A DECISION MATRIX BASED METHOD FOR DETERMINING PRIORITIES OF QUALITY IMPROVEMENT PROJECTS IN MANUFACTURING WITH INSPECTION ERROR AND REWORK

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ABSTRACT

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Today's competitive environments and heightened expectation of customers make it necessary to improve quality of products and processes continuously. Therefore, quality improvement is a major concern for companies. Determining improvement priorities for not only long but also short term bottom line results is a key problem in quality improvement management. In this thesis a practical decision matrix based method is developed for selecting quality improvement projects by considering throughput and quality loss in manufacturing environments with inspection error and rework. Performance of the proposed method under different experimental conditions is analyzed and results are discussed.

Keywords: Quality Improvement, Inspection Error, Rework, Quality Loss, Decision Matrix

ÖZ

MUAYENE HATASI VE YENİDEN İŞLEMENİN OLDUĞU İMALAT ORTAMLARINDA KALİTE İYİLEŞTİRME PROJELERİNİN ÖNCELİKLENDİRİLMESİ İÇİN KARAR MATRİSİ TEMELLİ BİR YÖNTEM

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Günümüzün rekabetçi ortamı ve yükselen müşteri beklentileri ürünlerin ve süreçlerin sürekli olarak iyileştirilmesini gerekli kılmaktadır. İyileştirme önceliklerinin yalnız uzun dönemde değil kısa dönemde de elde edilecek sonuçlar dikkate alınarak belirlenmesi kalite iyileştirme yönetiminde karşılaşılan önemli problemlerdendir. Bu tezde, muayene hatası ve yeniden işlemenin olduğu imalat ortamlarında kalite iyileştirme projelerinin karlılık ve kalite kaybı göz önünde bulundurularak seçimi için karar matrisi temelli pratik bir yöntem geliştirilmiştir. Geliştirilen yöntemin farklı deney koşulları altında performansı incelenmiş ve sonuçlar tartışılmıştır.

Anahtar Kelimeler: Kalite İyileştirme, Muayene Hatası, Yeniden İşleme, Kalite Kaybı, Karar Matrisi

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CHAPTER 1

INTRODUCTION

In today’s global market-place customers have more choices and have the advantage of getting information easily which helps them compare the alternatives to make their choices. This results in higher expectations for products and services and fierce competition among companies.

In order to survive in the competitive environment, organizations have focused attention on integrating quality principle into their management systems. Customer focus, teamwork and continuous quality improvement are key principles of modern quality management approaches such as total quality management (TQM) and six sigma programs.

According to most advocates of quality improvement programs, quality improvement (QI) is a long term activity and bottom line results should not be expected in the short term. Instead of focusing on specific improvements, they favor focusing on training and changing the corporate culture in the short term. Improvements are achieved as a result of these investments in the long term. However, as stated by Atwater and Chakravorty (1995), this long term process may create frustration in the organization. A focused program which will create bottom line improvements in the short term provides money for future projects and increases the program credibility. Besides, some organizations adopting TQM tend to emphasize quality and ignore the significance of internal costs of the organization. Breyfogle et al. (2001) report that due to this attitude some organizations experienced severe financial problems or even went bankrupt and they state that projects worthy of investment should have potential for significantly improving the bottom line in addition to being of primary concern to the customer.

In order to select the work center that has the greatest impact on bottom line, if improved, Atwater and Chakravorty (1995) utilize concepts of Theory of Constraints (TOC). In their study, they show that selecting a quality improvement project depends on product mix and that results of the quality improvements affect the product mix. By incorporating voice of customer, which is ignored in the TOC approach of Atwater and Chakravorty, Köksal (2004) has developed a method to simulatenously determine the product mix and the work center to improve. Mertoğlu (2003) proposes a practical method which takes into account effects of product mix on the selection problem.

These approaches assume a production environment in which rework operations are not carried out and inspection error is negligible. These assumptions make the methods very restrictive since it is known that inspection errors are observed even in the most modern production environments and rework operations are widespread. Hence, a practical and effective method to determine the work center to improve which takes rework operations and inspection errors as well as customer satisfaction and cost terms into account is needed. Development of such a method is the purpose of this study.

The study considers a manufacturing environment where each improvement project is associated with a work center (process or rework), improvement costs for the work centers are not significantly different from each other, each process determines a different quality characteristic of a product and the quality characteristic is not affected by the other processes, quality characteristics are distributed normally, target values for the quality characteristics are the nominal values, for each process if rework is possible it is performed at a separate unit, the work centers are in state of quality control, 100% inspection is performed after both process and rework, the measurement devices are calibrated but not precise, throughput accounting is appropriate and selling prices are fixed.

In such a production environment, the criteria that should be considered in selection of work center to improve are determined. For each planning period, the proposed method analyzes the relations between the products and the work centers based on the criteria. In order to synthesize the relationship values and product mix information, it utilizes a decision matrix. The product of the decision matrix is importance weight for each work center. Work center with the highest importance weight is selected as the first one to improve.

The thesis consists of four chapters. Chapter 2 provides the basic concepts used in this study and the related work. The proposed method is explained in Chapter 3. Chapter 3 also presents the analysis of performance of the method under different experimental conditions. Conclusion about the study and possible future research topics are provided in the last chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

2.1.1 Theory of Constraints

Theory of Constraints (TOC), introduced by Goldratt and Cox (1984), is a collection of system principles and tools to increase organizational performance. TOC likens the systems to chains. A system's performance is limited by the performance of its weakest link like a chain. Only the improvements to this weakest link will produce any tangible system improvement (Dettmer, 1997). Identifying the work center with the highest quality improvement requirement is the purpose of this study. Therefore, TOC methodology constitutes the main theme of this study.

It is a general assumption that if all processes are improved to their maximum, the maximum improvement for the entire system will be achieved. Since this view ignores the effects of interdependence between processes, TOC methodology does not agree on this assumption. Like a chain with its weakest link, a system at any point in time, has a constraint that prevents it from doing any better at achieving its goal. The constraint may be physical or policy, or it may lie in the environment of the system (for example, market demand) (Dettmer, 1997).

Application of TOC's principles and tools answers three fundamental questions about change (Dettmer, 1997).

1) What to change? (Where is the constraint?)
2) What to change to? (What should be done with the constraint?)
3) How to cause the change? (How should the organizations implement the change?)

In order to answer these questions five sequential steps are developed by Goldratt (Dettmer, 1997).

1) Identify the system constraint. To determine what to change, the weakest link of the system should be identified.
2) Decide how to exploit the constraint. Full utilization of the constraining component should be ensured.
3) Subordinate everything else. The rest of the system is adjusted such that the constraint operates at maximum effectiveness.
4) Elevate the constraint. If steps 2 and 3 are not sufficient to eliminate the constraint, the organization takes whatever action that is required to eliminate the constraint.
5) Go back to Step 1, but beware of "inertia". Strengthening its weakest link makes the chain stronger, but not infinitely stronger. Another link becomes the weakest one. Inertia shouldn't be allowed to become the system constraint.

The first step is related to the question "determine what to change". To determine "what to change to" it is necessary to decide how to exploit the constraint and subordinate the rest of the system to that decision. If these two steps do not give the expected result, the constraint is elevated. The forth and fifth steps answer the question "how to cause the change".

The tools utilized for answering the questions about change are the current reality tree, the conflict resolution diagram (evaporating cloud), the future reality tree, the prerequisite tree and the transition tree. These tools can be used individually or together and produce the thinking process.

The current reality tree tells what to change by helping examine the cause and effect logic behind the situation. The conflict resolution tree is used to discover the hidden conflicts that prevent solution of a problem and that make it chronic. The future reality tree is used to see whether an action will produce the desired results or not. These two tools provide an answer to the question “what to change to”. The prerequisite tree helps in implementation process of the decision. The transition tree provides the steps to take for implementation of the decision. Therefore, these two steps are utilized to answer the question “how to change”.

In order to evaluate the effects of local decisions on the global system, TOC provides goal-oriented financial performance measures: Throughput (T), Inventory (I), and Operating Expense (OE).

Throughput is the rate at which the system generates money through sales, mathematically sales minus totally variable costs (Balderstone and Keef, 1999). Inventory is defined as “all the money the system invests in things it intends to sell, or all the money tied up within the system”. It includes raw materials, equipments, facilities and the like. Operating expense is “all the money the system spends in order to turn inventory into throughput”. It includes direct labor, overhead costs, utilities, depreciation.

To improve a system, it is necessary to increase throughput while decreasing inventory and operating expenses. Potential for increasing throughput is generally higher than the potential for decreasing inventory and operating expense. Therefore, it would be more logical to put as much effort as possible on activities that tend to increase throughput primarily (Dettmer, 1997, Balderstone and Keef, 1999).

Throughput accounting is an accounting system where T, I and OE are used as management decision tools. Throughput accounting computes product costs as the sum of the totally variable costs of production. All other costs are treated as operating expenses for the period they occurred (Lea and Fredendall, 2002). Supporters of throughput accounting assert that overhead is a corporate cost since a feasible method of accurately tracing overhead to products does not exist. What’s more, it’s assumed that companies are unable to influence and eliminate it. Therefore, it is irrelevant to trace the overhead costs to products for decision making (Kee and Schmidt, 2000). Lea and Fredendall (2002) state that throughput accounting is suitable for production that has insignificant overhead and low automation and technology usage.

2.1.2 Process Capability Analysis

Process capability analysis, which is an essential part of a quality improvement program, is an engineering study to estimate process capability (Montgomery, 2005).

Process capability ratios express process capability in a simple, quantitative and unitless way. Among these ratios Cp, Cpk and Cpm are the most common ones.

Cp is the easiest way of estimating the process capability. Formulation of Cp is given below:

$$Cp = \frac{USL - LSL}{6\sigma} ,$$

where USL and LSL are the upper and lower specification limits, respectively. For one-sided specifications Cpu (upper specification only) and Cpl (lower specification only) can be used. They are calculated in the following way.

$$Cpu = \frac{USL - \mu}{3\sigma}\ , \qquad Cpl = \frac{\mu - LSL}{3\sigma}\ .$$

Using Cp or the ratios for one sided specification limits, number of products falling beyond specification limits can be calculated.

The process capability ratio Cp does not take the process location into account. It only measures the spread of the specifications relative to the six sigma spread in the process. Cpk is a process capability ratio developed to deal with the case of a process with mean that is not at target.

