LEAN FUNCTION DEPLOYMENT (LFD): DETERMINING THE LEAN IMPLEMENTATION POINT USING A CUSTOMER PERSPECTIVE

Amy Bugyis
IE 401 Integrated Manufacturing, University of Tennessee

Abstract

Lean Function Deployment (LFD) was developed to fill the need for a method that determines the lean implementation point using customer needs in determining process steps. LFD is a method developed by combining the underlying principles of Quality Function Deployment (QFD) and existing lean methods to detect where to implement lean in a process. The LFD methodology is an algorithm using paired comparison and relative rankings between needs, technical characteristics, process parameters, and process steps using input from both the customer and the process engineer.

LFD determines the critical-to-quality (CTQ) and the critical to lead-time process steps in the production of a product using 2 phases. LFD ultimately mitigates the problems of QFD by using a consistent and defined ranking system to quantify results. LFD uses a weighting system that connects expected weights for each step of the algorithm. Ultimately, the customer need rankings are tied to the final CTQ process ratings by carrying weights between sub-phases.

The effectiveness of the LFD tool was tested among subjects and proved to increase the distinction between ratings for process parameters because it has a decreased range in rankings among subjects. Finally, a computer program was developed and is available on a Web site to show the real-world application of the proposed lean implementation tool.

Background

The purpose of Quality Function Deployment (QFD) is to “define customer needs or requirements and translate them into specific plans to produce products that meet those needs” (Crow, 2006). The current model uses an arbitrary ranking system to allow customers to weigh the importance and relationships between needs, technical characteristics, part characteristics, and process steps. QFD relies on symbolic notation for depicting weak, medium, and strong relationships based on an individual’s viewpoint. The qualitative nature of this approach leaves room for large variation among rankings and relationships due to its reliance on human discretion. Not only can QFD be very tedious and time consuming, but the initial ranking of the importance of customer needs is fairly arbitrary and allows for customer contradiction.

An Analytical Hierarchy Process (AHP) can be used to solve the problem of customer contradiction. AHP “provides a powerful tool that can be used to make decisions in situations involving multiple objectives” (Winston, 2004). The process begins by creating an n x n Pairwise Comparison matrix. The entry in row i and column j displays how much more important objective i is than objective j. The importance ratings are then entered into the table. If a_{ij} = k, then for consistency, a_{ji}= (1/k). Next, the values in the pairwise comparison matrix are normalized for each relative column. A score is calculated from the pairwise comparison table by calculating the sum of each row, which represents the need. This calculation determines the weights for each need by averaging the normalized values by row. A comparison check is done by multiplying the comparison matrix times the weights. Finally, the consistency index is found by dividing each value from the consistency check matrix by the corresponding weight, and averaging these values. The number of values n is subtracted, and the entire row is then divided by $n-1$.

The consistency index shows the degree of customer contradiction among ratings, so lower index values are better. Surveys with large consistency indexes should be ignored or discarded. For a larger comparison matrix, the threshold of the allowable consistency index is larger before the survey has to be thrown out. The acceptability of a consistency index can be determined from a table that compares the sampled number of objectives n to the random index (RI) values. If the consistency index (CI) is lower than the RI for the corresponding value of *n*, then the consistency is acceptable. For example, if you have four objectives, you can have a CI of up to 0.90 before discarding the results. (Winston, 2004)

A few existing tools combine AHP and QFD, but in such projects as "Integrating QFD, AHP and Benchmarking in Strategic Marketing" (Lu, 1994), the ideas are combined without altering the QFD method, so without fixing the possible contradictions and arbitrary values obtained through QFD. Other improvements to QFD were also uncovered in the literature, but these improvements to QFD simply add a process or an analysis as a step either before or after the QFD, increasing the time for analysis and further complicating the process.

Another problem with QFD is that the tool does not tell the user how to apply the results obtained from the completed analysis. Numerous approaches have been used to address this problem, including, but not limited to choosing a subset of process parameters to concentrate on, linking the performance measure with the section of the organization that identifies with it, performing a Performance Measure Analysis, and completing a cost-benefit analysis (Katz, 2006). Although these approaches can help in understanding the QFD output or fixing some of the flaws found in QFD, adding such steps makes the entire process more time consuming, and often more complex.

