the top level managers down to the bottom level employees (US EPA et. al., 2004). When a company decides to do a *kaizen event,* a designated multi-disciplinary team works on one

specific improvement project (within 72 hours) and implements it. This improvement will stay permanently and all affected areas must adhere to the changes. A successful kaizen event brings numerous benefits to the company such as reduction of wastes and higher utilization of resources.

2. *5S Principles* – The elements of 5S are Sort (Seiri), Set in Order (Seiton), Shine (Seiso), Standardize (Seiketsu), and Sustain (Shitsuke). This ideology was formed to reduce waste and optimize productivity by maintaining an organized work environment. 5S is commonly seen in manufacturing companies where parts, tools, workspace, etc. have to be labeled and organized. It usually starts in individual units or departments and somehow exemplifies the "*cLean* as you go" policy. When one's work area is organized, efficiency and productivity increases. This is a very good practice because it provides a strong foundation for the development of other Lean concepts such as JIT, six-sigma, and quality assurance management.
3. *Total Productive Maintenance (TPM)* – The saying "prevention is better than cure" and "*cLean* up your own mess" perfectly fits the goal of TPM. Mostly seen in mass production industries, TPM teaches the workers to do preventive maintenance in the machines that are used daily. This reduces costs in repairs and maintenance and also reduces equipment downtimes. TPM can also prevent unforeseen issues in the quality of the products being processed when machines are maintained in good condition. The ultimate goal of TPM is to totally eliminate all losses which include breakdown, setup, defect, rework, stoppage, upset condition, and yield losses.
4. *Cellular Manufacturing/One-Piece Flow Systems* – Rearranging how machines and workers are lined up will lead to better process efficiency and faster production time. Cellular manufacturing is about arranging work stations in a certain way which would minimize transport and delay between process steps. The main goal of this system is to move parts or products one piece at a time base on customer demand. This is also known as pull production. Information regarding the demand for parts comes from the customer and that information works its way back to the raw material supplier and from there, products are getting "pulled" from storage and fed to the production line piece by piece in order to meet the demand in a rapid fashion (Womack, J. & Jones, D., 2003). This principle is very important because it minimizes unnecessary inventories in the warehouse. Keeping inventory for a long time indicates that no sales have taken place, which means that the company is performing poorly.
5. *JIT Production Systems/Kanban* – Cellular manufacturing is an essential part of JIT because they go hand in hand in reducing inventory and work-in-process (WIP). JIT has a similar concept as pull production. A JIT system will only produce products when the customer needs them and in the amount they want (Mohanty, R., Yadav, O., & Jain, R., 2007). This system may not be suitable for some production lines especially when a product has a very high demand. Suppliers of a company that use a JIT system are usually required to use JIT in their own system in order to keep up with the customer needs. The main benefits of JIT are reduction of WIP, unnecessary inventory, and overproduction.
6. *Six Sigma* – Motorola was the pioneer of the Six Sigma in the 1990's wherein they developed a system that detects product and process variations using statistical quality control techniques and data analysis methods. Six Sigma is popular in

companies that require a high level of quality in their products, such as aerospace. The Six Sigma quality level measures up to 3.4 defects per million products, which represents high quality and low process variation. The main benefits of Six Sigma to Lean companies are an increase in productivity, improvement in quality, and minimization of rework and defects. However, it is worth mentioning that companies which use Six Sigma may not necessarily be practicing Lean operation.

7. *Pre-Production Planning (3P)* – The main idea behind 3P is to eliminate waste during the design phase of the product. While the overall concept of Lean manufacturing is to eliminate waste in the production process, 3P focuses mainly on the product development. Upon completion of different designs, they will undergo feasibility analysis to facilitate the selection process. After choosing the best design, its prototype is created and tested to check if it satisfies the criteria given by the customer as well as the development team.
8. *Lean Enterprise Supplier Networks* – Studies show that a company that practices Lean can only implement 20-30% of the Lean principles if their suppliers are not Lean. In order to increase the success of implementing Lean concepts, Lean companies must create a strong supplier relationship and encourage them to practice Lean concepts. An efficient supply chain system will enable a Lean company to deliver products to end users promptly.

Most manufacturing companies practice Lean concepts in order to improve product quality, decrease overhead and operating costs, maximize profits, and reduce wastes. It is essential to decide on what Lean principles should a company apply in order to meet their goals. According to a news article from USA Today, Lean manufacturing has helped a lot of businesses amidst recession. One of the companies that was helped by practicing Lean manufacturing is Sealy, the world's top mattress maker. Their process used to do batch-and-queue production which took one mattress 21 hours to be produced. After implementing one-piece flow production, the time it takes to produce one mattress is only 4 hours. Sealy's Lean manufacturing methods have paid off since their earnings increased from $10.9 Million to $12.1 Million in 2009.

Although Lean concepts generates substantial benefits, implementing Lean system could be difficult since it requires tremendous effort and support from top management. There must be a strong support system between managers and workers because Lean is a collaborative team effort. Managers decide which Lean concepts to implement and direct the workers or the production team on how to execute these concepts (Huntzinger, J., 2006). All employees in a company must learn their roles so they equipped with a sense of accountability as they perform their tasks and this will help Lean implementation run smoothly across various processes.

1.2. Fuzzy-AHP Definition and Methodology

The development of Fuzzy-AHP was based on the simple AHP formulated by Thomas Saaty. Since AHP only deals with a crisp set of numbers, it cannot handle the uncertainties of scaling results in complex decision making. The case study of Vinodh, Shivraman, and Viswesh (2011) on the application of AHP in Lean concept selection may not have accurate results since the complexity of choosing among ambiguous choices is not put to consideration. On the other hand, Fuzzy-AHP can transform imprecise data into an outcome that incorporates all uncertainties in decision making because it can deal with partial membership, full membership, or even non-membership in fuzzy sets (Ballı, S & Korukoğlu, S., 2009). In 1996, Chang used triangular fuzzy numbers for pairwise comparison and the extent analysis method for synthetic values which improved the results in the old Fuzzy-AHP method (Demirel, T., et. al., 2008). Fuzzy-AHP is a powerful tool that considers uncertainties in the decision making process, both qualitative and quantitative, in order to select the best alternative especially in complex manufacturing processes (Jenab K., Khoury S., Sarfaraz A., 2012). However, Fuzzy-AHP also has some disadvantages. Decision makers must be able to thoroughly brainstorm and decide which criteria and alternatives to use since Fuzzy-AHP can have biased results. Fuzzy-AHP can be prone to errors and excessive deviating evaluations because it deals with large sets of number being compared to different levels of criteria (Buchmeister, B., 2006).