Cpk = min (Cpu, Cpl)

To deal with the process centering satisfactorily, Cpk is compared to Cp. Cp = Cpk implies that the process is centered while Cpk<Cp implies that the process is off-center. The value of Cpk alone does not tell anything about the location of the mean in the interval from USL to LSL.

Another process capability ratio, Cpm, is a better indicator of process centering.

$$Cpm = \frac{USL - LSL}{6\sqrt{\sigma^2 + (\mu - T)^2}}$$

This ratio is included in our study as a criterion expressing process capabilities of the work centers.

A given value of Cpm places a constraint on the difference between μ and the target value (T) (Montgomery, 2005).

Since in practice, the parameters μ and σ^2 are seldom known, these values are replaced by their estimates. This yields to estimates of the process capability ratios.

The interpretation of the process capability ratios is based on a normal distribution of output. Another assumption is that the process is in statistical control. The parameters of a process which is not in statistical control are unstable and uncertain in the future. Therefore, the meanings of the ratios are unclear in such a case.

Generally, a process with a process capability ratio greater than 1.33 is accepted as capable. A process capability ratio between 1 and 1.33 implies that the process is barely capable and must be monitored closely. If the process capability ratio is smaller than 1, the process is incapable (Kapadia, 2000).

2.1.3 Loss Function

Quality is commonly measured in terms of the fraction of the total number of defective units. This viewpoint, which is called goalpost view, implies that all products that are in specification limits are equally good. However, in reality performance of a product becomes worse as its response gets farther from the target. The best performance can be obtained when the quality characteristic is exactly on target. Therefore, products that meet tolerance also inflict a quality loss. Quality loss includes all costs incurred after the sale of a product to customer. This loss can adversely affect the sales of the product and reputation of the manufacturer (Phadke, 1989).

The quadratic loss function more accurately reflects the real situation. For a nominal-the-best type quality characteristic the quality loss is given by

$L(y) = k(y-m)^2$,

where m is the nominal value of the specification, y is the quality characteristic value and k is a constant called quality loss coefficient depending on the cost at the specification limits (Ross, 1996). This value can be calculated as

$$k = \frac{L_0}{\Delta^2},$$

where L_0 is the loss at the lower (upper) specification limit and Δ is the distance from the target value to the lower (upper) specification limit. L_0 includes repair or replacement cost of product and cost of transportation, loss due to the unavailability of the product during the replacement or repair period, regardless of whether the customer, the manufacturer or another party pays them (Phadke, 1989).

The quadratic loss function given above gives the quality loss per product shipped to customer with a quality characteristic y. The following equation gives the average quality loss for a large number of parts.

$$\overline{L} = k\ [\ (\mu\text{-}m)^2 + \sigma^2],$$

where μ and σ^2 are the mean and variance of y, respectively.

The loss function can also be applied to quality characteristics other than the situation in which the nominal value is the best.

- Smaller-the-better type characteristics: Their ideal value equals to zero and as the value of the quality characteristic increases, the performance becomes worse. Waiting time for order delivery at a restaurant, pollution from an automobile are examples of this type of quality characteristic.

Loss for an individual part = $k(y^2)$

Average loss per part in a distribution = $k(\sigma^2 + \mu^2)$

- Larger-the-better type characteristics: Their ideal value is infinity. This type of quality characteristics do not take negative values and zero is the worst value. As the quality characteristic value increases the performance becomes better. Strength of a material, fuel efficiency are examples of this type of quality characteristic.

Loss for an individual part = $k(\frac{1}{y^2})$

Average loss per part in a distribution = $k(\frac{1}{\mu^2})(1 + \frac{3\sigma^2}{\mu^2})$

Since in practice, the parameters μ and σ^2 are generally not known, these values are replaced by their estimates.

In our study, loss coefficient is taken as one of the criteria used to evaluate improvement needs of the work centers.

2.1.4 Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP), developed by Saaty, assists decision makers to make effective decisions on complex problems by decomposing the problem into a multi-level hierarchic structure of objectives, criteria, subcriteria and alternatives. The contribution of each element at a lower level is pairwise compared in terms of the elements at the upper level to determine relative priorities of the elements. To compare the elements the question “how many times more strongly does this element contribute to, or dominate, satisfy the upper level element than does the element with which it is being compared?” is answered (Saaty,1999). The number used to express “how many” belongs to the fundamental scale of absolute numbers 1-9 of the AHP. A ratio scale of relative magnitudes expressed in priority units is then derived from each set of comparisons. An overall ratio scale of priorities is synthesized to obtain a ranking of the alternatives (Saaty,1990).

One may need to compare alternatives with a standard in his memory that has been developed through experience. In absolute measurement intensity ratings, for example Poor, Fair, Good, Very Good, Excellent, are designed for each criterion and each intensity is assigned relative weights by pairwise comparisons. Criteria are also pairwise compared and their weights are obtained. For each alternative the appropriate intensity under each criterion is chosen. The priority of the intensity is weighted by the importance of the criterion and these values are added to obtain an overall score for the alternative. Saaty states that the absolute measurement is particularly useful in large scale and ongoing activites (Saaty, 2000). This method is utilized in determination of the relationship values which is explained in section 3.2.4.

Saaty defines four axioms on which the AHP is based. Let A be a finite set of n elements called alternatives and C be a set of properties or attributes with respect to which the elements of A are compared.

Axiom 1 (Reciprocal). Given any two alternatives A_i, $A_j \in A$ the intensity of preference of A_i over A_j is inversely related to the intensity of preference of A_j over A_i.

$$P_C(A_i, A_j) = \frac{1}{P_C(A_j, A_i)} \qquad \forall A_i, A_j \in A, \quad c \in C$$

When pairwise comparisons are made, both members of the pair to judge the relative value need to be considered. The smaller one is used as the unit for the corresponding criterion. Then the other is estimated as a multiple of that unit.

The unit is different in every pairwise comparison. The comparison matrices are formed by making paired reciprocal comparisons (Saaty,1994).

Axiom 2 (ρ-homogeneity). Given a hierarchy H, $x \in H$ and $x \in L_k \subset H$, then $x^- \subseteq L_{k+1}$ is ρ-homogenous for all k = 1,2,…,h-1.

Axiom 2 deals with our limited cognitive capabilities and states that the elements of a particular level in a hierarchy H must be comparable. Since it is likely to make large errors in comparing widely different elements, Saaty considers homogeneity essential for comparing the elements. If they are not homogenous, they are clustered into homogenous groups of five to nine so they can be meaningfully compared. Saaty explains this procedure as placing the elements in separate gradually increasing homogeneous groups or clusters with a common pilot used as the largest element of the next cluster. The pivot is the largest element of the previous cluster. In each set of comparisons the 1-9 scale is used. The weight of the elements in the second group are divided by the priority of the pivot in that group and then multiplied by the priority of the same pivot element from the first group, making two clusters comparable on the same ratio scale and can now be put in one cluster. The process is then continued to the next cluster and so on. One or more alternatives may be much larger or smaller than other with respect to a criterion. In this case of non-homogeneity it is meaningless to use dummy alternatives of intermediate sizes to link their comparisons. The largest homogenous ones are compared and the weight of the criterion is distributed among them. If there is a single such largest alternative, the total weight of the criterion is assigned to this alternative. The smaller homogenous elements are assigned the zero value (Saaty,1994).

Axiom 3 (Dependence). Let H be a hierarchy with levels $L_1, L_2, \ldots, L_h$. For each L_k, k = 1,2,…,h-1

(1) L_{k+1} is outer dependent on L_k,

(2) L_k is not outer dependent on L_{k+1},

(3) L_{k+1} is not inner dependent with respect to any $x \in L_k$ (Saaty, 2000).

Axiom 4 (Expectations). All criteria and alternatives are represented in the hierarchy. An exact replica or copy of an alternative with respect to C should only be added if it adds a truly new alternative to the set A by either altering the set of criteria C, or the priorities assigned to the criteria and the to the alternatives. In order to believe that two alternatives are copies, we must believe that there exists no criterion on which one could differentiate between these alternatives, or that C is complete (Harker and Vargas, 1987). Saaty suggests eliminating alternatives from consideration that score within 10 percent of another alternative (Dyer, 1990).

Despite its popularity, AHP has been criticized by some researchers since its development in 1970s. The scale used to measure the intensity of preference and rank reversal are two of the essential areas that the AHP has been criticized. Dyer (1990) regards rank reversal as an indicator of an important problem with the AHP, that is rankings produced by this procedure are arbitrary. Then he suggests synthesizing the AHP with the concept of multi-attribute utility theory in two ways. In Method 1, the weights on the criteria can be obtained in the traditional AHP manner and the decision maker is asked to specify the ranges over which he assumed the alternatives vary on each other. If the actual alternatives do not have values that cover the entire range, dummy alternatives are generated. The evaluation of the alternatives then proceeds in the usual AHP manner. In Method 2, relative importance of a change from the least preferred to the most preferred value for each criterion is pairwise compared. This process gives the importance of the criteria. There is no need to introduce dummy alternatives. He writes:

“The eigenvectors for the criteria determined by the AHP should then be scaled by subtracting the smallest component in each eigenvector from all components in the eigenvector, and then dividing this modified eigenvector by its largest component.”

Saaty states that a robust theory must allow rank reversal when appropriate and not allow when inappropriate. AHP addresses both situations by supporting two types of synthesis procedures- Distributive Mode and Ideal Mode.

The distributive mode normalizes the alternative scores under each criterion so that they sum to one. Alternatives depend on what alternatives are considered and how well other alternatives perform, thus, adding or deleting alternatives can lead to change in the final rank. This shows that no mathematically unjustified rank reversal occurs in the AHP.

Ideal mode divides the score of each alternative only by the score of the best alternative under each criterion. The preference for any given alternative is independent of the performance of other alternatives, except for the best alternative under each criterion.

In relative measurement, ideal mode preserves rank from irrelevant alternatives, distributive mode allows it to reverse. In absolute measurement the ideal mode preserves rank not only with respect to irrelevant alternatives but also with respect to any alternatives whether relevant or not (Saaty, 1997).

Millet and Saaty (2000) clarify the issue of selecting a synthesis mode. They state that the choice of a synthesis mode should depend on the decision making problem. They write:

"The Distributive Synthesis Mode should be used when the decision maker is concerned with the extent to which each alternative dominates all other alternatives under the criterion. The Ideal Mode should be used when the decision maker is concerned with how well each alternative performs relative to a fixed benchmark."