Other research has tried to improve the QFD process by modifying the current design. One example of such a modification is Modular Function Deployment^{TM} (MFD). The MFD concept closely follows the methodology of the well-known Quality Function Deployment (QFD), with the addition of a "modularity" concept. The first step utilizes the QFD matrix to determine customer requirements, slightly modified by putting "modularity" in as the first design requirement. The MFD concept later introduces Module Drivers^{TM}, which translate a company's objectives into guidelines for modularizing product design. Module Drivers form the base of a systematic evaluation of the technical solutions for a given product. The overall theory of MFD is that increased product modularity improves the total flow of information and materials -- from development and purchasing to storage and delivery. The disadvantage of MFD is that it does not solve the issue of individual variance created in the ranking system. (Erixon, 2006)

QFD has also been applied with Lean Design/Implementation to find a process that creates a product or service that meets customer needs effectively and efficiently, reducing both variance and lead time. In fact, QFD is included in some Lean Product Development Workshops (DRM Associates, 2006). The existing tools to determine where to implement lean in a process are lengthy and require assessing the entire process. Some existing assessment processes include time-consuming value stream mapping (mapping out the entire production path), a possible interview, a metric analysis to determine bottlenecks, etc. (Sahwney, 2006).

Objective

Lean Function Deployment (LFD) was developed in response to the need for a tool that determines the lean implementation point using a customer perspective. LFD is a method developed by combining the underlying principles of deployment and lean to detect where to implement lean in a process. The LFD methodology is an algorithm that determines the critical-to-quality (CTQ) and the critical to lead-time process steps in the production of a product. LFD mitigates the problems of QFD by using a consistent and defined ranking system with paired comparison to quantify results. It also uses the relative differences between relationships to reduce subjectivity. LFD is more efficient than current lean implementation methods because only the critical process steps are identified. A critical process step is a dependent process step that will affect the process as a whole.

Method

Lean Function Deployment Methodology

The LFD process includes two phases. Phase I determines the critical-to-quality process steps using a customer interface, and four sub-phases. The sub-phases are exploded, which means that the output from one sub-phase determines the output for the next sub-phase. Sub-phase 1 relates each customer need to product technical characteristics. Sub-phase 2 then relates each technical characteristic to the product part characteristics. Sub-phase 3 relates each product's part characteristics to the process parameters required to achieve that characteristic. Sub-phase 4 relates each process parameter to a process step in product production. An example of the defined customer needs, technical characteristics, part characteristics, process parameters, and process steps using a piston head casting is shown in

Figure 1. The example will be referenced throughout the paper.

LFD Phase II determines the critical-to-lead-time processes. The final output includes a quality weight determined in Phase I and a percentage lead-time for the total process time defined. The final weightings and percentages for the critical process steps are combined to determine where lean implementation should begin in the production process. The scope of the lean deployment in LFD is from raw materials to finished goods.

Customer Needs	
N1	External shape slip fits to cyclinder
N2	Compression rings fit to compression grooves
N3	Oil ring press fit to oil groove
N4	Surface is wear resistant
N5	Clearance between pin and wrist pin hole allows for adequate lubrication

Phase 1 Tech Characteristics	
TC1	Skirt Thickness
TC2	Skirt Surface finish
TC3	Compression Ring Dimensions
TC4	Oil Ring Dimensions
TC5	Wrist-pin hole dimensions

Phase 2 Part Characteristics	
PC1	Radius of Piston Dome (1.816 in.)
PC2	Casting Thickness beyond nominal (0.0625 in)
PC3	Compression Ring 1 Depth (0.1505 in)
PC4	Compression Ring 2 Depth (0.2125 in)
PC5	Compression Ring Width (0.0430 in)
PC6	Oil Ring Width (0.0990 in)
PC7	Oil Ring Depth (0.1405 in)
PC8	Diameter of the wrist-pin hole (0.9390 in)

Phase 3 Process Parameters	
PP1	Piston Radius Tolerance (0.0005 in)
PP2	Compression Ring Tolerance (0.0001 in)
PP3	Oil Ring Tolerance (0.0001 in)
PP4	Wrist-pin hole tolerance (0.00075 in)

