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# PERFORMANCE MEASUREMENT IN A CLOSED-LOOP SUPPLY CHAIN NETWORK

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## INTRODUCTION

An effective management of supply chain is a key factor for the better realization of organizational goals and customer expectations. In the era of globalization of markets and business process outsourcing, many firms realize the importance of continuous monitoring of their supply chain's performance for its effectiveness and efficiency [1]. In the modern era, performance measurement has a far more significant role than just quantification and accounting. It provides the management important feedback to monitor performance, reveal progress, diagnose problems and enhances transparency among the several tiers of the supply chain thus making a phenomenal contribution to decision making particularly in re-designing business goals and strategies and re-engineering processes [2], [3]. Developing the performance measurement systems is a difficult aspect of performance measure selection. It involves the methods by which an organization creates its measurement system. Important questions that need to be addressed include: What to measure? How often to measure? How are multiple individual measures integrated into a measurement system? [4].

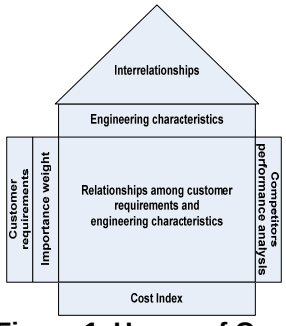
A reverse supply chain consists of a series of activities required to retrieve a used-product from a consumer and either recover its left over market value or dispose it off. The combination of traditional/forward supply chain and reverse supply chain forms the closed-loop supply chain (CLSC). While this process is mandatory in many European nations, it is still in its infancy in the United States. Due to the inherent differences in various aspects between the forward and the reverse supply chains, the performance metrics and evaluation techniques used in traditional supply chain cannot be extended to the reverse supply chains.

## METHODOLOGY

In this chapter, we identify appropriate performance metrics and their enablers for a reverse/closed-loop supply chain environment and propose a linear physical programming (LPP) based quality function deployment optimization approach to evaluate a reverse/closed-loop supply chain network for its performance. A numerical example is considered to illustrate the methodology.

## APPLYING LPP TO QFD

Quality function deployment (QFD) developed by Yoji Akao in the 1960s, links the customer requirements with design, development, engineering, manufacturing and service functions. QFD can be viewed as a comprehensive quality system for customer satisfaction. The house of quality (HOQ) (figure 1) shows the customer requirements, engineering characteristics, their interrelationships and the competitor's performance analysis. HOQ is used to assist in converting the customer's demands to substitute quality characteristics. Figure 2 illustrates the steps involved in applying LPP to QFD optimization [5]. The roof of the HOQ shows the interrelationships among the performance metrics ($=\gamma_{jk}$ correlation between the $j^{th}$ and $k^{th}$ performance metrics). These relationships are based on the knowledge and experience of the design team.



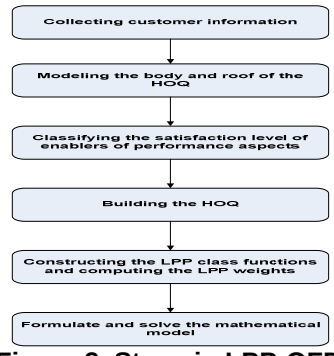




**Figure 1. House of Quality** **Figure 2. Steps in LPP-QFD Optimization**

The body of the HOQ shows the relationships between performance metrics and enablers. $R_{ik}$ denotes the relationship between $i^{th}$ enabler and $j^{th}$ performance metric. These relationships are evaluated in a scale (1-9), while one represents the weakest relationship, nine represents the strongest relationship. In order to quantify the impact of the dependencies between the engineering characteristics on the relationship between the customer requirements, the model transformation shown in equation (10.1) is used.

$$R_{ij}^{norm} = \frac{\sum_{k=1}^{n} R_{ik}\gamma_{kj}}{\sum_{j=1}^{n}\sum_{k=1}^{n} R_{ij}\gamma_{jk}}, i = 1,2,..., m; j = 1,2,..., n \quad (1)$$

where, $R_{ij}^{norm}$ can be interpreted as the incremental change in the level of fulfillment of the $i^{th}$ enabler when the $j^{th}$ performance metric is satisfied to a certain level; $m$ is the number of enablers and $n$ is the number of performance metrics. Using LPP, the satisfaction level of each customer requirement is classified in one of the six different ranges, namely, ideal, desirable, tolerable, undesirable, highly undesirable and unacceptable. The bottom of the HOQ shows the cost index ($c_j$) for each performance metric, which indicates the cost involved in achieving the maximum value of that performance metric.