Saaty's 1 to 9 scale has also been subject to debate. Salo and Hämäläinen (1997) state that the ratios $\frac{1}{9},\frac{1}{8},...,\frac{1}{2},1,2,..,8,9$ lead to uneven dispersion of local priorities. They write:

"... the effect of replacing the ratio by 1 to 2, for instance, is 15 times greater than the local priority difference between the ratios 8 and 9".

They propose a balanced scale for pairwise comparisons. The balanced scale is obtained by choosing priorities which were equally far apart from each other in the range [0.1, 0.9] or the unit range [0,1]. The priorities 0.1, 0.15, 0.2, ..., 0.80, 0.85, 0.9 led to the scale 1, 1.22, 1.50, 1.86, 2.33, 3.00, 4.00, 5.67, 9.00 and the 17 priorities in the range [0,1] led to the scale 1, 1.27, 1.62, 2.09, 2.78, 3.86, 5.80, 10.3, 33.3.

Saaty (1997) points out that in paired comparisons one cannot ignore what also happens to the priorities of the second element and that the difference in the resulting priority of the second element is also 15, hence the ratios between the priorities are preserved.
Harker and Vargas (1990) claim that use of the 1-9 scale does not affect the theory of AHP, that is if one is forced to compare two alternatives within the 1-9 scale instead of using scale with a higher upper bound although they are not homogenous according to the 1-9 scale and a value higher than 9 is necessary to make a consistent judgement, resulted weights are not much different. They support their claim with a numerical example and write:

"... as the above example suggests, the AHP is fairly robust even if 'errors' are made."

In order to evaluate n alternatives on m criteria $m\frac{n(n-1)}{2}$ comparisons are required. Using elements more than seven in a comparison scheme is not suggested in AHP. Saaty (1999) writes:

"The AHP often uses seven elements to maintain reasonable consistency in judgements and puts them in clusters. If there are more than seven elements, they are divided into two or more clusters, ..".

If the alternatives cannot be compared within 1-9 scale there is again a need for clustering. Thus, number of operations needed may become very large in the AHP.

Macharis et al. (2004) propose a procedure which integrates some AHP features into PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations). The procedure starts with performing pairwise comparisons in the standard AHP-manner in order to determine the first row of the matrix. The complete matrix is obtained from the first row by considering that we want a reciprocal consistent matrix. The complete matrix is presented to the decision maker. If the decision maker agrees with the matrix, the procedure is completed. If the decision maker wants to change one or more elements of the matrix, making some other changes is required to maintain the consistency. The consequences of every change are shown to the decision maker. Macharis et al. state that since the approach permitted more flexibility, they avoided the use of the 1-9 scale.

2.1.5 Measurement System Analysis

Decisions about processes are based on measurements. Therefore, capability of measurement system plays an important role in effectiveness of the decisions. Two properties about measurement systems are accuracy and precision. Precision is about the inherent variability of the measurement system. Accuracy is related with the ability of the measurement device (gage) to measure the true value correctly on average. In this study, it is assumed that the measurement system is accurate but not precise.

The total observed measurement, y, can be represented by the model

$$y=x+\varepsilon$$

where x is the true value of the measurement on a unit of product, ε is the measurement error and x and ε are normally and independently distributed random variables with means μ and 0, and variances σ_p^2 and σ_{Gage}^2 (σ_M^2), respectively. Then, the variance of the total observed measurement, y is

$$\sigma_T^2 = \sigma_p^2 + \sigma_{Gage}^2$$

Gage variability consists of two components: repeatability and reproducibility. Repeatability expresses the variability of the gage when it is used to measure the same unit under the same conditions. Reproducibility represents the variability arising from different conditions such as different operators or time periods (Montgomery, 2005).

The studies performed to measure the components of the measurement error or gage variability are often referred to as gage repeatability and reproducibility (GR&R) studies. One of the methods used to analyze the results of the GR&R studies is the Analysis of Variance Method. The standard GR&R experiment uses a two-factor design with parts and operators (Burdick et al., 2003). For a randomly selected parts and b randomly selected operators if each operator measures every part n times, response variable, the measurements, can be represented by the model

$$y_{ijk} = \mu + P_i + O_j + (PO)_{ij} + \varepsilon_{ijk}$$
$$i = 1,2,...,a;\ j = 1,2,...,b;\ k = 1,2,...,n;$$

where P_i, O_j, $(PO)_{ij}$ and ε_{ijk} are independent and normally distributed random variables representing effects of parts, operators, the interaction of parts and operators, and random error. If it is assumed that means of the model parameters are zero and variances are σ_p^2, σ_o^2, σ_{po}^2 and σ^2, the variance of any observation is represented by

$$V(y_{ijk}) = \sigma_p^2 + \sigma_o^2 + \sigma_{po}^2 + \sigma^2$$

The variance components may be estimated by using a statistical computer program such as Minitab.

Usually, σ^2 is taken as the repeatability and sum of the operator and interaction of part and operator variance components is taken as reproducibility (Montgomery, 2005).

$$\sigma^2_{\mathrm{Re}\,peatability} = \sigma^2$$
$$\sigma^2_{\mathrm{Re}\,producibility} = \sigma_o^2 + \sigma_{po}^2$$

Therefore, the gage variability is

$$\sigma^2_{Gage} = \sigma^2_{\mathrm{Re}\,peatability} + \sigma^2_{\mathrm{Re}\,producibility}$$

More information on the procedure can be found in Montgomery, 2005, Burdick et al., 2003.

Precision-to-tolerance (P/T) ratio is a commonly reported ratio in GR&R studies and calculated as

$$\text{P/T}=\frac{k\hat{\sigma}_{Gage}}{USL-LSL}$$

k is generally chosen as 5.15 or 6. Values of the estimated ratio P/T 0.1 or less indicate adequate measurement system (Burdick et al., 2003, Montgomery, 2005, Pearn and Liao, 2005, Arıtürk, SPAC Six Sigma Consulting, Personal Communication, 2006). The measurement systems having an estimated P/T ratio between 0.1 and 0.3 may be deemed as adequate based on the importance of the application and cost terms and a estimated value of P/T ratio greater than 0.3 indicates that the measurement system needs improvement (Pearn and Liao, 2005, Arıtürk, SPAC Six Sigma Consulting, Personal Communication, 2006). There are some criticisms on P/T ratio that it does not necessarily give a good indication of the adequacy of the measurement systems.

Another ratio of gage capability is the ratio of measurement system variability to total variability. Interpretation of the estimated values of this ratio is the same as the interpretation of the P/T ratio (Arıtürk, SPAC Six Sigma Consulting, Personal Communication, 2006). These two ratios are considered in our study as gage capability criterion.

2.2 Related Work

Atwater and Chakravorty (1995) draw attention to low success rates of QI programs. They do not question the value of QI programs but rather they investigate why some programs fail while others are successful. Based on studies of Shaffer and Thomson (1992) and Myers and Ashkenas (1993) they state that lack of focus on results is the main reason behind the unsuccessful QI efforts. They point at the importance of result-oriented projects in successful QI programs and apply TOC principles for the selection of a QI project in manufacturing. They study a manufacturing system having four work centers and three products and investigate the effects of improving each work center on throughput. It is assumed that improving a work center eliminates scrap at that work center. It is shown that for that manufacturing setting throughput can be increased by improving the constraint work center rather than improving the work center that has the largest scrap rate. It is also shown that improving the succeeding work center of the constraint has a considerable impact on throughput. However, customer aspects and their long term effects on throughput are not taken into account in this study.

Karşılıklı (2001) incorporates the quality loss with the TOC-based algorithm to consider the customer dissatisfaction and attempt to develop a method which utilizes a linear programming model to determine the product mix and work center to improve simultaneously. The true formulation is given by Köksal (2004).

Although the Throughput-Loss Method developed by Köksal (2004) gives optimal results, it has some disadvantages in application. Determining the values of the model parameters is not easy in practice. Mertoğlu (2003) proposes a practical method for prioritizing QI activities in manufacturing environment which is called “Integrated Quality Function Deployment (QFD) Method”. This method determines the work center to improve first by considering product mix, process capability, customer satisfaction and cost terms. Assumptions made in their study are listed below.

1. All of the products produced are sold immediately.
2. Improvement costs are not significantly different from one work center to another.
3. There is one key quality characteristic of a part at a work center to be measured. The quality characteristics are assumed to be distributed normally with mean at the target ($T=\mu$)
4. Labor or overhead costs are assumed to be insignificant compared to raw material costs. Only raw material costs are taken into consideration.

5. Scrap rate at a work center does not depend on the product processed there.
6. Inspection and detectability are assumed as 100%. Gages are controlled in such a way that the inspection error is negligible.
7. Nonconforming items are scrapped (no rework takes place).

The proposed algorithm is as follows.

1. For the period under consideration, determine the optimal product mix based on demand, selling price, raw material cost, processing time, capacity and scarp rate figures of products and work centers.
2. Fill in the QFD matrix of Table 2.1 with suitable relationship values using Table 2.2, and the current product mix determined at step 1.

Table 2.1 The QFD matrix

Work Centers / Products	1	2	…	n	Share in production (SR_i)
1	R_{11}	R_{12}	…	R_{1n}	SR_1
2	R_{21}	R_{22}	…	R_{2n}	SR_2
…	…	…	…	…	…
m	R_{m1}	R_{m2}	…	R_{mn}	SR_m
Importance Weight (IW_k)	IW_1	IW_2	…	IW_n	

In Table 2.1, R_{ik} implies the relationship value assigned to product i at work center k using Table 2.2, SR_i denotes the ratio of amount of product i to the total number of items to be produced. IW_k represents the importance weight of work center k. This value demonstrates the improvement requirement of the work center and is calculated by taking a weighted sum of R_{ik} values of the related work center.

$$IW_k = \sum_{i=1}^{m} SR_i * R_{ik}$$

3. Compute IW_k values and decide to improve the work center that has the highest importance weight. If it is decided to continue improvement activities go back to step 1, otherwise stop.