Fuzzy-AHP is widely used in different industries such as production, service, logistics, supply chain, information technology, health, and finance. The most prevalent industry that often uses Fuzzy-AHP is the Supply Chain Management (SCM) since the supply and quality of raw materials depends primarily on SCM's efficiency and on-time supply of goods to the production line (Ku, C. et. al., 2009). Globalization played an important role in manufacturing firms to engage in global competition rather than to compete domestically. In light of this, SCM has improved supplier selection with the use of Fuzzy-AHP to not only measure precise quantitative data but also to tackle ambiguous qualitative facts about the alternatives being considered.

In connection with SCM, Fuzzy-AHP is gradually being introduced in Lean concept selection because Lean encompasses SCM's effectiveness when JIT, 5S, Six Sigma and other Lean tools are implemented. There have only been few researches done about the application of Fuzzy-AHP in Lean concept selection in manufacturing industries. Over the years, Lean principles have been proven to be effective in various production firms and they have been stressing the importance of selecting the best Lean concept to be applied. The main issue in Lean concept selection is that there are numerous Lean concepts and not all of them are applicable in all production firms. Top managers of these production firms must be able to select the best Lean concepts that fit their business capabilities and processes. With that said, Fuzzy-AHP is a good tool to address the ambiguity and uncertainty in Lean concept selection. The following steps presented below are describing the Fuzzy-AHP methodology based on Chang's (1996) proposed method:

TABLE 1. FUZZY-AHP LINGUISTIC SCALE.

Linguistic Scale for Importance	Triangular Fuzzy Scale	Triangular Fuzzy Reciprocal scale
Equally important	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly more important	(1, 3/2, 2)	(1/2, 2/3, 1)
Strongly more important	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strongly more important	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more important	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

1. Determine the hierarchy structure for the Lean concept selection. The hierarchy structure will be converted to the numerical pairwise comparison matrix.
2. Select the Fuzzy-AHP scale to be used. In this case, the triangular fuzzy scale formulated by Kahraman, et. al. (2006) will be used as shown in Table 1.
3. Use the triangular fuzzy scale and its reciprocal to create a pairwise comparison matrix for the criteria.
4. Create a pairwise comparison matrix for the Lean concept alternatives based on each criterion discussed in the previous step.
5. The first step in calculating the Fuzzy Synthetic Extent Values (S_i) is to get the sum of all low (l), middle (m), and upper (u) in each vector column and place them in its respective column for *l, m, u*. All the $M_{g_i}^{j}$ are triangular fuzzy numbers (see "(1)").

$$S_i = \sum_{j=1}^{m} M^j\, g_i \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M^j\, g_i\right]^{-1} \quad (1)$$

6. The next step is to multiply each column cell to the sum inverse in the same column using the fuzzy addition operation for finding *l, m, u* represented by "(2)". Values derived from this operation will be used as inputs in finding the degrees of freedom within the alternatives.

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M^j\, g_i = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right) \quad (2)$$

7. After aggregating the sum of all the *l, m, u* values into a matrix, the piecewise continuous membership function (Mikhailov, L. & Tsvetinov, P., 2003) is then calculated using "(3)".

$$V(M_2 \geq M_1) = \begin{cases} 1, & if\ m_2 \geq m_1, \\ 0, & if\ l_1 \geq u_2, \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{cases} \quad (3)$$

8. On this stage, the degree of possibility shown in "(4)" creates a vector by calculating the summation of the product of minimum values derived from "(3)" and the total sum of the said vector.

$$V(M_2 \geq M_1) = \sup_{y \geq x} \left[\min\left(\mu_{M_1}(x), \mu_{M_2}(y)\right)\right] \quad (4)$$

9. Aggregate all criteria-alternative weight vectors into a new matrix and multiply them to the criteria weight vector which is comprised of a vector to get the final results.

More details of this approach with an example can be obtained in Chang's study (1996).

1.3. Quality Function Deployment (QFD) Definition and Methodology.

The most important aspect of any business is the customer. Shigeru Mizuno and Yoji Akao, introduced QFD to incorporate customer requirements, expectations, and dislikes into the design phase of the product (Mazur, G., 2010). Since QFD can handle multiple causes of a problem, companies who need a more extensive root-cause analysis use it in their brainstorming sessions. Santa Cruz and Tamayo (2004) mentioned that when QFD is set to focus on customer needs, external customers are the ones usually considered in the process. According to Dr. Deming (1997), true quality occurs when every stage of a process is synchronized with each other to achieve the ultimate goal.

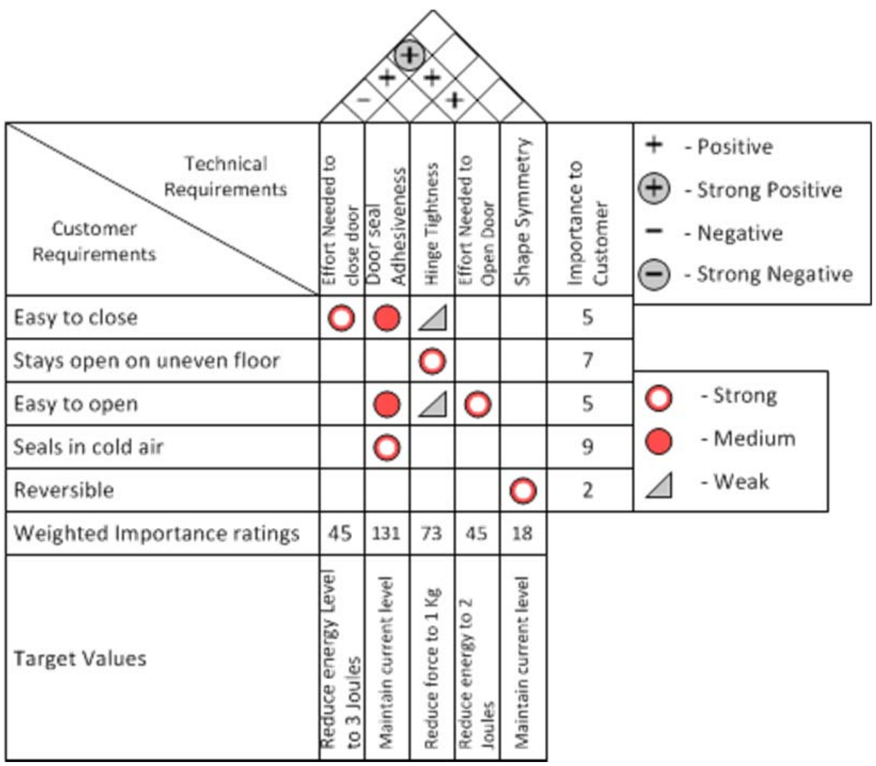

FIGURE 1. EXAMPLE OF HOUSE OF QUALITY DIAGRAM. (DAVIS, M. ET.AL., 2007, P.57)