## PERFORMANCE METRICS AND ENABLERS IN A CLOSED-LOOP SUPPLY CHAIN

The following are the performance metrics (PM) and enablers were identified in our methodology:

1. *Reputation*: This metric deals with the firms overall reputation in the industry. It is driven by enablers such as on-time delivery ratio, returning customer's ratio, the firms 'green image' etc. Green image can be measured in a number of different ways like the environmental expenses incurred or the amount of waste disposed or the fairs/symposiums related to environmentally conscious manufacturing the firm participates in etc. In our methodology, we consider the amount of waste disposed to measure the 'green-image'.
2. *Innovation and Improvement*: This metric is driven by enablers such as R&D expenses ratio, the number of new products and processes launched etc.
3. *Public Participation*: This metric is a measure of the firms marketing capabilities can be driven by enablers such as flexibility, or the firm's ability to handle uncertainties, after sales service efficiency and the markets targeted (markets targeted is quantified as the percentage of customers that are knowledgeable about the firms product, the more knowledgeable the better is the participation and better can be the customer service). After sales service efficiency can be defined as the ratio between the number of customers, seeking customer service to the total number of customers served.

4. *Facility Potentiality*: Potentiality of the remanufacturing facilities can be driven by several enablers such as the location of the facilities, the increment in the quality of products remanufactured (=quality of outgoing – quality of incoming products), disassembly time multiplied by the throughput, throughput divide by the supply of used-products, usage of automated disassembly systems etc. We quantify *location* by specifying it as the distance from the customer/markets/or the nearest major city and *usage of automated disassembly systems* as the amount of money spent on automated disassembly systems.
5. *Responsiveness*: This metric reflects how well the firm responds to the ever-changing customer specifications, as well as their level of customer service and can be driven by enablers such as flexibility, or the firm's ability to handle uncertainties and the firms after sales service efficiency. We quantify *flexibility* by the number of different varieties of products the firm manufactures/remanufactures.
6. *Delivery Reliability*: This metric reflects how well the firm meets the due dates specified by the customers and can be driven by enablers such as the effectiveness of the firms master production schedule, the usage of automated disassembly systems, the supply of used-products, the quality of used-products etc. Effectiveness of firms master production schedule can be defined, as the ratio of the number of orders delivered no later than due date to the total number of orders delivered.

Other operational metrics such as resource utilization, cost per operating hour and manufacturing lead-time that are self-explanatory are also considered in our study. For brevity purpose, the performance metrics and enablers are not explained in detail.

## MATHEMATICAL MODEL FORMULATION

The LPP problem is formulated as:

$$Minimize \quad \sum_{i=1}^{m} \sum_{s=2}^{5} \left[ \tilde{w}_{is}^{-} d_{ps}^{-} + \tilde{w}_{is}^{+} d_{ps}^{+} \right] \tag{2}$$

where, $\tilde{w}_{is}$ represents the LPP weights obtained using the algorithm presented in [6], $d_{ps}$ represent the deviations of the enablers from their target values.

Subject to

$$\sum_{j=1}^{n} R_{ij}^{norm} - d_{is}^{+} \le t_{i(s-1)}^{+} \quad and \quad \sum_{j=1}^{n} R_{ij}^{norm} \le t_{i5}^{+}, (for\ all\ i\ in\ classes\ \ 1S, 3S, 4S, i = 1,2,.., n_{sc}; s = 2,..,5) \tag{3}$$

$$\sum_{j=1}^{n} R_{ij}^{norm} + d_{is}^{-} \ge t_{i(s-1)}^{-} \quad and \quad \sum_{j=1}^{n} R_{ij}^{norm} \ge t_{i5}^{-}, (for\ all\ i\ in\ classes\ \ 2S, 3S, 4S, i = 1,2,.., n_{sc}; s = 2,..,5) \tag{4}$$

$$B \ge \sum_{j=1}^{n} c_j x_j \tag{5}$$

where, $c_j$ is the achievement level of performance metric $j$ and $c_j x x_j$ represents the budget allocation to the performance metric $j$, B is the maximum available budget (=19000 in our illustrative example).