Table 2.2 Relationship values for QFD matrix

Process Capability Index (Cp)	Loss Coefficient	Closeness to Constraint	Raw Material Cost	Relationship Value
Low	High	At/next	Low	8
Low	High	At/next	High	9
Low	High	Far	Low	7
Low	High	Far	High	7.5
Low	Low	At/next	Low	6
Low	Low	At/next	High	6.5
Low	Low	Far	Low	5
Low	Low	Far	High	5.5
Medium	High	At/next	Low	6
Medium	High	At/next	High	6.5
Medium	High	Far	Low	5
Medium	High	Far	High	5.5
Medium	Low	At/next	Low	4
Medium	Low	At/next	High	4.5
Medium	Low	Far	Low	2.5
Medium	Low	Far	High	3.5

Table 2.2 (Continued)

Process Capability Index (Cp)	Loss Coefficient	Closeness to Constraint	Raw Material Cost	Relationship Value
High	High	At/next	Low	4.5
High	High	At/next	High	5
High	High	Far	Low	4
High	High	Far	High	4.5
High	Low	At/next	Low	3
High	Low	At/next	High	3.5
High	Low	Far	Low	1
High	Low	Far	High	2

They arrange the criteria from most important to least as ‘Process Capability Index’, ‘Loss Coefficient’, ‘Closeness to Constraint’ and ‘Raw Material Cost’. This ranking is reflected to relationship values.

The results obtained under different experimental conditions are compared with the optimal solutions obtained from the Throughput-Loss Method and with the solutions obtained by using only Cp values of the work centers for selection. According to this analysis QFD Method’s maximum deviation is 3.53% while Cp method’s maximum deviation is 7.6% from Throughput-Loss Method. However, the manufacturing environment considered in this study does not accurately reflect real world which is the basic disadvantage of the QFD Method.

Rework operations are common in practice. Moreover, inspection errors occur even in the manufacturing environments where sophisticated measurement devices are used. Therefore, assumptions of negligible inspection errors and not performing rework operations make the application area of the methods highly limited.

Şarbak (2006) proposes a method to determine the product mix and work center to improve simultaneously. The proposed method utilizes a linear programming model given below.

$$Max.\sum_{i=1}^{m}(SP_i\ S_i-\sum_{k=1}^{n}U_{ik}\ TVCP_{ik})-\sum_{i=1}^{m}\ \sum_{t=n+1}^{2n}(RT_{it}R_{it}\ TVCR_{it})-\sum_{i=1}^{m}\ \sum_{k=1}^{n}(S_i\ \overline{L}_{ik})$$

Subject to

$$R_{i,k+n}=U_{ik}RR_{ik} \qquad i=1,...,m,\quad k=1,...,n$$

$$R_{it}YRR_{it}+U_{ik}\ YR_{ik}=U_{i,k+1} \qquad i=1,...,m,\quad k=1,...,n-1,\quad t=k+n$$

$$R_{i,2n}YRR_{i,2n}+U_{in}\ YR_{in}=S_i \qquad i=1,...,m$$

$$S_i\leq D_i \qquad i=1,...,m$$

$$\sum_{i=1}^{m}(U_{ik}\ t_{Pik})\leq CAP_k \qquad k=1,...,n$$

$$\sum_{i=1}^{m}(RT_{it}R_{it}\ t_{Rit})\leq CAR_t \qquad t=n+1,...,2n$$

$$U_{ik},S_i,R_{it}\geq 0 \qquad i=1,...,m,\quad k=1,...,n,\quad t=n+1,\ldots,2n.$$

Where

SP_i: Selling price of product i

S_i: Number of sold units of product i produced within the specified time frame

U_{ik}: Total number of parts to be processed at process unit k to satisfy production requirements of product i

$TVCP_{ik}$: Totally variable cost due to process of product i at process unit k

$\overline{L}_{ik}$: Average loss incurred per product i due to its processing at process unit k and rework unit k+n.

RT_{ik}: Number of rework operations occured for product i at rework unit k.

R_{ik}: Total number of parts to be reprocessed at rework unit t to satisfy production requirements of product i

$TVCR_{it}$: Totally variable cost due to rework operation of product i at rework unit t

RR_{ik}: The probability that a product i is sent to rework unit k+n from process unit k.(Rework rate)

YRR_{it}: Yield rate of rework unit t of product i. The probability that a product i is sent to process unit k+1 from rework unit t=k+n.

YR_{ik}: Yield rate of process unit k of product i. The probability that a product i is sent to process unit k+1 from process unit k.

D_i: Market demand of product i.

t_{Pik}: Production time per unit at process unit k for product i.

t_{Rit}: Production time per unit at rework unit t for product i.

As mentioned before, quality loss includes the costs that occur after sale of a product. Therefore, in calculation of average quality loss distribution of the accepted items should be considered. The distribution of the accepted items in a production environment where there are inspection error and a separate rework unit is determined by Taşeli (2004). Mean and variance of the resulting distribution are also determined.

The LP model is solved for the number of candidate work centers for improvement. Each time one work center is assumed to be improved and the model parameters are computed accordingly (here, it is necessary to predict the effect of improvement). Since the improvement will become effective at the beginning of the next period, forecasted values of demand, selling price, totally variable cost and capacity for the next period are used. The work center which yields the maximum objective function value is the work center to improve first.

CHAPTER 3

THE PROPOSED METHOD FOR QUALITY IMPROVEMENT PROJECT SELECTION

3.1 Introduction

Quality is a necessary condition for organizations to survive in the competitive global marketplace. As a result, quality improvement is a major concern for companies. Unfortunately, unless the efforts for quality improvement are arranged properly, tangible results in terms of quality, productivity and financial improvements cannot be achieved. Defining strategic focus areas and organizing manageable projects for these areas are crucial for a successful quality improvement program.

When considering a typical manufacturing environment which consists of products and work centers, possible focus areas for improvement are the work centers. Since generally it is not possible to improve all the work centers at the same time and improving each work center will have a different impact on the organizational performance, problem of determining the work center to improve is a significant one.

In a typical manufacturing environment scrap rates, rework costs and customer complaints are taken into consideration in determination of candidate work centers for quality improvement. Expected gains of the projects planned for the work centers are tried to be specified. As demonstrated by Atwater and Chakravorty (1995), using scrap rates or process capability indices as the only evaluation criterion may not result in the most profitable selection. What's more ignoring inspection errors gives rise to unreliable assessments since the data used is contaminated with the inspection errors. On the other hand, estimation of the project gains is a difficult issue, hence the results of directing the quality improvement efforts based only on these estimations may not meet the expectations. Organizations which realize importance of considering inspection errors in process control and quality improvement activities carry out gage repeatability and reproducibility studies for the candidate work centers (Arıtürk, SPAC Six Sigma Consulting, Personal Communication, 2006).

Amount of products produced at the work centers are affected by the yield ratios. Improving a work center results in higher yield ratios. Therefore, improvement decision affects the product mix and product mix information affects improvement needs of the work centers. These two problems should be handled together. Typically, the product mix information is accepted as given rather than solving these two problems simultaneously. The aim is to give higher priority to the work centers in which higher amount of items are processed. If small amount of items are processed in a work center, although its scrap rate is high or the work center is worse than the others on some other aspects, improving that work center may not be a profitable action. But this approach has some disadvantages. First, it ignores the completion time of the project. Improvement efforts cannot give results immediately. Hence, using the current period's product mix which is determined by considering the period's demand information does not serve the purpose. What's more the consequence of improving a work center which is not used in production of a particular product or processes low amount of items due to its high scrap rate is not evaluated. Improving that work center may result in increased outputs and profit.

The criteria involved in QI project selection are many and employing the criteria separately does not give the desired results. Therefore, a practical method which tackles the problem in a multi-perspective manner to support decision makers in manufacturing environments is proposed. Assumptions related to the considered manufacturing environment are listed below.

1. All of the products are sold immediately.
2. Volume of production is high.
3. Overhead costs are insignificant.
4. Workers are paid on hourly basis.
5. Cost of improvement is negligibly different or the same for all work centers.
6. Only one quality characteristic is produced at one process or rework unit. The distribution of the quality characteristic is not affected by the operations at the succeeding work centers.
7. The quality characteristic of items produced in processing unit has a normal distribution with mean μ_p^2 and variance σ_p^2.
8. There is a separate rework unit for the cases where rework is possible.
9. If an item is sent to rework the quality characteristic value it gained at processing unit does not affect the quality characteristic value it will gain at the rework unit.
10. The quality characteristic of items that are reworked has a normal distribution with mean μ_r^2 and variance σ_r^2.
11. 100% inspection takes place after both process and rework. At the end of inspection, the items that are within specification limits are accepted, those that are out of scrap limits are scrapped. The items that are out of specification limits but within scrap limits are sent to rework.
12. Specification and scrap limits are two sided and symmetric.
13. The measurement system is accurate but not precise. (Measurement error has a normal distribution with mean 0 and variance σ_m^2.)
14. Measurement error does not depend on the true value of the quality characteristic.

15. Quality characteristics are nominal-the-best type.
16. The processes are under statistical control (constant mean and variance).

The assumptions related with the measurement system and distribution of the quality characteristics are the assumptions made in the study of Taşeli (2004). The same assumptions are adopted in our study since the results obtained by Taşeli (2004) are used in calculation of the average quality loss values necessary for determination of Throughput-Loss values which are used to analyze the performance of the method.

3.2 Decision Matrix Method

The proposed method utilizes a decision matrix to select the work center with the highest improvement need for each planning period. A decision matrix allows decision makers to evaluate and prioritize a list of options on the basis of several criteria. In this study, options are the candidate work centers for quality improvement. Criteria are used to evaluate the work centers so that improvement efforts can be focused on the areas that have the most benefit to customers and bottom line of an organization. A work center's performance based on the criteria can be different for different products it processes. Therefore, work centers are evaluated against each criterion for each product. The method provides the decision makers with a relationship value table in this evaluation process. Importance weights, indicators of the degree of improvement requirements of the work centers, are determined by taking into account this evaluation and share in production values. The work center with the highest importance weight is selected for improvement.

Following sections of this chapter present the criteria used in the study, the algorithm and determination of the relationship values. After these, details of the experimental design and determination of parameter values used in the analysis, conducted with Şarbak as a part of our study and analysis on performance of the method are given.

3.2.1 Criteria Selection

Being a simple way to express process capability, process capability indices are used by many practitioners to evaluate processes. Cpm is one of these indices and takes into account process centering and standard deviation. However, in practical applications, the process standard deviation is seldom known and hence replaced by an estimate. Using this estimate yields an estimate of Cpm. Inspection errors can severely affect estimation of process capability indices. Therefore, conclusions drawn from these indices can be misleading in existence of inspection errors which is a case encountered even with highly advanced measurement instruments. An estimate of process variability isolated from the measurement instrument variability can be calculated ($\sigma_p^2 = \sigma_T^2 - \sigma_M^2$). In this study, by 'process capability' criterion, the estimate of Cpm which is calculated by using the estimate of process standard deviation isolated from measurement error is referred.