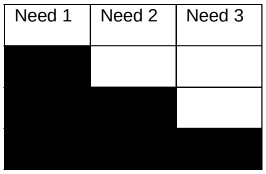
Phase 4 Process Steps	
PS1	Surface Finishing
PS2	Lathing of Compression Grooves
PS3	Lathing of Oil Groove
PS4	Hole Finishing

Figure 1. Piston Head LFD Phase I

Phase I. Determine CTQ Processes

Customer Interface

In Phase I the importance weights of each customer need are determined. The customer is asked by an administrator to complete a series of questions obtained from a paired comparison matrix like the one in Figure 2. For the paired comparison, the customer starts with the need in the first row and compares that need to the needs in each column.



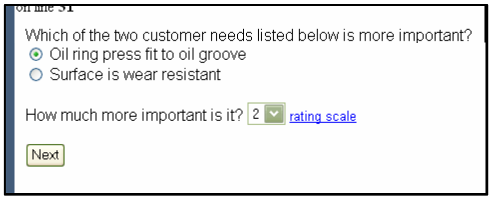
Need 1	Need 2	Need 3
■		
■	■	
■	■	■

Figure 2. Paired Comparison Matrix

The customer needs in the matrix are determined through prior survey research or through historical customer relationships. The computer application of the LFD converts the matrix form of the paired comparison into a question-answer format shown in Figure 3. The computer interface asks the customer which need is more important and then the customer inputs by how much the need chosen is more important using the following rating scale:

- 0 Importance difference is negligible
- 1 Importance difference is marginal
- 2 Importance difference is substantial
- 3 Importance difference is extreme

The customer must specify the importance difference and answer an importance question for each pair of needs.



Which of the two customer needs listed below is more important?

● Oil ring press fit to oil groove

○ Surface is wear resistant

How much more important is it? 2

Figure 3. Customer Question-Answer Format

The customer inputs are converted to AHP matrix form in order to determine importance weights for each customer need and to complete a consistency check on the customer ratings. If the consistency check is not within specification, then the process is stopped until better data on need importance is obtained from the customer.

Sub-phase 1. Technical Characteristics

After the customer need weights (wn_i) are determined, the weights are stored for future calculations. An engineer or a group familiar with the production of the product determines the technical characteristics (TC) associated with each customer need. A technical characteristic is defined as the deliverable of the part or *what we want it to do*.

A paired comparison analysis is completed by the engineer for **each** set of technical characteristics associated with **each** need. For example, the piston head has five customer needs, so there will be five technical characteristic paired comparisons completed by the engineer. The LFD computer application simplifies the process by asking the user which TC is more important than the other TC as related to the specified need similar to the format in Figure 3. Using the piston example, the user will be asked *Which of the two technical characteristics fulfills Need 1 more?* for each pair of technical characteristics. Before the user completes the series of questions, the user will specify whether the relationship between the need and technical characteristic is zero, thus reducing the number of questions the user must answer. The user indicates by how much the chosen TC fulfills the need using the following rating scale:

- 0 Need is not fulfilled at all by TC
- 1 Need is marginally fulfilled by TC
- 2 Need is adequately fulfilled by TC
- 3 Need is substantially fulfilled by TC

Once the user has completed the series of questions regarding which TC fulfills each need more adequately and by how much using the rating scale, the customer need weights are used in conjunction with paired comparison scoring to determine each technical characteristic weight (wtc_i). Therefore, the weights from the customer needs are carried through sub-phase 2 to determine the TC importance. Likewise, the TC weights will be used to determine the part characteristic (PC) weights in Sub-phase 3.

The calculation to determine the technical characteristic weights is summarized in Figure 4. The score matrix limits the technical characteristics to two instead of five as specified in Figure 1 for the piston head. Each customer need weight (wn_i) in the top row is multiplied by the score for each technical characteristic as it relates to each need. The relative differences indicated by the user are added to determine the scores in the rows for Skirt thickness and Skirt Surface finish. The need weights are all 0.2 for simplicity in explaining how to determine the technical characteristic weights. The *Total TC* score for Skirt Thickness is found by adding $0.2*0 + 0.2*1 + 0.2*3 + 0.2*6 + 0.2*3 = 2.4$. The final technical characteristic weight for Skirt Thickness is found by dividing the individual *Total TC* score (2.4) by the sum of all *Total TC* scores (4.2) for all technical characteristics. The weight determined in Figure 4 for Skirt Thickness is 0.571 (2.4/4.2).