$$d_{is}^{+} \ge 0; d_{is}^{-} \ge 0 \tag{6}$$

$$0 \le x_j \le 1 \tag{7}$$

Apart from the goal constraints mentioned above, we consider the following system constraints also in our methodology:

$$x_{potentiality} \le 0.85 \tag{8}$$

$$x_{\mathrm{Re}\,sourceUtilization} \le 0.8 \tag{9}$$

$$\sum_{j} R_{Ontime\ \ Delivery\ \ Ratio,j}^{norm} x_j \ge 0.65 \tag{10}$$

Using equation (1), the relationships between performance metrics and enablers are normalized and the normalized scores form the body of the HOQ. Table 1 shows the HOQ for the performance measurement. For simplicity, the roof has been removed after normalizing $R_{ij}$ .

## Table 1. House of Quality for Performance Measurement

| **PM** | Reputation | I&I | PP | RES | FP | DR | RU | C/Oh | MLT | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Enablers** | | | | | | | | | | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
| On-time Delivery Ratio | 0.138 | 0.091 | 0.087 | 0.093 | 0.134 | 0.114 | 0.12 | 0.106 | 0.114 | 100 | 80 | 75 | 65 | 50 |
| Returning Customers Ratio | 0.142 | 0.092 | 0.097 | 0.091 | 0.131 | 0.101 | 0.116 | 0.881 | 0.111 | 100 | 90 | 80 | 75 | 65 |
| Green Image | 0.117 | 0.093 | 0.096 | 0.084 | 0.112 | 0.102 | 0.098 | 0.098 | 0.113 | 0 | 1200 | 1500 | 2000 | 2500 |
| R&D Expenses Ratio | 0.128 | 0.075 | 0.091 | 0.078 | 0.12 | 0.101 | 0.102 | 0.093 | 0.102 | 50 | 45 | 40 | 35 | 30 |
| | | | | | | | | | | 60 | 65 | 75 | 80 | 100 |
| New Products/Processes | 0.122 | 0.078 | 0.09 | 0.085 | 0.109 | 0.095 | 0.102 | 0.082 | 0.098 | 20 | 15 | 10 | 8 | 5 |
| | | | | | | | | | | 25 | 30 | 35 | 40 | 45 |
| Flexibility | 0.128 | 0.091 | 0.092 | 0.085 | 0.105 | 0.106 | 0.1 | 0.083 | 0.098 | 65 | 55 | 50 | 40 | 35 |
| After Sales Service Efficiency | 0.122 | 0.083 | 0.08 | 0.088 | 0.109 | 0.106 | 0.096 | 0.104 | 0.095 | 100 | 85 | 75 | 60 | 50 |
| Markets Targeted | 0.128 | 0.083 | 0.075 | 0.0884 | 0.115 | 0.109 | 0.1 | 0.102 | 0.096 | 100 | 80 | 75 | 60 | 55 |
| TP*DT | 0.13 | 0.087 | 0.078 | 0.082 | 0.126 | 0.104 | 0.116 | 0.1 | 0.181 | 100 | 90 | 80 | 75 | 65 |
| TP/SU | 0.135 | 0.084 | 0.08 | 0.08 | 0.126 | 0.109 | 0.116 | 0.102 | 0.11 | 100 | 95 | 85 | 70 | 65 |
| QO-QI | 0.124 | 0.087 | 0.078 | 0.079 | 0.12 | 0.104 | 0.111 | 0.1 | 0.111 | 65 | 60 | 50 | 45 | 40 |
| Effectiveness of MPS | 0.135 | 0.088 | 0.075 | 0.083 | 0.131 | 0.102 | 0.115 | 0.102 | 0.107 | 100 | 85 | 75 | 70 | 65 |
| Facility Location | 0.125 | 0.076 | 0.079 | 0.078 | 0.126 | 0.102 | 0.108 | 0.088 | 0.102 | 35 | 30 | 25 | 20 | 15 |
| | | | | | | | | | | 20 | 25 | 35 | 40 | 50 |
| Labor Cost | 0.125 | 0.09 | 0.082 | 0.079 | 0.121 | 0.108 | 0.113 | 0.094 | 0.112 | 20 | 25 | 35 | 40 | 50 |
| Usage of Automated DA Systems | 0.13 | 0.094 | 0.078 | 0.081 | 0.124 | 0.103 | 0.112 | 0.097 | 0.105 | 1000 | 750 | 600 | 500 | 250 |
| | | | | | | | | | | 2000 | 2500 | 3500 | 4000 | 5000 |
| **Cost Index** | 4000 | 2500 | 2000 | 2500 | 2500 | 3000 | 2000 | 2000 | 2000 | | | | | |