Although helpful, QFD must be treated as a tool that could potentially bring benefits to the company as opposed to an ultimate tool. Managers must thoroughly research on the benefits of QFD in the organization and justify its application on production planning. A common pitfall in an organization that uses QFD is having high expectations that this tool will bring great results without even testing it on any project (Daetz,D., Barnard, B., & Norman, R., 1995). Learning about the fluctuating needs in various aspects of the company, including end-users, will help decide whether QFD can bring substantial benefits. This method is called gathering the "voice of the customer (VOC)", which is the start of every QFD process, according to Daetz, Barnard, and Norman (1995).

The VOC enables companies, especially manufacturing companies, to produce products with high efficiency, low cost, and minimal waste. In Lean manufacturing, customers are the ones who control the system because every process is based on customer demand. It has been proven that QFD provides significant inputs during any production planning phase using the tool called House of Quality (HOQ) (Daetz,D., Barnard, B., & Norman, R., 1995). Dr. Shanin (2005) reported that many researchers have integrated QFD with other quality engineering techniques to be applied in several decision-making problems. The principles of QFD set no limitations as to where it can or cannot be applied (Chan, L., Wu, M., 2002). In this regard, QFD can be applied in almost any industry, service or product, and integrated with decision-making tools such as Fuzzy-AHP. An Example of HOQ is presented in Figure 1. There are six major parts of the HOQ according to Johnson, et. al. (2001):

- *Customer Requirements* – determines what are the important factors or criteria that customers look for. This section is tied with the VOC because all inputs come from the customer needs.
- *Technical Requirements* – transforms the customer requirements into tangible requirements which helps satisfying these requirements. This section does not only address the customer requirements but also the management and regulatory bodies' requirements.
- *Planning Matrix* – identifies how well the team meets the customer requirements compared to its competitors. On Fig. 1, the column named *importance to customer* is the planning matrix.
- *Interrelationship Matrix* – establishes a connection between customer requirements and technical requirements. This matrix shows the direct relationship between the components of the customer requirements and technical requirements. Common ratings are strong (9), medium (5), weak (1), and blank for no relationship.
- *Technical Correlation Matrix* – compares each of the technical requirements with each other to see if they are correlated. This section identifies conflicts between requirements and up to what degree. The ratings are positive, strong positive, negative and strong negative as shown below.
- *Technical Properties and Targets* – sets the design targets and benchmarks based on competitors. This section is denoted by the rows named weighted importance ratings and target values. The highest rated technical requirement among all others must be prioritized.

II. INTEGRATION OF FUZZY AHP AND QFD METHODOLOGY

There are many benefits in integrating Fuzzy-AHP with QFD. First, it provides accurate results which not only considers organizational factors but also takes into account external factors such as customers. Second, since Fuzzy-AHP deals with ambiguities, QFD helps focus these ambiguities on critical decisions that are customer oriented (Shanin, A., 2005). Lastly, most of the verbal data that comes from QFD can be easily converted to logical data with the help of Fuzzy-AHP. Fuzzy-AHP integrated with QFD methodology can effectively be utilized by manufacturing companies to identify the proper Lean concept.

The methodology that will be used on the integration of Fuzzy AHP and QFD will be derived from the case study done by Bakshi, Sakar, and Sanyal [2012]. The steps involved in the integration of Fuzzy-AHP and QFD are shown in Fig. 2.

In Fig. 2, equations "(5)" and "(6)", W_j is the j_{th} area model degree (j = 1, 2 . . . n), R_{ij} is the association between i_{th} area and j_{th} area, and C_i is the imperativeness weighting of the i_{th} prerequisite (i = 1, 2, m)

III. CASE STUDY

Daioku Company, a manufacturer of automotive components for a major car company in India, was having problems in their drag links, center links and tie rods assembly line. Their client began to practice Lean manufacturing and required them, as their supplier, to do the same. Daioku's managers had a meeting to discuss the need for selecting the two best Lean concepts to be applied based on their capabilities. There were five Lean concepts that were brought up during the meeting: 5S, JIT, TPM, Kaizen and one-piece flow production.

Top management felt that if they started with the simple implementation of 5S, they would have a good chance to do a Kaizen event and then the rest of the Lean principles would follow through. However, the production team presented the problem regarding the high volume of work-in-process (WIP) and suggested starting off with implementing a one-piece flow instead of a batch- and-queue production. All managers agreed to first evaluate the five chosen Lean principles using Fuzzy-AHP and QFD before they finally decide on which two concepts to use.