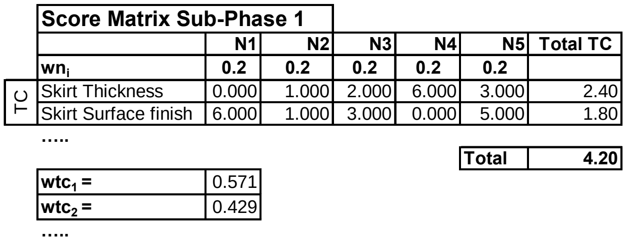
Sub-phase 2. Part Characteristics

After the TC weights (wtc_i) are determined, the weights are stored for the part characteristic weight calculations at the end of sub-phase 2. In sub-phase 2, the part characteristics (PC) are determined for each technical characteristic. A technical characteristic is defined as the deliverable of the part or *what we want it to do*. Therefore, a part characteristic is defined as the attribute of the part that meets that deliverable or *how the part or product does what we want it to do.* Referring to the piston example in Figure 1, the technical characteristic of Skirt Surface Finish will perform to specifications only if the casting thickness beyond the nominal dimension is known. Casting Thickness meets the deliverable of Surface Finish.

A question-answer analysis is completed by the engineer for **each** set of TC's associated with **each** part characteristic. For example, the piston head has 5 TC's, so there will be 5 PC question-answer analyses completed by the engineer. The user begins another series of questions to determine which part characteristic better fulfills each TC and by how much the part characteristic better fulfills the technical characteristic using a similar rating scale:

- 0 TC is not fulfilled at all by PC
- 1 TC is marginally fulfilled by PC
- 2 TC is adequately fulfilled by PC
- 3 TC is substantially fulfilled by PC

The scores related to each part characteristic are summed, and a weighted PC score is determined as it was determined in Figure 4 for the technical characteristics. Each technical characteristic weight is multiplied by the PC score and a part characteristic weight is determined.



Score Matrix Sub-Phase 1

		N1	N2	N3	N4	N5	Total TC
	wn_i	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	
TC	Skirt Thickness	0.000	1.000	2.000	6.000	3.000	2.40
	Skirt Surface finish	6.000	1.000	3.000	0.000	5.000	1.80
	…..						
						Total	**4.20**

wtc_1 =	0.571
wtc_2 =	0.429
…..	

Figure 4. Determining Technical Characteristic Weights

Sub-phase 3-4. Process Parameters/Steps

In a fashion similar to that in sub-phases 1 and 2, the same process is repeated for process parameters and process steps. The part characteristic weights are used to determine the expected process parameter scores and process parameter weights. The process parameter is defined as *how the desired attribute is acquired.*

The process parameter final weights are used to determine the expected process step scores and process step weights. The process step is defined as *the application within which the process parameter is required in part or product production*.

Phase I Output

The final outputs for Phase I are the critical-to-quality processes required for the production of a part and the corresponding weights of quality importance (Q) as they ultimately relate back to the customer. A sample output for LFD Phase I using the piston example is in Figure 5.

Process Steps	**Q_i**
Surface Finishing	0.06
Lathing of Compression Grooves	0.37
Lathing of Oil Groove	0.39
Hole Finishing	0.18

Figure 5. Sample Output For LFD Phase 1

The Q's define the first part of the weighting system used to determine the lean implementation point in a process. The next components required before determining the lean penetration point are the critical-to-lead time processes.

Phase II. Determine Critical-to-Lead Time Processes

Determine Process times for CTQ Processes

The process step results from Phase I are carried into Phase II. The CTQ process steps are assigned process times as shown in Figure 6 because they could also be critical to lead time. The time for each step is the time required to complete the step during the production of one part.