Precision to tolerance ratio (P/T=$\frac{6\sigma_M}{USL - LSL}$) and ratio of inspection error variability to total variability (σ_M^2 / σ_T^2) are two ratios used as measures of gage capability. Precision to tolerance ratio compares the estimate of standard deviation of inspection error to the width of the tolerance band. The ratio of inspection error variability to total variability explains the contribution of measuring instrument to the total observed variance of the measurement. Since generally estimated values are used in calculation, estimated ratios are obtained. These two ratios, generally used together in practice, constitute the 'gage capability' criterion. Since the criteria should be independent of each other these two ratios are considered as a combined criterion.

‘Totally variable cost’ criterion is included to take the cost dimension into account. In this study, raw material costs and labor costs are considered as totally variable costs. Any other costs that increase directly because of an increased level of production can also be taken as totally variable costs. Value of an item increases as it proceeds through the work centers. Therefore, totally variable cost of an item at a work center is the cumulative totally variable costs required by the product until that work center.

TOC defines a constraint as anything that limits the performance of a system relative to its goal and suggests direction of improvement efforts based on their impact on the constraint. In their study, Atwater and Chakravorty (1995) show that improving the constraint work center is the best way to exploit it. They also demonstrate the considerable impact on throughput of improving the succeeding work center of the constraint work center according to production sequence. As the distance to the constraint work center increases, impact of improving the work center decreases. In order to give importance to the constraint work center and the first successor work center, ‘closeness to constraint’ criterion is included in the analysis.

In order to take the customer aspects into account, ‘loss coefficient’ criterion is considered.

3.2.2 The Algorithm for QI Project Selection

As mentioned before, using the current period’s product mix in quality improvement decision has some disadvantages. Using improved yield rates and rework rates of work centers in determination of the product mix gives a chance to the work center which is not used due to its high scrap rate or rework rate to produce some items. And it can be decided whether to improve that work center or not. Furthermore since the improvement activities cannot give results immediately, it is more reasonable to take into account the next period’s forecasted demand, selling price, totally variable cost and capacity figures in determination of the product mix which is used in the improvement decision. Therefore, in calculation of share in production values a product mix which is obtained by considering improved yield rates and rework rates of the candidate work centers and forecasted demand, selling price, cost values is used. This product mix is called ‘ideal product mix’.

Step 1 Forecast the next planning period’s demand, selling price, totally variable cost, capacity figures. Estimate the effect of improving each and all of the candidate work centers on their yield rate, rework rate and expected number of rework operations (for candidate rework units). Determine the ideal product mix based on these values.

Step 2 Calculate the share in production values (SR_i). Share in production value for a product is the ratio of amount of product to the total number of products to be produced.

$$SR_i = \frac{S_i}{\sum_{i=1}^{m} S_i}$$

Step 3 Fill in the decision matrix of Table 3.1 with suitable relationship values (RV_{ik}) using the relationship values table given in Appendix B and share in production values determined at Step 2. In order to use the relationship values table appropriate level under each criterion should be determined. Suggested methods for level determination for the criteria are given in the following section.

Step 4 Compute the importance weights. Importance weight of a work center (IW_k) demonstrates improvement requirement of that work center and it is calculated by

$$IW_k = \sum_{i=1}^{m} SR_i * RV_{ik}$$

The work center with the highest importance weight is the work center suggested for improvement by this method. If it is decided to continue improvement activities go to Step 1, otherwise stop.

Table 3.1 The decision matrix for project selection

Work Centers Products (k) (i)	1	2	…	n	Share in production (SR_i)
1	RV_{11}	RV_{12}	…	RV_{1n}	SR_1
2	RV_{21}	RV_{22}	…	RV_{2n}	SR_2
…	…	…	…	…	…
m	RV_{m1}	RV_{m2}	…	RV_{mn}	SR_m
Importance Weight (IW_k)	IW_1	IW_2	…	IW_n	

3.2.3 Constructing the Decision Matrix

LP model used to generate the product mix is given below.

$$Max \sum_{i=1}^{m} (SP_i \; S_i - \sum_{k=1}^{n} U_{ik} \; TVCP_{ik} - \sum_{t=n+1}^{2n} (RT_{it} R_{it} \; TVCR_{it}))$$

Subject to

$$R_{i,k+n} = U_{ik} RR_{ik} \qquad i = 1,...,m, \quad k = 1,...,n$$

$$R_{it} YRR_{it} + U_{ik} \; YR_{ik} = U_{i,k+1} \qquad i = 1,...,m, \quad k = 1,...,n-1, \quad t = k+n$$

$$R_{i,2n} YRR_{i,2n} + U_{in} \; YR_{in} = S_i \qquad i = 1,...,m$$

$$
\begin{aligned}
&S_i \le D_i && i = 1,\ldots,m \\
&\sum_{i=1}^{m} (U_{ik}\ t_{Pik}) \le CAP_k && k = 1,\ldots,n \\
&\sum_{i=1}^{m} (RT_{it} R_{it}\ t_{Rit}) \le CAR_t && t = n+1,\ldots,2n \\
&U_{ik}, S_i, R_{it} \ge 0 && i = 1,\ldots,m, \quad k = 1,\ldots,n, \quad t = n+1,\ldots,2n.
\end{aligned}
$$

First two constraints determine the number of processed units in rework units and process units, respectively. The third constraint gives the number of sold units of each type of product. The forth constraint ensures that number of sold units is not more than the market demand. The fifth and the sixth constraints are the capacity constraints. Next comes the non-negativity constraint.

Calculations of yield rate of a process unit and probability that an item is sent to rework unit from a process unit are shown below. Φ represents the distribution function of standard normal distribution.

$$
\mathrm{YR}_{ik} = \Phi\left(\frac{USL_{ik} - \mu_{ik}}{\sigma_{ik}}\right) - \Phi\left(\frac{LSL_{ik} - \mu_{ik}}{\sigma_{ik}}\right),
$$

$$
\mathrm{RR}_{ik} = \Phi\left(\frac{ULs_{ik} - \mu_{ik}}{\sigma_{ik}}\right) - \Phi\left(\frac{USL_{ik} - \mu_{ik}}{\sigma_{ik}}\right) + \Phi\left(\frac{LSL_{ik} - \mu_{ik}}{\sigma_{ik}}\right) - \Phi\left(\frac{LLs_{ik} - \mu_{ik}}{\sigma_{ik}}\right),
$$

where μ_{ik} is the mean and σ_{ik} is the standard deviation of the distribution of measured quality characteristic value of product i processed at process unit k. USL and LSL are the upper and lower specification limits respectively. ULs denotes the upper scrap limit and LLs denotes the lower scrap limit.

In order to find the expected number of rework operations for an item at a rework unit and probability that rework unit sends an item to the next process unit, the states that can be observed for an item are considered as an absorbing Markov

Chain. After inspection an item can be sent to rework (R), accepted as confirming (C) or scrapped (S). The transition matrix is given below.

$$\begin{array}{cc} & \begin{array}{c|cc} R & C & S \end{array} \\ R & \left[\begin{array}{c|cc} p_1 & p_2 & p_3 \end{array}\right] \end{array}$$

The states C and S are the absorbing states while R is the transient state. Transition probabilities are given below.

$$p_1 = \Phi\left(\frac{ULs_{itr} - \mu_{itr}}{\sigma_{itr}}\right) - \Phi\left(\frac{USL_{itr} - \mu_{itr}}{\sigma_{itr}}\right) + \Phi\left(\frac{LSL_{itr} - \mu_{itr}}{\sigma_{itr}}\right) - \Phi\left(\frac{LLs_{itr} - \mu_{itr}}{\sigma_{itr}}\right)$$

$$p_2 = \Phi\left(\frac{USL_{itr} - \mu_{itr}}{\sigma_{itr}}\right) - \Phi\left(\frac{LSL_{itr} - \mu_{itr}}{\sigma_{itr}}\right)$$

$$p_3 = 1 - p_1 - p_2$$

μ_{itr} is the mean and σ_{itr} is the standard deviation of the distribution of measured quality characteristic value of product i processed at rework unit t.

The element at the first column of the matrix $(I-Q)^{-1}*R$ gives the probability that an item sent to rework operation will eventually be accepted as conforming where Q is a matrix that represents transitions between transient states and R is a matrix representing transitions from transient states to absorbing states. I is identity matrix. $(I-Q)^{-1}$ gives the expected number of rework operations for an item at a rework center before it is either scrapped or accepted as conforming (Winston, 1994).

Suitable relationship values are chosen from the table of relationship values. In order to use this table for each product at each work center, the appropriate level under each criterion should be determined. In this study the levels are generated in the following ways.

Process Capability Index (Cpm)

For each Cpm_{ij} value, j=1,…,w (here w denotes the number of candidate work centers for quality improvement)

Cpm is labelled as ‘Low’ if $Cpm_{ij} \leq 1$
‘Medium’ if $1<Cpm_{ij} \leq 1.33$
‘High’ if $Cpm_{ij} >1.33$

Gage Capability

P/T is labelled as ‘Low’ if $P/T_{ij} \leq 0.1$
‘Medium’ if $0.1<P/T_{ij} \leq 0.3$
‘High’ if $P/T_{ij} >0.3$

σ_M^2 / σ_T^2 is labelled as ‘Low’ if $(\sigma_M^2 / \sigma_T^2)_{ij} \leq 0.1$
‘Medium’ if $0.1<(\sigma_M^2 / \sigma_T^2)_{ij} \leq 0.3$
‘High’ if $(\sigma_M^2 / \sigma_T^2)_{ij} >0.3$

Loss Coefficient (A_{ik})

Range = R= $\max\{A_{ij}\}-\min\{A_{ij}\}$

Loss coefficient is labeled as ‘Low’ if $A_{ij} < \min\{A_{ij}\}+R/3$
‘Medium’ if $\min\{A_{ij}\}+R/3 \leq A_{ij} < \min\{A_{ij}\}+2R/3$
‘High’ if $\min\{A_{ij}\}+2R/3 \leq A_{ij}$

Closeness to Constraint

Constraining work center is determined by computing the work loads of work centers for satisfying the demand placed on them according to the ideal product mix. If the most loaded work center is loaded very close to its capacity limit (differs at most 10% from the capacity limit), it is defined as the constraint work center. The constraint work center and its successor work center are labeled as ‘At/Next’ while the other work centers are labeled as ‘Far’.