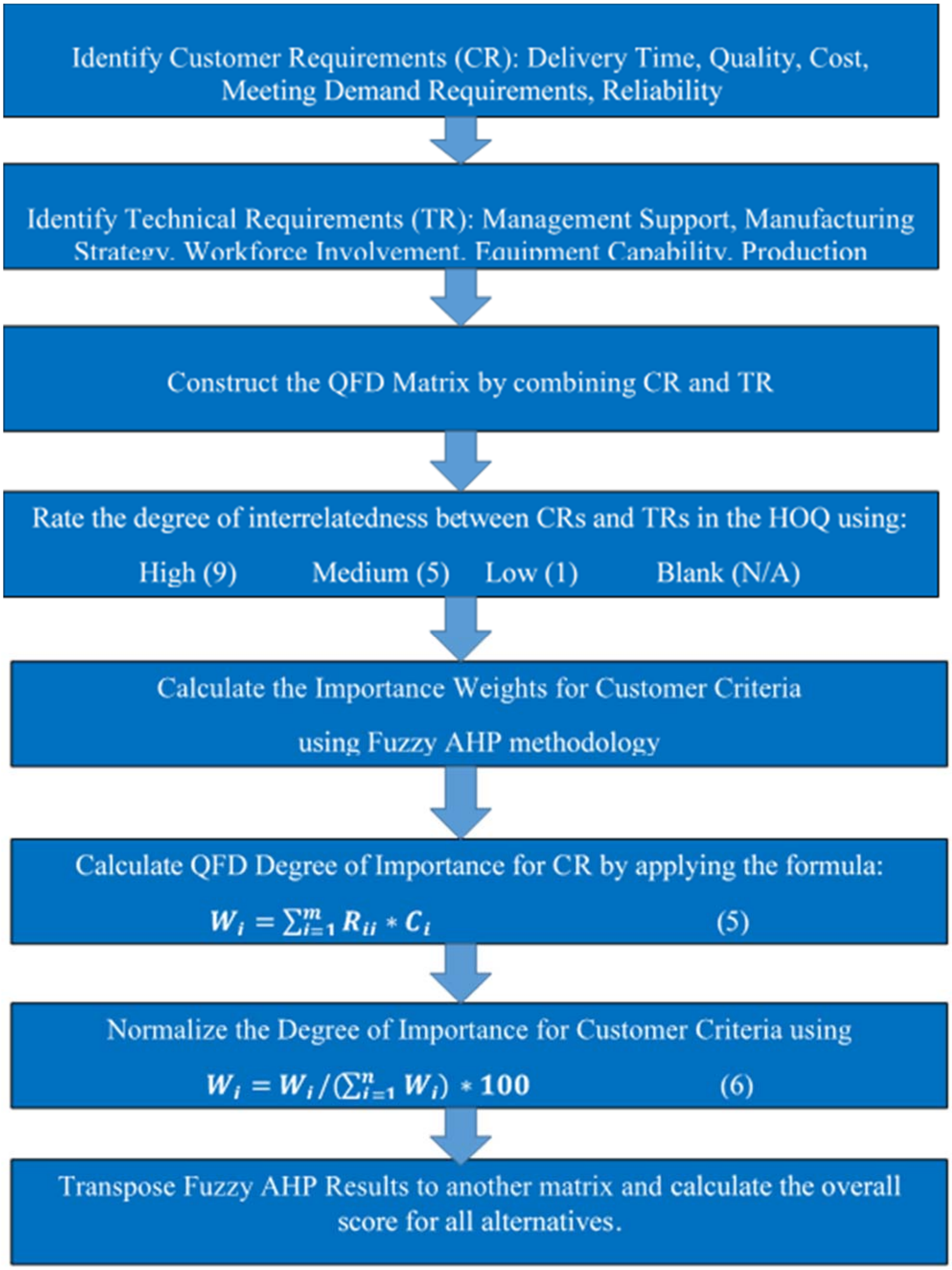

FIGURE 2. FUZZY AHP AND QFD INTEGRATION METHODOLOGY.

IV. FUZZY-AHP APPLICATION

Lean concept selection involves a high level of understanding regarding different Lean principles. Fuzzy-AHP should be utilized since there are many gray areas and ambiguities in the concept selection. Since there are over 50 Lean manufacturing principles to choose from, management of Daioku should focus on the five major Lean principles that are suitable for their needs.

The production team together with the top managers formed a Lean team to effectively brainstorm and implement the selected Lean concept. They began the process by developing the steps that they need to take in order to choose the two best Lean concepts. The steps that they took are as follows:

a. Determine the hierarchy structure for the Lean concept selection. The five Lean concepts mentioned earlier are 5S, JIT, TPM, Kaizen and one-piece flow production which become the alternatives for the pairwise comparison based on five criteria. The five criteria that Diaoku should choose are:

   - Management Support – Daioku's top level managers must support and involve themselves in the Lean concept selection project in order to be successful in the process. Without the top managers' support on Daioku's shift to Lean environment, implementation will be very difficult to achieve because the existence of tendency against the change in all organizations.
   - Manufacturing Strategy – In order to achieve a Lean environment in the company, the production process must be able to adapt to certain changes. Lean implementation can drastically change Daioku's manufacturing styles and strategies and it is important to have a robust and agile manufacturing plan.
   - Workforce Involvement – Without the support of the middle to low level employees, Lean concept selection and implementation will not come through. This criterion ties directly with management support.
   - Equipment Capabilities – Replacing machines and equipment can be expensive because of the adaptation of Lean manufacturing. It is crucial for the production team to identify the possible areas that will be affected by the changes in the production line.
   - Production Planning – In context of this case study, production planning refers to the customer requirements and demand needs. For a successful implementation of the manufacturing strategy, inputs from production planning are very helpful in fulfilling customer needs as well as organizational goals.

   The criteria mentioned are essential in the decision making process because those are the ones that direct the outcome of this study. The Lean team should rate all these criteria based on their skills and knowledge about Daioku's production process in order to determine an optimal criteria weight vector that will be multiplied to the weight vector of the alternatives. Fig. 3 presents the hierarchy structure for the Lean concept selection case study.

b. Select the Fuzzy-AHP scale to be used and as mentioned earlier in the Fuzzy-AHP methodology, the triangular fuzzy scale formulated by Kahraman, et. al. (2006) is used.

c. Use the triangular fuzzy scale and its reciprocal to create a pairwise comparison matrix for the criteria. The most important criteria based on the company's background and production process should be management support, manufacturing strategy, workforce involvement, equipment capability, production planning. Table 2 shows the breakdown of scale ratings for the criterion.

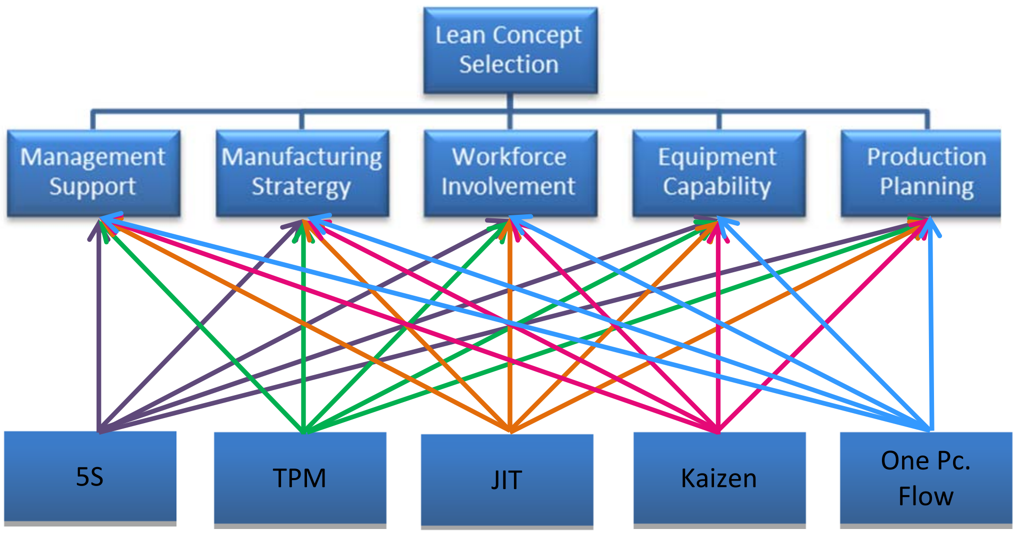

FIGURE 3. LEAN CONCEPT SELECTION HIERARCHY.