CTQ Process Steps	**Time (sec)**
Surface Finishing	6
Lathing of Compression Grooves	3
Lathing of Oil Groove	10
Hole Finishing	3

Figure 6. Process Times for CTQ Process Steps

Determine Process times for Delay Processes

The CTQ Process steps do not account for all process steps critical to lead time, so the delay processes in part production must also be identified. A delay process (DP) is a process that links the CTQ process steps in part production, and more than one delay process can link two CTQ process steps. The delay processes are defined for the piston head in Figure 7. Figure 8 defines the delay process.

Piston Delay Processes	**Time (sec)**
Place Bung and Load into Turning Center	20
Tooling Change	0.5
Unload from Turning Center	7
Inspection Surface Finish and Grooves	12
Load from Turning Center to JIG	7
Inspection Hole	12
Unload and Place on Conveyer	2

Figure 7. Delay Processes for the Piston Head

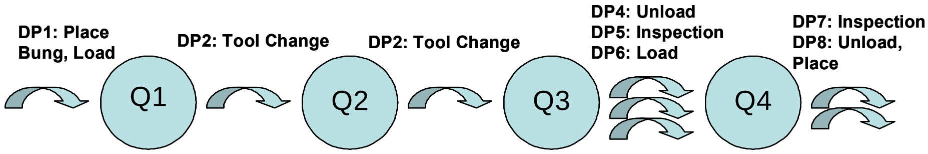


Figure 8. Clarification of Delay Processes

Piston Processes (Time > TAC)		Q	L	Total
Q_3	Lathing of Oil Groove	0.39	0.121	0.168
DP_1	Place Bung and Load into Turning Center	0	0.242	0.242
DP_5	Inspection Surface Finish and Grooves	0	0.145	0.145
DP_7	Inspection Hole	0	0.145	0.145

Figure 9. Sample LFD Final Output

Determine Lean Implementation Point

The first step in identifying the lean implementation point is defining the desired takt time based on customer demand. The takt time is the rate that a completed product is produced off the line. The takt time for the piston example is determined from a customer demand of 2000 parts per day. Based on a 6.5 hour production day with one hour inspection, the takt time is 9.9 seconds (5.5*3600/2000). Therefore, a completed piston should be finished every 9.9 seconds to meet customer demand.

If the CTQ process step time or the delay process step time is greater than the takt time, then the corresponding process step time is used when determining the lean implementation point. If there are no process steps with times greater than the takt time, then all process steps are used in the final scoring based on quality and lead time.

Each process can be assigned two factors to determine the point of lean implementation in a process. Each CTQ process step is assigned the Q value or the critical to quality weight factor found in Phase I. The delay processes are assigned Q values of zero because they are not CTQ. Then, an L value or the percentage of the defined lead time or the process step time over the total defined process time is determined. The piston example final ratings are in Figure 9. Q determines the weight given to the process time percentage so the L value of 0.121 is multiplied by 1+Q (1.39) to obtain the final process time percentage of 0.168. The highest possible score for a process is 1. The score for the Placement of the Bung Hole and Loading the Part into the Turning Center is determined as the point of lean implementation with the highest process time percentage of 24.2 percent.

Analysis

LFD Phase I relates customer needs to process parameters, and QFD also relates customer needs to process parameters. The output of both tools is the importance of process parameters related to customer needs, but the techniques use different algorithms. Therefore, the LFD Phase 1 output can be compared to the QFD output. The outputs were compared to determine if LFD reduces variation in importance rankings between process parameters.

Since the ending numbers for both tools are different, the rankings and not the end values were added, and the variance was determined between the sums of the rankings for each parameter. The resulting weights for process parameters in LFD Phase I were ranked using a scale from one to the number of process parameters defined by giving the highest resulting weight a rank of one.

Eight subjects were asked to do a QFD and an LFD for the same product. The resulting variance between rankings for the eight product process parameters are in columns two and three of Figure 10. The LFD Phase I variance for each process parameter is lower for each rating except process parameter five (only 0.09). The F-test results show that the variance among rankings for process parameters seven and eight is significantly lower using LFD than the variance using QFD with a significance level of 0.05. Process parameters two and six are almost significantly lower in variance. Therefore, four out of the eight process parameter rankings have a considerable decrease in variance using LFD.