Totally Variable Cost

Totally variable cost of an item at any work center is expressed as the total cost of all raw material and labor hour requirements of the item until that work center.

$CTVC_{ij}$: Cumulative totally variable cost of product i at work center j.

Range = R= $\max\{CTVC_{ij}\}-\min\{CTVC_{ij}\}$

Loss coefficient is labeled as ‘Low’ if $CTVC_{ij} < \min\{CTVC_{ij}\}+R/3$

‘Medium’if $\min\{CTVC_{ij}\}+R/3 \leq CTVC_{ij} < \min\{CTVC_{ij}\}+2R/3$

‘High’ if $\min\{CTVC_{ij}\}+2R/3 \leq CTVC_{ij}$

In this study cumulative costs are calculated as follows

For k=1,2,3,4 and t=5,6,7,8

For a rework unit:

$CTVCR_{it}= CTVCP_{i,t-4}+ TVCR_{it}*YIS_{it}$

For a process unit:

$$CTVCP_{ik}= \frac{YR_{i,k-1}}{YR_{i,k-1}+RR_{i,k-1}*YRR_{i,k+3}}CTVCP_{i,k-1}+\frac{YRR_{i,k+3}*RR_{i,k-1}}{YR_{i,k-1}+RR_{i,k-1}*YRR_{i,k+3}}CTVCR_{i,k+3}+TVCP_{ik}$$

(A process unit receives items from both the previous process unit and rework unit. Totally variable costs are multiplied by the related portions.)

3.2.4 Relationship Values

One of the steps of constructing the decision matrix is to evaluate each alternative against criteria. For this purpose, a rating scale for each criterion is established and each alternative is rated against each criterion based on the rating scale. Score of each alternative under each criterion is found by multiplying its rating by the weight of the criterion. This procedure is repeated for each criterion and by adding the scores a total score for the alternative is determined. In our method, decision maker is not required to apply this procedure. By considering each situation that can be observed for a product at a work center, a table for total scores is constructed. These total scores are called the relationship values.

Scale values for the ratings are established through relative measurement under each criterion. Ratings under each criterion are pairwise compared by using AHP's 1-9 scale. Under each criterion, the ratings are divided by the highest value. Scale values for the ratings are given in Table 3.2. Comparison matrices can be seen in Appendix A.

All possible combinations of the ratings are tabulated. Each case is scored by multiplying the score under a criterion by the weight of that criterion and adding these scores up. At first, criteria are considered as equally important in the improvement decision. Later, different weight sets are generated. The results obtained by all of these weight sets are analyzed and the set which gives the best results is chosen. Weight set determination is explained in sections 3.3.2 and 3.3.3.1 The relationship values table constructed based on the chosen weight set is given in Appendix B.

Table 3.2 Scale values for the ratings

rating	Gage Capability	rating	Cpm	LC	TVC	rating	Closeness to constraint
low-low	0.1111	low	1	0.107	0.107	at/next	1
low-medium	0.2222	medium	0.2073	0.518	0.518	far	0.1111
medium-low	0.3333	high	0.1074	1	1		
medium-medium	0.4444						
low-high	0.5556						
high-low	0.6667						
medium-high	0.7778						
high-medium	0.8889						
high-high	1						

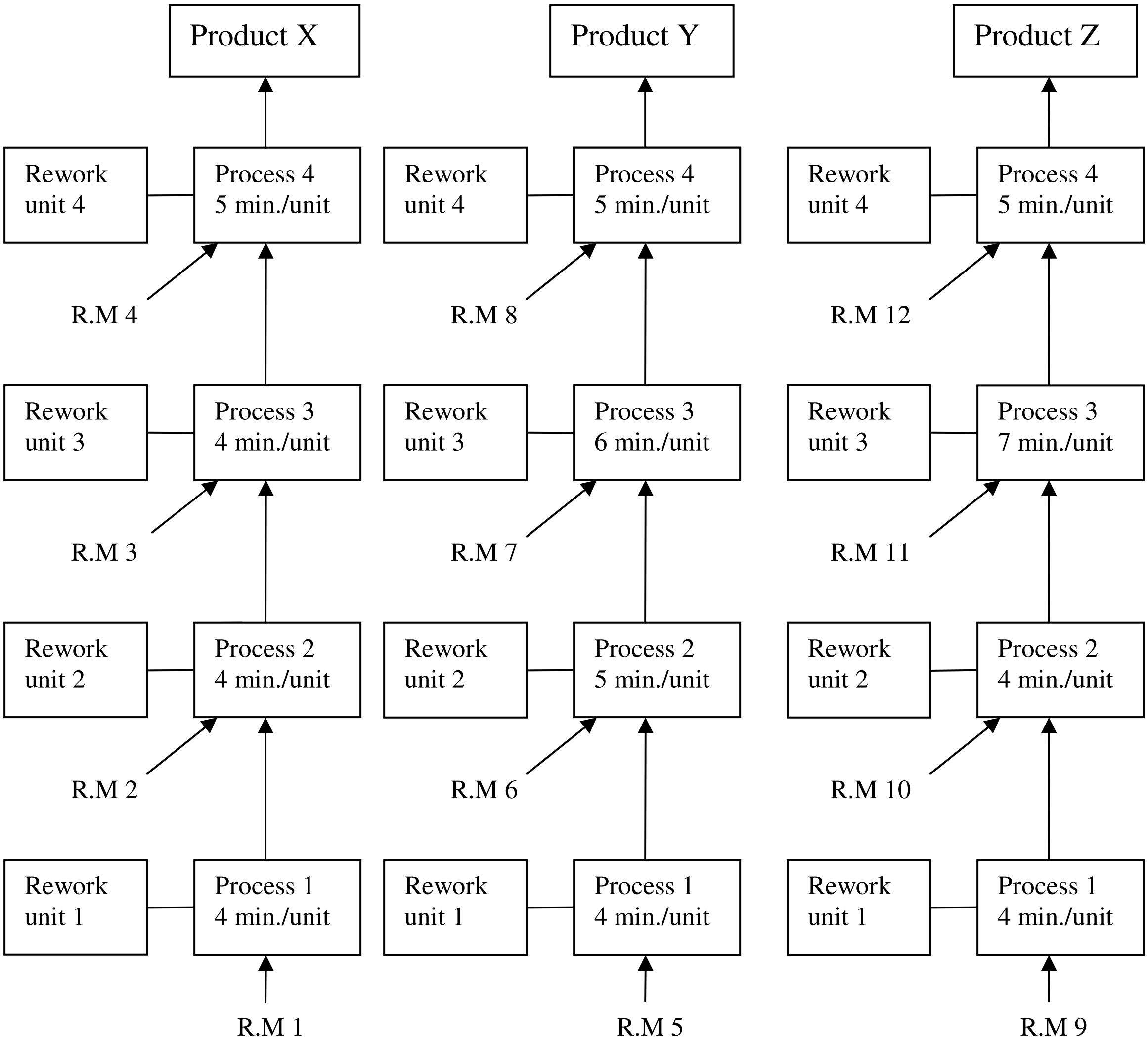
3.3 Application of the Method on Different Cases

3.3.1 Experimental Design

In order to examine the performance of the proposed method under different cases, different experiments are conducted by assigning different parameters to a case problem adapted from the case problem of Atwater and Chackravorty (1995) and illustrated in Figure 3.1. The results obtained under different experimental conditions are compared with the results obtained from the Throughput-Loss (T-L) Method. Effect of changes in criteria weights on results is also of concern. For this purpose different weight sets are tried under these cases. Determination of the different weight sets is explained in the following section.

Standard deviations of the quality characteristics produced in process and rework units, deviations of means from target values, standard deviation of inspection error, loss coefficients, and totally variable costs at both process and rework units are the factors thought to be effective in determination of product mix and QI project selection for fixed specification limits and selling prices. Since a more elaborate operation is carried out in a rework center, the process mean at a rework center is assumed to be at target value, and its variance is assumed to be smaller than that of the related process unit.

When the figure is investigated it is seen that the number of factors that should be included in the design is very high. In order to keep the design in a manageable size the factors related to the rework units are removed from the analysis. Their values are determined in proportion to the related process unit's value just as a starting point. Totally variable cost in a rework unit is determined as 0.5*totally variable cost in the related process unit and standard deviation in the rework center is 0.75*standard deviation of the related process unit. As mentioned before, this dependence is valid only at the starting point. Therefore, 12 'standard deviation' factors, 4 'deviation from target' factors, 4 'inspection error' factors, 12 'loss coefficient' factors and 12 'totally variable cost' factors, a total of 44 factors are included to the experiment. Each factor is assumed to have three levels. The factors and their levels are presented in Table 3.3.



Information:

- Plant operates 8hrs/shift, 2 shifts/day, 4 weeks/month
  4 months planning period (76800 minutes)
- Rework time equals half of processing time
- R.M: Raw material

Figure 3.1 Process flow of the case problem selected for experimentation

Table 3.3 Factors and selected levels

Factor Levels	σ_p	μ-T	σ_m	LC	TVC_p
1	$\frac{1}{12}$(USL-LSL)	0	$0.1\sigma_p$	10	0.12SP
2	$\frac{1}{6}$(USL-LSL)	$1\sigma_p$	$0.25\sigma_p$	150	0.15SP
3	$\frac{1}{3}$(USL-LSL)	$1.5\sigma_p$	$1\sigma_p$	400	0.18SP

Levels of ‘standard deviation of process’ factor is determined in terms of specification range. Selected levels are $\frac{1}{12}$ (USL-LSL), $\frac{1}{6}$(USL-LSL) and $\frac{1}{3}$(USL-LSL).

Deviations from target up to 1.5σ may not be detected using traditional Shewart control charts and the process may be deemed in statistical control (Montgomery, 2005). Therefore, the highest level for ‘deviation from target’ factor is $1.5\sigma_p$. The other two selected levels for this factor are 0 (the process mean is at target) and $1\sigma_p$.

For the three levels of σ_p and the three levels of μ-T, Cpm value of a process changes between 0.277 and 2. This is the range intended to investigate.

If a measurement system has an estimated precision to tolerance value less than or equal to 10% it is deemed acceptable, if this value is between 10% and 30%

the system may be acceptable according to importance of application, cost of measurement and so on. Values of estimated ratio P/T greater than 30% are taken to imply an inadequate measurement system (Pearn and Liao, 2005, Arıtürk, SPAC Six Sigma Consulting, Personal Communication, 2006). However, in practice P/T values up to 200% can be observed (Arıtürk, SPAC Six Sigma Consulting, Personal Communication, 2006). Hence, levels for 'standard deviation of inspection error' factor are selected so that the range from 5% to 200% can be scanned. For these levels (σ_M^2 / σ_T^2) values change between 0.9% and 50%.