TABLE 2. PAIRWISE COMPARISON MATRIX FOR CRITERIA.

Criteria	Mgmt. Support			Mfg. Strategy			Wrkfrce Involve.			Eqpt. Capability			Prod. Planning		
	l	*M*	*u*	*l*	*m*	*U*	*L*	*m*	*u*	*L*	*m*	*U*	*L*	*m*	*u*
Mgmt. Support	1.000	1.000	1.000	1.000	1.500	2.000	1.500	2.000	2.500	2.500	3.000	3.500	1.000	1.500	2.000
Mfg. Strategy	0.500	0.667	1.000	1.000	1.000	1.000	1.000	1.500	2.000	1.500	2.000	2.500	2.000	2.500	3.000
Wrkfrce Involv.	0.400	0.500	0.667	0.500	0.667	1.000	1.000	1.000	1.000	0.500	1.000	1.500	1.000	1.500	2.000
Eqpt. Cap.	0.286	0.333	0.400	0.400	0.500	0.667	0.667	1.000	2.000	1.000	1.000	1.000	1.000	1.500	2.000
Prod. Planning	0.500	0.667	1.000	0.333	0.400	0.500	0.500	0.667	1.000	0.500	0.667	1.000	1.000	1.000	1.000

TABLE 3. PAIRWISE COMPARISON MATRIX FOR ALTERNATIVES BASED ON MANAGEMENT SUPPORT.

Alternatives	5S			TPM			JIT			Kaizen			One-Pc. Flow		
	l	*m*	*u*	*l*	*m*	*u*	*L*	*m*	*u*	*l*	*m*	*u*	*l*	*M*	*u*
5S	1.000	1.000	1.000	2.000	2.500	3.000	0.500	1.000	1.500	1.000	1.500	2.000	2.500	3.000	3.500
TPM	0.333	0.400	0.500	1.000	1.000	1.000	1.500	2.000	2.500	0.500	0.667	1.000	1.000	1.500	2.000
JIT	0.667	1.000	2.000	0.400	0.500	0.667	1.000	1.000	1.000	0.400	0.500	0.667	0.400	0.500	0.667
Kaizen	1.000	1.500	2.000	1.000	1.500	2.000	1.500	2.000	2.500	1.000	1.000	1.000	2.000	2.500	3.000
One-Pc. Flow	0.286	0.333	0.400	0.500	0.667	1.000	1.500	2.000	2.500	0.333	0.400	0.500	1.000	1.000	1.000

TABLE 4. PAIRWISE COMPARISON MATRIX FOR ALTERNATIVES BASED ON MANUFACTURING STRATEGY.

Alternatives	5S			TPM			JIT			Kaizen			One-Pc. Flow		
	l	*m*	*u*	*l*	*m*	*u*	*L*	*m*	*u*	*l*	*m*	*u*	*l*	*M*	*u*
5S	1.000	1.000	1.000	1.500	2.000	2.500	0.500	0.667	1.000	1.000	1.500	2.000	0.400	0.500	0.667
TPM	0.400	0.500	0.667	1.000	1.000	1.000	0.333	0.400	0.500	0.667	1.000	2.000	0.286	0.333	0.400
JIT	1.000	1.500	2.000	1.500	2.000	2.500	1.000	1.000	1.000	1.000	1.500	2.000	0.667	1.000	2.000
Kaizen	0.500	0.667	1.000	0.500	1.000	1.500	0.500	0.667	1.000	1.000	1.000	1.000	0.400	0.500	0.667
One-Pc. Flow	1.500	2.000	2.500	2.500	3.000	3.500	0.500	1.000	1.500	1.500	3.000	2.500	1.000	1.000	1.000

TABLE 5. PAIRWISE COMPARISON MATRIX FOR ALTERNATIVES BASED ON WORKFORCE INVOLVEMENT.

Alternatives	5S			TPM			JIT			Kaizen			One-Pc. Flow		
	l	*m*	*u*	*l*	*m*	*u*	*L*	*m*	*u*	*L*	*m*	*u*	*l*	*M*	*U*
5S	1.000	1.000	1.000	1.500	2.000	2.500	2.000	2.500	3.000	1.000	1.500	2.000	1.500	2.000	2.500
TPM	0.400	0.500	0.667	1.000	1.000	1.000	0.500	0.667	1.000	0.500	0.667	1.000	0.333	0.400	0.500
JIT	0.333	0.400	0.500	1.000	1.500	2.000	1.000	1.000	1.000	0.286	0.333	0.400	0.500	1.000	1.500
Kaizen	0.500	0.667	1.000	1.000	1.500	2.000	2.500	3.000	3.500	1.000	1.000	1.000	2.000	2.500	3.000
One-Pc. Flow	0.400	0.500	0.667	2.000	2.500	3.000	0.667	1.000	2.000	0.333	0.400	0.500	1.000	1.000	1.000

TABLE 6. PAIRWISE COMPARISON MATRIX FOR ALTERNATIVES BASED ON EQUIPMENT CAPABILITIES.

Alternatives	5S			TPM			JIT			Kaizen			One-Pc. Flow		
	l	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*L*	*m*	*u*	*l*	*M*	*u*
5S	1.000	1.000	1.000	1.500	2.000	2.500	2.500	3.000	3.500	2.000	2.500	3.000	1.000	1.500	2.000
TPM	0.400	0.500	0.667	1.000	1.000	1.000	2.000	2.500	3.000	1.500	2.000	2.500	1.000	1.500	2.000
JIT	0.286	0.333	0.400	0.333	0.400	0.500	1.000	1.000	1.000	0.500	0.667	1.000	0.400	0.500	0.667
Kaizen	0.333	0.400	0.500	0.400	0.500	0.667	1.000	1.500	2.000	1.000	1.000	1.000	0.500	0.667	1.000
One-Pc. Flow	0.500	0.667	1.000	0.500	0.667	1.000	1.500	2.000	2.500	1.000	1.500	2.000	1.000	1.000	1.000

TABLE 7. PAIRWISE COMPARISON MATRIX FOR ALTERNATIVES BASED ON PRODUCTION PLANNING.