Because there is a decrease in variance for almost each process parameter ranking using

LFD, there should be an increase in the distinction between ratings. This means that there should be an increase in the overall variance among all process parameters. The proof of increased rating distinction with LFD is seen by examining the overall standard deviation for each process and the ranking ranges.

The standard deviation in rankings for all process parameters is 15.63 ranking points using LFD, and is 7.005 ranking points using QFD. Consequently, the variance is 244 and 49.09 respectively. The range of ranking sums for process parameters is 11 to 53 ranking points for LFD, and only 25 to 44 ranking points for QFD. The larger range in the ranking sums means that the rankings are more uniform for each parameter among subjects using LFD. The rankings were summed so that a large range means that the process parameters were consistently ranked as high or low using the LFD method. The smaller range using QFD means that the rankings were more evenly spread between each parameter, and there was not a distinctive set of parameters ranked as high and low. **Since the range between ranking sums for each parameter is larger using LFD, there is more distinction between rankings to determine process parameter importance.**

Application

A Web site has been developed for the use of Lean Function Deployment, as was mentioned previously in the discussion of the tool. The computer application allows a user to easily go through the LFD process by inputting the customer needs, technical characteristics, process parameters, and process steps as well as the associated process times and delay process times. The program will provide the user with the CTQ weights (Q's) and the percent lead time defined for the process. The user can start a new project by entering his or her username and password.

Visit www.leanfd.com and enter the username *guest* and password *user* to see the piston LFD used for explanation in the method section of the paper.

Test Results LFD versus QFD			
Parameters	**Phase I σ^2**	**QFD σ^2**	**F-Test P-value**
1	3.07	4.41	0.645
2	1.64	6.41	**0.093**
3	1.55	3.71	0.273
4	3.13	5.07	0.538
5	3.07	2.98	0.970
6	0.98	3.55	**0.111**
7	0.27	2.29	**0.011**
8	0.27	2.50	**0.009**

Figure 10.

Conclusion

LFD detects the lean implementation point with a greater distinction than provided by QFD methods between CTQ process ratings. LFD uses a customer perspective, and it determines the lean implementation point in less time than existing methods because the algorithm determines only the CTQ and critical-to-lead time processes. The LFD tool output is the part of the process where lean should be implemented, so the use of tool results is very clear. LFD is a scientific and pragmatic alternative that appears more efficient than QFD in conjunction with value-stream mapping.

References

Badiru, Adedeji B. Handbook of Industrial and Systems Engineering. Taylor & Francis Group, LLC, 2006. ENGnetBASE. Hodges Library, Knoxville, TN. 20 Nov. 2006.

Crow, Kenneth. "Customer-Focused Development with QFD." DRM Associates. Fall 2006. 30 Aug. 2006 <http://www.npd-solutions.com/qfd.html>.

DRM Associates. "LEAN PRODUCT DEVELOPMENT WORKSHOP." npd-solutions. 2006. 20 Nov. 2006 <http://www.npd-solutions.com/.html>.

Ericsson, Anna, and Gunnar Erixon. Controlling Design Variants: Modular Product Platforms . Dearborn: Society of Manufacturing Engineers, 1999.

Erixon, Gunnar. "Modular Function Deployment (MFD), Support for Good Product Structure Creation." WDK. Centre for Industrial Engineering at Dalarna University and KTH, Stockholm. 28 Nov. 2006 <http://users.du.se/~gex/paper/wdk.html>.

Katz, Gerald M. "After QFD: Now What?" visions. 20 Nov. 2006 <http://www.pdma.org//.php?doc=apr01/_qfd.html>.

LU, Min Hua, et al. "Integrating QFD, AHP and Benchmarking n Strategic Marketing." Journal of Business & Industrial Marketing 9.1 (1994): 41-50.

Sawhney, Rupy. "IE 401." Department of Industrial Engineering at the University of Tennessee. University of Tennessee. Fall 2006.

Winston, Wayne L. Operations Research. Toronto: Thomson, 2004.

Biographical Sketch

The group was created from the Fall 2006 Integrated Manufacturing Systems class under the instruction of Dr. Rupy Sawhney. Each member is an upperclassman in the Industrial Engineering Department at the University of Tennessee in Knoxville. With each class project, each member's teamwork skills were further developed in conjunction with working towards the objectives of the course.