Table 2 shows the normalized LPP weights of the enablers (1S, 2S, 4S represent the LPP classes the enablers were classified into) obtained using the algorithm presented in [6].

## Table 2. Normalized LPP Weights of Enablers

| Enablers | Weights | | | |
|---|---|---|---|---|
| On-time Delivery Ratio (2S) | $\tilde{w}_{12}^{-}$ =0.000068 | $\tilde{w}_{13}^{-}$ =0.00414 | $\tilde{w}_{14}^{-}$ =0.028 | $\tilde{w}_{15}^{-}$ =0.967 |
| Returning Customers Ratio (2S) | $\tilde{w}_{22}^{-}$ =0.000224 | $\tilde{w}_{23}^{-}$ =0.0034 | $\tilde{w}_{24}^{-}$ =0.034 | $\tilde{w}_{25}^{-}$ =0.956 |
| Green Image (1S) | $\tilde{w}_{32}^{+}$ =0.000114 | $\tilde{w}_{33}^{+}$ =0.006 | $\tilde{w}_{34}^{+}$ =0.05 | $\tilde{w}_{35}^{+}$ =0.93 |
| R&D Expenses Ratio (4S) | $\tilde{w}_{42}^{-}$ =0.0002 | $\tilde{w}_{43}^{-}$ =0.003 | $\tilde{w}_{44}^{-}$ =0.06 | $\tilde{w}_{45}^{-}$ =0.93 |
| | $\tilde{w}_{42}^{+}$ =0.001 | $\tilde{w}_{43}^{+}$ =0.0073 | $\tilde{w}_{44}^{+}$ =0.251 | $\tilde{w}_{45}^{+}$ =0.74 |
| New Products/Processes (4S) | $\tilde{w}_{52}^{-}$ =0.00016 | $\tilde{w}_{53}^{-}$ =0.0023 | $\tilde{w}_{54}^{-}$ =0.094 | $\tilde{w}_{55}^{-}$ =0.9 |
| | $\tilde{w}_{52}^{+}$ =0.00027 | $\tilde{w}_{53}^{+}$ =0.0034 | $\tilde{w}_{54}^{+}$ =0.06 | $\tilde{w}_{55}^{+}$ =0.935 |
| Flexibility (2S) | $\tilde{w}_{62}^{-}$ = 0.00041 | $\tilde{w}_{63}^{-}$ =0.0122 | $\tilde{w}_{64}^{-}$ =0.084 | $\tilde{w}_{65}^{-}$ =0.902 |
| After Sales Service Efficiency (2S) | $\tilde{w}_{72}^{-}$ =0.000183 | $\tilde{w}_{73}^{-}$ =0.0043 | $\tilde{w}_{74}^{-}$ =0.039 | $\tilde{w}_{75}^{-}$ =0.956 |