Alternatives	5S			TPM			JIT			Kaizen			One-Pc. Flow		
	l	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*L*	*m*	*u*	*l*	*M*	*u*
5S	1.000	1.000	1.000	1.000	1.500	2.000	0.400	0.500	0.667	0.500	0.667	1.000	0.333	0.400	0.500
TPM	0.500	0.667	1.000	1.000	1.000	1.000	0.286	0.333	0.400	0.333	0.400	0.500	0.400	0.500	0.667
JIT	1.500	2.000	2.500	2.500	3.000	3.500	1.000	1.000	1.000	1.500	2.000	2.500	0.500	1.000	1.500
Kaizen	1.000	1.500	2.000	2.000	2.500	3.000	0.400	0.500	0.667	1.000	1.000	1.000	0.500	0.667	1.000
One-Pc. Flow	2.000	2.500	3.000	1.500	2.000	2.500	0.667	1.000	2.000	1.000	1.500	2.000	1.000	1.000	1.000

Management Support is the most important element among all of the criteria because without the support of the top level managers, Lean concept selection and implementation cannot begin. Manufacturing strategy is the second most important criteria because it deals with production process capabilities, styles, and requirements.

d. Create a pairwise comparison matrix for the Lean concept alternatives based on each criterion. It is important to note that every criterion must be considered when ranking the alternatives and must have their own pairwise matrix. The following tables show the pairwise comparison matrix for Lean concept alternatives based on the five different criteria that were previously discussed.

e. Table 8 shows the result of Equation 1 when applied to the Pairwise Comparison for Management Support from Table 3. Same procedures were done with the other 4 criteria.

f. The table below shows the result when the Fuzzy Addition Operation is applied to the values derived from Table 8.

TABLE 8. FUZZY SYNTHETIC EXTENT VALUES FOR MANAGEMENT SUPPORT.

Alternatives	lower	middle	upper
5S	7.00	9.00	11.00
TPM	4.33	5.57	7.00
JIT	2.87	3.50	5.00
Kaizen	6.50	8.50	10.50
One-Pc. Flow	3.62	4.40	5.40
Sum	24.32	30.97	38.90
Sum Inverse	0.03	0.03	0.04

TABLE 9. APPLICATION OF FUZZY ADDITION OPERATION TO THE FUZZY SYNTHETIC EXTENT VALUES.

DoF Var.	Alternatives		lower	middle	upper
L1	5S		0.180	0.291	0.452
L2	TPM		0.111	0.180	0.288
L3	JIT		0.074	0.113	0.206
L4	Kaizen		0.167	0.274	0.432
L5	One-Pc. Flow		0.093	0.142	0.222

TABLE 10. VALUES FOR THE DEGREES OF FREEDOM MEMBERSHIP FUNCTION IN THE MANAGEMENT SUPPORT CRITERION.

Management Support									
L1>L2 =	1.0000	L2>L1 =	0.4932	L3>L1 =	0.1262	L4>L1 =	0.9397	L5>L1 =	0.2208
L1>L3 =	1.0000	L2>L3 =	1.0000	L3>L2 =	0.5853	L4>L2 =	1.0000	L5>L2 =	0.7460
L1>L4 =	1.0000	L2>L4 =	0.5604	L3>L4 =	0.1926	L4>L3 =	1.0000	L5>L3 =	1.0000
L1>L5 =	1.0000	L2>L5 =	1.0000	L3>L5 =	0.7948	L4>L5 =	1.0000	L5>L4 =	0.2933

TABLE 11. DEGREE OF POSSIBILITY FOR MANAGEMENT SUPPORT CRITERION.

Alternatives	Min. Value	Vector Mgmt. Supp.
5S	1.0000	0.3597
TPM	0.4932	0.1774
JIT	0.1262	0.0454
Kaizen	0.9397	0.3380
One-Pc. Flow	0.2208	0.0794
Total Sum	**2.7800**	

TABLE 22. CRITERIA MATRIX AND CRITERIA WEIGHT VECTOR MULTIPLICATION AND FINAL RESULTS.

Alternatives	Mgmt. Supp.	Mfg. Strat.	Wrkfce Inv.	Eqpt. Cap.	Prod. Planning		Criteria	Weight Vector			Results	
5S	0.3597	0.1975	0.3776	0.5003	0.0622		**Mgmt. Support**	0.3653		**5S**	**0.3314**	**first choice**
TPM	0.1774	0.0315	0.0000	0.3339	0.0000		**Mfg. Strat.**	0.3051		**TPM**	0.1334	fourth
JIT	0.0454	0.2882	0.0764	0.0000	0.3784	**X**	**Workforce Involve.**	0.1327	=	**JIT**	0.1223	fifth
Kaizen	0.3380	0.0743	0.3618	0.0000	0.2245		**Eqpt. Cap.**	0.1767		**Kaizen**	0.1987	third
One-Pc. Flow	0.0794	0.4086	0.1843	0.1658	0.3350		**Prod. Planning**	0.0201		**One-Pc. Flow**	**0.2142**	**second choice**

g. The results for the calculation of the degrees of freedom are shown below using the values derived from Table 5. The variable for Lean concept alternative denoted by L_i is used instead of M_i for the purpose of this study.

h. Table 11 shows the summary of results for management support when Equation 4 is applied to the values derived from Table 6 on the previous stage. This process will be used for the criteria and the rest of the alternatives.

i. Once all the alternatives have undergone all the stages that were previously discussed, a new 5x5 matrix will be formed which will be multiplied by the weight vector of the criteria, which has also undergone the same Fuzzy-AHP stages as the other alternatives (5x1 matrix). Table 12 presents the aggregated values with the final results of the Fuzzy-AHP for Lean concept selection case study.

V. FUZZY-AHP ANALYSIS OF RESULTS

The results shown in Table 8 using Fuzzy-AHP methodology ties with the needs of Daioku based on the case study presented earlier. It is important to note that the criteria weight vector showed high emphasis on Management Support with 0.37 or 37% (see Table 12) followed by Manufacturing Strategy with 31%, Equipment Capability with 18%, Workforce Involvement with 13%, and Production Planning with only 2%. This result indicates that Management Support and Manufacturing Strategy have significant influence on the final selection of Lean concepts. Top managers preferred to use 5S and the production team preferred to use one-piece flow production. Additionally, looking back at the data in Table 12, notice that TPM had zero ratings in Workforce Involvement and Production Planning while Kaizen and JIT has a zero ratings in Equipment Capability. This only means that the judgments are non-fuzzy on these areas.