The three levels selected for 'loss coefficient' factor are 10, 150 and 400.

One of the levels for 'totally variable cost at process' is 0.12SP. The other levels are 0.15SP and 0.18SP.

A design which permits analyzing 44 factors in 3 levels is Box-Behnken Design. The design matrix is provided in a CD at the back of the thesis. Using this design 3785 different cases can be investigated. (The matrix consists of 3796 rows but the last 12 rows are the same.)

The analysis considers 4 periods each of which consists of 4 months. The first period is the last planning period of the previous year. The improvement activities start at that period but results of the activities start to be effective at the beginning of the first period of the new year. It is assumed that the work center selected for improvement at the beginning of a period is improved to the desired level at the end of the period. Improving a work center is associated with centering its mean, reducing its variation and improving the related measurement system so that the variation is removed. The amount of reduction in process variation depends on the Cpm value of the work center. Table 3.4 represents assumed scenarios for variance reduction.

Table 3.4 Variance reduction scenarios

Cpm	Cpm>2	2≥ Cpm>1.33	1.33≥ Cpm>1	1≥ Cpm
Improved σ	$^{15}/_{16}\sigma$	$^{14}/_{16}\sigma$	$^{12}/_{16}\sigma$	$^{8}/_{16}\sigma$

At the beginnings of the second, third and forth periods, product mix for the period is determined and T-L value is calculated according to this product mix. At the end of the forth period, a total T-L value is computed. Since the first improvement decision can be effective at the beginning of the second period, first period is not included to this total.

3.3.2 Generating Different Weight Sets

For the purpose of weight set generation, a mixture experiment is constructed by using Minitab. Mixture experiments are a special class of response surface experiments and they are used when the response is a function of the proportions of the different ingredients in the mixture. Type of the chosen design is Simplex Lattice. Simplex Lattice design permits addition of points interior of the design space. These points improve coverage of the design space by providing information on the interior of the response surface (Minitab Help, 2005). Since it is desired to keep all of the components (criteria in our method) in the model, lower bounds are set for the components. Lower bound is set as 0.1 for Cpm and 0.05 for other factors. Number of design points generated by this way is 21. The table presenting the weight sets is given in Appendix C.

3.3.3 Analyzing Solutions

3.3.3.1 Weight Sets

As mentioned in Chapter 2, the same problem is also considered by Şarbak (2006) and a method (T-L Method) which utilizes a mathematical model is proposed. This method yields optimal results for each planning period. Decision Matrix Method and T-L Method are applied to 3785 different cases and deviation of the total T-L value obtained by Decision Matrix Method from the result of T-L Method is calculated for each case. Generated codes for this purpose are given in in the CD at the back of the thesis. Average and standard deviation of these deviations are considered as responses in the analyses reported in this section and in the following section.

When weights of the criteria are taken as equal average deviation is 68.3%, and standard deviation of the deviations is 27.79%. Among 21 different weight sets, the weight set that gives the smallest average deviation is 0.45, 0.40 and 0.05 for Process Capability (Cpm) criterion, Loss Coefficient (LC) criterion and the other criteria, respectively. When this weight set is used, the average deviation is calculated as 29.05% that is, decrease in total T-L value resulted by using Decision Matrix Method instead of T-L Method is 29.05% on the average. The standard deviation of the deviations is calculated as 17.27%.

Nonlinear optimization is also performed by using Minitab's Response Optimizer in order to determine the weight set that minimizes the average and standard deviation of the deviations. After suggesting an initial solution, Minitab allows the user to interactively change the input variable settings which are the criteria weights in our case. Contour plots are useful for this purpose. Figure 3.2 is the mixture contour plot generated to determine the component proportions that yield the smallest average of deviations. This plot shows that the average of deviations is smallest when the weight of the Gage Capability (GC) criterion is small and the weight of the Cpm is slightly more than weight of the LC.

The criteria weights determined by this way are 0.575 for Cpm, 0.275 for LC and 0.05 for the other criteria. This weight set is expected to yield an average of 28% and a standard deviation of 16% for deviations. But the results obtained by these weights are 31% for the average and 18% for the standard deviation. After trying two more weight sets it is seen that an average smaller than 29% cannot be obtained, therefore the weights 0.45, 0.40 and 0.05 for Cpm, LC and the other criteria, respectively are adopted. The histogram of the deviations obtained by this weight set is given in Figure 3.3.

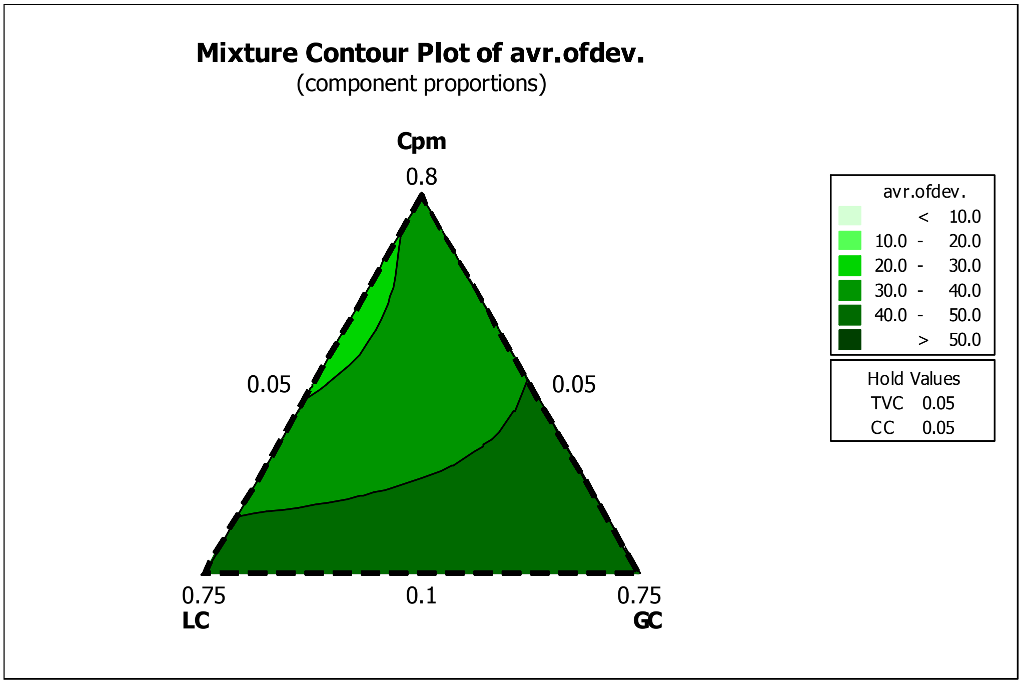


Figure 3.2 Mixture contour plot

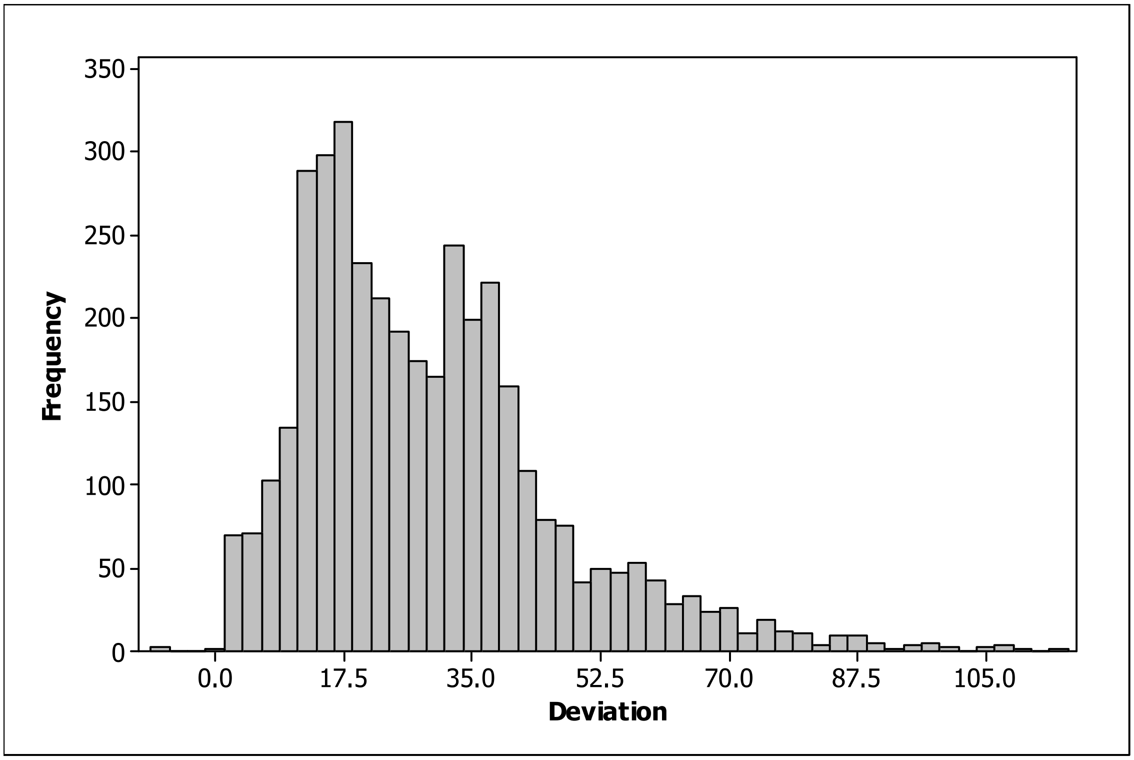


Figure 3.3 Histogram of the deviations

The shape of the histogram and positive skewness value of 1.14 indicate that the distribution is right skewed. Median of the deviations is 25.99% and it is smaller than the mean which equals to 29.05%. A few high deviations make the mean greater than the median. The maximum deviation is 114.9%. Although this is a high deviation, number of such deviations is small and 75% of the deviations is smaller than or equal to 37.75%. Minimum deviation is -7.99%.