| | | | | |
|---|---|---|---|---|
| Markets Targeted (2S) | $\tilde{w}^{-}_{82}$ =0.00006 | $\tilde{w}^{-}_{83}$ =0.00414 | $\tilde{w}^{-}_{84}$ =0.0174 | $\tilde{w}^{-}_{85}$ =0.97 |
| TP*DT (2S) | $\tilde{w}^{-}_{92}$ =0.000274 | $\tilde{w}^{-}_{93}$ =0.0039 | $\tilde{w}^{-}_{94}$ =0.125 | $\tilde{w}^{-}_{95}$ =0.87 |
| TP/SU (2S) | $\tilde{w}^{-}_{102}$ =0.00028 | $\tilde{w}^{-}_{103}$ =0.0018 | $\tilde{w}^{-}_{104}$ =0.019 | $\tilde{w}^{-}_{105}$ =0.97 |
| QO-QI (2S) | $\tilde{w}^{-}_{112}$ =0.00028 | $\tilde{w}^{-}_{113}$ =0.0018 | $\tilde{w}^{-}_{114}$ =0.06 | $\tilde{w}^{-}_{115}$ =0.935 |
| Effectiveness of MPS (2S) | $\tilde{w}^{-}_{122}$ =0.00009 | $\tilde{w}^{-}_{123}$ =0.002 | $\tilde{w}^{-}_{124}$ =0.06 | $\tilde{w}^{-}_{125}$ =0.935 |
| Facility Location (4S) | $\tilde{w}^{-}_{132}$ =0.000274 | $\tilde{w}^{-}_{133}$ =0.0039 | $\tilde{w}^{-}_{134}$ =0.06 | $\tilde{w}^{-}_{135}$ =0.93 |
| | $\tilde{w}^{+}_{132}$ =0.00054 | $\tilde{w}^{+}_{133}$ =0.0036 | $\tilde{w}^{+}_{134}$ =0.125 | $\tilde{w}^{+}_{135}$ =0.87 |
| Labor Cost per hour (1S) | $\tilde{w}^{+}_{142}$ =0.0006 | $\tilde{w}^{+}_{143}$ =0.006 | $\tilde{w}^{+}_{144}$ =0.05 | $\tilde{w}^{+}_{145}$ =0.94 |
| Usage of Automated DA Systems (4S) | $\tilde{w}^{-}_{152}$ =0.0002 | $\tilde{w}^{-}_{153}$ =0.006 | $\tilde{w}^{-}_{154}$ =0.155 | $\tilde{w}^{-}_{155}$ 0.83 |
| | $\tilde{w}^{+}_{152}$ =0.0005 | $\tilde{w}^{+}_{153}$ =0.003 | $\tilde{w}^{+}_{154}$ =0.125 | $\tilde{w}^{+}_{155}$ =0.87 |

The model is solved using LINGO 8, tables 3 and 4 shows the results. Table 3 shows the budget allocation and the achievement levels of performance metrics and Table 4 shows the satisfaction levels of the enablers ($=\sum_j R_{ij}^{norm} x_j$).

**Table 3. Budget Allocation and Achievement Levels of Performance Metrics**

| | Reputation | I&I | Public Participation | Responsiveness | Facility Potentiality | Delivery Reliability | Resource Utilization | Cost/Op.hr | Manufacturing Lead Time |
|---|---|---|---|---|---|---|---|---|---|
| Budget Allocation | 1272 | 2500 | 2000 | 2500 | 2125 | 2700 | 1600 | 2000 | 1520 |
| Achievement Level ($x_i$) | 0.318 | 1.0 | 1.0 | 1.0 | 0.85 | 0.9 | 0.8 | 1.0 | 0.76 |

**Table 4. Enabler satisfaction Levels**

| Enabler | Satisfaction Level (%) |
|---|---|
| On-time Delivery Ratio | 82.21 |
| Returning Customers Ratio | 82.18 |
| Green Image | 77.27 |
| R&D Expenses Ratio | 72.84 |
| New Products/Processes | 73.35 |
| Flexibility | 73.74 |
| After Sales Service Efficiency | 73.07 |
| Markets Targeted | 72.41 |
| TP*DT | 81.82 |
| TP/SU | 76.42 |
| QO-QI | 76.53 |
| Effectiveness of MPS | 76.73 |
| Facility Location | 74.49 |
| Labor Cost per hour | 76.20 |
| Usage of Automated DA Systems | 74.28 |

## CONCLUSIONS

Traditionally, performance measurement is defined as the process of quantifying the effectiveness and efficiency of action. Developing the performance measurement systems is a difficult aspect of performance measure selection. Due to the inherent differences in various aspects between the forward

and the reverse supply chains, the performance metrics and evaluation techniques used in traditional supply chain cannot be extended to the reverse supply chains. Customer satisfaction is an indication of the standard level of service, however, for different industries, customers look at different measures. Thus, the weighting of each performance measurement is industry specific. To this end, in this chapter, we identified some of the important performance metrics and their enablers in a reverse/closed-loop supply chain environment and employed a linear physical programming based quality function deployment optimization approach to evaluate a reverse/closed-loop supply chain for its performance.

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