Since Fuzzy-AHP accounted for all the uncertainties and ambiguities in every stage of the decision making process, it is pragmatic to recommend that the top two Lean concepts from the results must be chosen. In addition, it is essential to focus on customer's perspective on Daioku's decision to go Lean. In order to address this matter, results from Fuzzy-AHP shall now become inputs to the QFD methodology in the next chapter.

VI. INTEGRATED FUZZY-AHP AND QFD APPLICATION

The Voice of the Customer (VOC) is the main focus of QFD. Daioku's Lean team must incorporate VOC in the selection of Lean concept so that every facet of the project is put to consideration. All aspects of the case study requirements shall be realized upon the completion of this stage.

The Technical Requirements criteria were derived from Fuzzy-AHP as an integration process to achieve soundness of data. Customer Requirements criteria are a new addition to the integration process and have to undergo the Fuzzy AHP methodology in order to get the results for the importance weights. Customer Requirements consist of the following:

- Delivery Time – Since Daioku's clients are implementing Lean Manufacturing in their organization, Daioku needs to keep up with their client's timeline. Ensuring on-time delivery can help the company be at par with their client's production pace.
- Quality – Every company must achieve quality in everything they do. Daioku must prioritize the quality of their products through good Lean techniques.
- Cost – Company expenses must always be accounted for in order to bring down the selling price of products. It is very important to keep in mind all the costs associated in production because high costs translate to higher selling price which is not good for customers.
- Meeting Demand Requirements – Although demand varies from time to time, Daioku management must learn how to balance their production capabilities with the customer demand. Make sure to keep inventories at a safe level where there will be no surplus.
- Reliability – One main reason for implementing Lean manufacturing is to reduce defects and increase reliability in finished products. Daioku's automobile parts must be at par with the standards of their customers in order to gain trust and loyalty.

TABLE 13. FUZZY EVALUATION MATRIX FOR CUSTOMER REQUIREMENTS AND IMPORTANCE WEIGHTS.

Alternatives	lower	Middle	upper	Importance Weights
Delivery Time	0.087	0.151	0.254	0.4113
Quality	0.167	0.274	0.432	1.0000
Cost	0.154	0.248	0.391	0.8926
Quantity	0.070	0.104	0.171	0.0243
Reliability	0.089	0.145	0.260	0.4195

TABLE 14. HOUSE OF QUALITY INTERRELATIONSHIP MATRIX, DEGREE OF IMPORTANCE AND NORMALIZED DEGREE OF IMPORTANCE FOR CUSTOMER CRITERIA.

Technical Requirements / Customer Requirements (Rij)	Management Support	Manufacturing Strategy	Workforce Involvement	Equipment Capability	Production Planning	Importance Weight (CI)
Delivery Time		9	5	9	9	0.41
Quality	5	9	9	5	5	1.00
Cost	9	5			5	0.89
Meeting Demand Req'ts	1	5	5	9	5	0.02
Reliability		9	9	1		0.42
Degree of Importance for Customer Criteria (¯Wj)	13.06	21.061	14.953	9.34	13.29	
Normalized Degree of Importance for Customer Criteria	18.21	29.375	20.856	13.03	18.53	

Table 13 shows the Fuzzy Evaluation Matrix for the Customer Requirements and the results after calculating the Degree of Possibility which will become the importance weights on HOQ. This matrix serves as an additional step to fulfill the integration of Fuzzy-AHP results and HOQ rankings. Also, creating the Fuzzy Matrix for the HOQ helps achieve coherence in data collection.

The HOQ presented on Table 14 followed the first seven steps as show on Fig. 2.

After normalizing the degree of importance for customer criteria, the next step is to move the data into another matrix that computes for the overall scores of each alternative. The data that shall be used in the alternatives matrix comes from the criteria matrix in Table 12. The normalized Degree of Importance for customer criteria shall then become the weight vector for calculating overall scores on the alternatives matrix. To get the overall score for the alternatives matrix, "(5)" from Fig. 2 is utilized.

VII. INTEGRATED FUZZY-AHP AND QFD ANALYSIS OF RESULTS

The integration of Fuzzy-AHP and QFD only shows that even if the two methodologies are combined, there is still consistency in the results. Although the prioritization of the importance weights is slightly different from the Fuzzy AHP criteria weight vector, the overall scores were still very similar to each other. The two best Lean concepts from this methodology are 5S and One-Piece Flow then followed by Kaizen, JIT, and TPM. As an observation, JIT had a much higher score than TPM in this methodology than Fuzzy-AHP primarily because of the customer requirements matrix. Further analysis show that JIT has higher rankings for Manufacturing Strategy with 0.288 and Production Planning with 0.378 than TPM. Since Manufacturing Strategy and Production Planning also have high importance weights with 29.375 and 18.531 respectively, it boosted JIT's overall score.

TABLE 15. QFD OVERALL RESULTS.

Technical Requirements	Normalized Importance Weight	5S	TPM	JIT	Kaizen	One-Pc. Flow
Management Support	18.212	0.360	0.177	0.045	0.338	0.079
Manufacturing Strategy	29.375	0.197	0.031	0.288	0.074	0.409
Workforce Involvement	20.856	0.378	0.000	0.076	0.362	0.184
Equipment Capability	13.027	0.500	0.334	0.000	0.000	0.166
Production Planning	18.531	0.062	0.000	0.378	0.224	0.335
Overall Score		27.897	8.505	17.897	20.043	25.658

The results presented definitely demonstrated how powerful it is to integrate two ranking systems into another decision making system. The consistency of data proves that this methodology can be applied on any decision making process; may it be qualitative, quantitative or both. Daioku's team will not have any problems in using these combine methodologies for selecting the top two Lean concepts because the results for the two separate methodologies are very similar.

VIII. CONCLUSION

The combination of Fuzzy-AHP and QFD is a very effective tool in gathering information and transforming that information into numerical and logical data. There is no doubt that both Fuzzy-AHP and QFD are flexible decision making tools in terms of integration because they have close similarities in their methods. Compared to AHP, Fuzzy-AHP is indeed superior in terms of the methodology because results are more accurate and consistent. AHP by itself is not a very good tool in solving complex and abstract problems like the Lean concept selection.

In order to derive accurate results in Fuzzy-AHP and QFD, it is recommended to brainstorm carefully to decide on which criteria to use and what alternatives to choose from. There will always be pitfalls in utilizing any methodology. In order to mitigate any risks involved, expertise and experience in the field is essential and should be highly considered. Other than that, it is highly recommended to integrate similar methods of any decision making tool to acquire accurate and feasible results.

REFERENCES

Bakshi, T., Sarkar, B., and Sanyal, S. "A Novel Integrated AHP-QFD Model for Software Project Selection under Fuzziness". *International Journal of Computer Applications,* 54(7), 2012, 36-43.

Chan, K. "An Enhanced Fuzzy AHP Method with Extent Analysis for Determining Importance of Customer Requirements". *Studies in Computational Intelligence*. Vol. 403, 2012, 79-93.

Chan, L. and Wu M. "Quality function deployment: A literature review." *European Journal of Operational Research.* 143, 2002, 463–497.

Chang, D. Y. "Applications of the Extent Analysis Method on Fuzzy AHP." *European Journal of Operational Research*, 95, 1996, 649-655.

Chatterjee, Debmallya. "Study of Fuzzy-AHP Model to Search the Criteria In the Evaluation of the Best Technical Institutions." *International Journal of Science and Tech.* 2(7), 2010 2499–2510.

Daetz, D., Barnard, B., & Norman, R. *Customer Integration: The Quality Function Deployment (QFD) Leader's Guide for Decision Making.* New York : John Wiley & Sons, Inc. 1995

Davidson, P. "Lean manufacturing helps companies survive recession." *USA Today.* Retrieved on Oct. 23, 2012 from http://usatoday30.usatoday.com/money/industries/manufacturing/2009-11-01-Lean-manufacturing-recession_N.htm?loc=interstitialskip

Davis, M.M., Heineke, J. & Balakrishnan, J. *Fundamentals of Operations Management 2nd Edition.* Toronto, Ontario: McGraw Hill Ryerson, 2007.

Deming, W.E. *Out of the Crisis*. Newton, MA: Butterworth-Heinemann, 1997.

Demirel, T., Muşdal, H., Demirel, N. & Yücenura, G. Multi-Criteria Evaluation of Land Cover Policies Using Fuzzy AHP and Fuzzy ANP: The Case of Turkey. *Human and Ecological Risk Assessment: An International Journal Volume 15, Issue 4, 2009.*

Earley, T. (2012). "*History of Lean Manufacturing*". Retrieved on Oct. 25, 2012 from http://Leanman.hubpages.com/hub/History-of-Lean-Manufacturing

Huntzinger, J. "*Lean Cost Management : Accounting For Lean By Establishing Flow."* Ft. Lauderdale, FL: J. Ross Pub. 2006.

Jenab K., Khoury S., Sarfaraz A. “Manufacturing complexity analysis with fuzzy AHP.” *International Journal of Strategic Decision Sciences (IJSDS)* Vol.3, No.2, 2012, pp.31-46.

Johnson, G., Tapke, J., Muller, A., and Sieck, J. *House of Quality: Steps in Understanding the House of Quality*. Retrieved on Nov. 17, 2012 from http://www.public.iastate.edu/~vardeman/IE361/f01mini/johnson.pdf

Kahraman, C., Ertay, T., & Buyukozkan, G. (2006). “A fuzzy optimization model for QFD planning process using analytic network approach.” *European Journal of Operational Research*, 171(2), 2006, 390-411.

Kocakülâh, M., Brown, J., & Thomson, J. “Lean Manufacturing Principles and Its Application In Plastics Manufacturing.” *Decision Sciences Institute Proceedings, 2008.*

Koul, S. & Verma, R. “Dynamic Vendor Selection: A Fuzzy AHP Approach.” *Institute of Electrical and Electronics Engineers Journal, 2009.*

Ku, C., Chang, C., & Ho, H. “Global supplier selection using fuzzy analytic hierarchy process and fuzzy goal programming.” *Quality & Quantity Vol. 44 N. 4 2010.*

Kwong, CK. “Determining the Importance Weights for the Customer Requirements in QFD Using a Fuzzy AHP with an Extent Analysis Approach.” *IIE Transactions*, 2010.

Lean Enterprise Institute. “A Brief History of Lean.” Retrieved on Nov. 10, 2012 from http://www.Lean.org/WhatsLean/History.cfm.

Miller, G., Pawloski, J., & Standridge,C. “A case study of Lean, sustainable manufacturing.” *Journal of Industrial Engineering and Management.* Vol. 3 N1., 2010, p11-32.

McBride, D. “The 7 Manufacturing Wastes.” *EMS Consulting Group Articles.* Retrieved on Oct. 25, 2012 from http://www.emsstrategies.com/dm090203article2.html

Mohanty, R., Yadav, O., & Jain, R. “Implementation of Lean Manufacturing Principles in Auto Industry.” *Xavier Institute of Management Bhubaneswar Journal of Management, 2007.*

Ruiz, J. & Enriquez, F. “QFD application for tackling Internal Customers’ Needs as a base for building a Lean Manufacturing System.” Retrieved on Nov. 28, 2012 from http://www.qfdlat.com/English/Papers/Lean_Manufacturing_System_and_QFD.pdf

Saaty, T. L. “Decision Making with the Analytic Hierarchy Process.” *Int. J. Services Sciences*, 1 (1), 2008, 83-98.

Saaty, T. L. “How to make a Decision: The Analytic Hierarchy Process.” *European Journal of Operational Research*. 48, 1990, 9 – 26.

Shanin, A. “Quality Function Deployment: A Comprehensive Review.” *Total Quality Management-Contemporary Perspectives and Cases*. Andhra Pradesh: ICFAI University Press, 2008.

Taipei, Republic of China. “Study Meeting on Customer Satisfaction in Competitive Markets.” Retrieved on Nov. 28, 2012 from apo-tokyo.org: www.apo-tokyo.org/publications/files/pjrep-0023.pdf

Womack, J. & Jones, D. *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. 2nd ed. New York: Free Press, 2003.

Zahedi, H. “Database Management System Evaluation and Selection Decision.”

Decision Sciences, Vol.16, No.1,1985, pp.91-116.

Zhen, H., Ershi, Q., & Zixian, L. "A Study on Continuous Quality Improvement Strategies and Methods." Retrieved on Nov. 20, 2012 from www.paper.edu.cn/index.php/default/scholar/downpaper/hezhen-8.

Vinodh, S., Shivraman, K.R., and Viswesh, S. "AHP-based Lean concept selection in a manufacturing organization." *Journal of Manufacturing Technology Management,* Vol. 23 Iss: 1, 2011, pp. 124 – 136.