A deviation smaller than 0, in other words a total T-L value for 3 periods obtained by Decision Matrix Method greater than the total T-L value obtained by T-L Method is not expected. But it is seen that although T-L Method gives the optimal result for the period it is applied, that selection may not be the optimal choice for multiple periods. Therefore, better decisions are possible. Below is an illustration of such a case. The manufacturing environment is as explained in section 3.3.1. Standard deviations of the quality characteristics, standard deviation of inspection error, loss coefficients and totally variable costs are given in Tables 3.5, 3.6, 3.7 and 3.8, respectively. At processing units mean deviates 1σ from target. Decision matrices are provided in Appendix D. Appendix D also explains the construction of the decision matrix for the first period.

Table 3.5 Standard deviations of the quality characteristics

σ	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	1.1868	1.1187	0.9588	0.8954	0.8901	0.8390	0.7191	0.6716
Product 2	1.1509	1.0955	0.9800	0.9172	0.8632	0.8216	0.7350	0.6879
Product 3	1.1155	1.0625	0.9867	0.9066	0.8366	0.7968	0.7400	0.6799

Table 3.6 Standard deviation of inspection error

σ_m	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	0.2967	0.2797	0.2397	0.2239	0.2967	0.2797	0.2397	0.2239
Product 2	0.2877	0.2739	0.2450	0.2293	0.2877	0.2739	0.2450	0.2293
Product 3	0.2789	0.2656	0.2467	0.2266	0.2789	0.2656	0.2467	0.2266

Table 3.7 Loss coefficients

LC	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	10	150	150	400	10	150	150	400
Product 2	150	150	150	150	150	150	150	150
Product 3	150	150	150	150	150	150	150	150

Table 3.8 Totally variable costs

TVC	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	300	300	300	300	150	150	150	150
Product 2	375	375	375	375	187.5	187.5	187.5	187.5
Product 3	450	450	450	450	225	225	225	225

Table 3.9 shows the work centers chosen for improvement by Decision Matrix Method and T-L Method. The last row shows the result of the T-L Method when the 4th work center is chosen for improvement at the first period. In fact, the 4th work center is the second best choice in the first period, but as it is seen from the table it is a better choice when the result for multiple periods is considered.

Table 3.9 Results of the methods

Method	Work Center Chosen For Improvement			Total T-L Value
	Period 1	Period 2	Period 3	
Decision Matrix	4	3	2	15 687 825
T-L	1	4	2	14 526 298
T-L Manipulated	4	2	3	16 520 653

3.3.3.2 Relative Scale versus Absolute Scale and Ideal Product Mix versus Product Mix of the Current Planning Period

Levels for Cpm and GC are chosen in absolute scale and in determination of the constraint work center and share in production values ideal product mix is used. In order to see whether choosing levels of the factors relatively and using the current period's product mix in determination of share in production values and constraint work center improve the performance of the method or not, necessary modifications are made in the method and T-L values under different experimental conditions are obtained.

If the levels of Cpm and GC are chosen relatively, in other words if the method used for determination of levels for LC and TVC is also applied to Cpm and GC, average difference is 44.94% and standard deviation of the differences is

30.46%. Since these results are worse than the previous results it is decided not to make any modifications on level determination.

When the period's product mix instead of the ideal product mix is used, the average difference is 29.05% and the standard deviation is 17.27%. Using the product mix of the period instead of the ideal product mix does not generate any difference in average and standard deviation of the deviations since our cases do not cover the extreme situations mentioned before. Since the usage of the ideal product mix will be beneficial when an extreme case occurs and using the current product mix does not gives better results in other cases, usage of the ideal product mix is suggested. An example illustrating the advantage of using the ideal product mix is given below. For this example the manufacturing environment is the same as the environment described in section 3.3.1 except the unit processing times. Unit processing times for this example are given in Table 3.10. Table 3.11 gives the standard deviations of quality characteristics produced at work centers, Table 3.12 shows the standard deviation of inspection error, Table 3.13 shows loss coefficients and Table 3.14 gives the totally variable costs. Deviations from target values are seen in Table 3.15.

Table 3.10 Unit processing times

	WC1	WC2	WC3	WC4
Product 1	4	4	4	5
Product 2	6	5	4	5
Product 3	7	4	4	5

Table 3.11 Standard deviations of quality characteristics

σ	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	2.3736	2.2374	1.9177	1.7908	0.7802	1.6780	0.4383	1.3431
Product 2	0.5754	2.1910	0.9800	0.4586	0.4316	1.6432	0.7350	0.3440
Product 3	0.5577	1.0625	0.4934	0.4533	0.4183	0.7968	0.3700	0.3400

Table 3.12 Standard deviation of inspection error

σ_m	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	2.3736	0.5593	1.9177	0.4477	2.3736	0.5593	1.9177	0.4477
Product 2	0.5754	0.5477	0.9800	0.1147	0.5754	0.5477	0.9800	0.1147
Product 3	0.5577	0.2656	0.4934	0.1133	0.5577	0.2656	0.4934	0.1133

Table 3.13 Loss coefficients

LC	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	400	10	10	150	400	10	10	150
Product 2	150	150	10	10	150	150	10	10
Product 3	400	10	10	150	400	10	10	150

Table 3.14 Totally variable costs

TVC	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	360	240	360	360	180	120	180	180
Product 2	375	375	375	375	187.5	187.5	187.5	187.5
Product 3	450	450	450	450	225	225	225	225

Table 3.15 Deviations form target values

μ-T	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	3.5604	0	2.8765	1.7908	0	0	0	0
Product 2	0.8632	0	1.4700	0.4586	0	0	0	0
Product 3	0.8366	0	0.7400	0.4533	0	0	0	0

The following three tables show the decision matrices when the period's product mix is used in construction of the decision matrix for three periods. Importance weight of the selected work center for improvement is shown in bold type. The product mix used to calculate the share in production values for the three periods is 0, 4800 and 3200. Therefore, the share in production value of the first product is zero.

Table 3.16 Decision matrix for the first period for the period’s product mix case

WC Product	1	2	3	4	5	6	7	8	SR
1	0.91	0.54	0.57	0.72	0.91	0.54	0.57	0.75	0
2	0.36	0.70	0.57	0.16	0.32	0.72	0.17	0.17	0.6
3	0.55	0.16	0.22	0.33	0.51	0.14	0.20	0.33	0.4
IW	0.436	0.484	0.43	0.228	0.396	**0.488**	0.182	0.234	

Table 3.17 Decision matrix for the second period for the period’s product mix case

WC Product	1	2	3	4	5	6	7	8	SR
1	0.91	0.54	0.57	0.72	0.91	0.11	0.57	0.75	0
2	0.36	0.70	0.57	0.16	0.32	0.29	0.17	0.17	0.6
3	0.55	0.16	0.22	0.33	0.51	0.13	0.20	0.33	0.4
IW	0.436	**0.484**	0.43	0.228	0.396	0.226	0.182	0.234	

Table 3.18 Decision matrix for the third period for the period’s product mix case

WC Product	1	2	3	4	5	6	7	8	SR
1	0.91	0.15	0.57	0.72	0.91	0.11	0.57	0.75	0
2	0.36	0.67	0.57	0.16	0.32	0.29	0.17	0.17	0.6
3	0.55	0.11	0.22	0.33	0.51	0.13	0.20	0.33	0.4
IW	0.436	**0.446**	0.43	0.228	0.396	0.226	0.182	0.234	

When the ideal product mix is used in construction of the decision matrix, the following three matrices are obtained for the three periods.

Table 3.19 Decision matrix for the first period for the ideal product mix case

WC Product	1	2	3	4	5	6	7	8	SR
1	0.95	0.58	0.57	0.72	0.95	0.54	0.57	0.75	0.4445
2	0.41	0.75	0.57	0.16	0.36	0.72	0.17	0.17	0.3332
3	0.60	0.21	0.22	0.33	0.55	0.14	0.20	0.33	0.2222
IW	**0.692**	0.554	0.492	0.447	0.664	0.511	0.354	0.463	

Table 3.20 Decision matrix for the second period for the ideal product mix case

WC Product	1	2	3	4	5	6	7	8	SR
1	0.55	0.58	0.57	0.72	0.95	0.54	0.57	0.75	0.4445
2	0.32	0.75	0.57	0.16	0.36	0.72	0.17	0.17	0.3332
3	0.51	0.21	0.22	0.33	0.55	0.14	0.20	0.33	0.2222
IW	0.464	0.554	0.492	0.447	**0.664**	0.511	0.354	0.463	

Table 3.21 Decision matrix for the third period for the ideal product mix case

WC Product	1	2	3	4	5	6	7	8	SR
1	0.55	0.58	0.57	0.72	0.51	0.54	0.57	0.75	0.4445
2	0.32	0.75	0.57	0.16	0.32	0.72	0.17	0.17	0.3332
3	0.51	0.21	0.22	0.33	0.51	0.14	0.20	0.33	0.2222
IW	0.464	**0.554**	0.492	0.447	0.446	0.511	0.354	0.463	

Table 3.22 gives the work centers selected for improvement and resulted T-L values. Since the first product is not produced, when the ideal product mix is not used improvement need of the first work center due to the first product cannot be evaluated although the corresponding relationship value is high. By using the ideal product mix in construction of the decision matrix it is seen that improving the first work center is a profitable decision.

Table 3.22 Results of the methods

Method	Work Center Chosen For Improvement			Total T-L Value
	Period 1	Period 2	Period 3	
Decision Matrix with Ideal Product Mix	1	5	2	17 511 444
Decision Matrix with Product Mix of Current Period	6	2	2	14 523 929

CHAPTER 4

CONCLUSION AND FUTURE STUDY

In this thesis, we develop a method to select a work center for improvement by considering customer satisfaction, cost and time terms in manufacturing environments. We assume a manufacturing environment where there is a separate rework unit for each processing unit where rework is possible, only one quality characteristic is produced by a processing unit and the processing units are independent of each other. The distribution of the quality characteristic of items produced at a processing unit or at a rework unit is assumed to be normal. Furthermore, target values for the quality characteristics are the nominal values and 100% inspection is performed after both process and rework. In addition, the inspection devices are calibrated but not precise. The processes are under statistical control.

A method to select a work center for improvement where there is no rework and no inspection error is developed by Mertoğlu (2003). Study of Mertoğlu (2003) also assumes that quality characteristics of the products have means at their target values. We improve this method by relaxing these assumptions. In order to take account of deviations from target values, Cpm, which is a process capability index that considers both process centering and standard deviation is selected as process capability criterion. Existence of inspection error necessitates GR&R studies. The GR&R studies yield estimated values of the components of observed variation. Gage capability criterion is included to take inspection error into account. Since there is inspection error in the environment and this can affect estimation of the process capability index, in calculation of this index estimate of process standard deviation isolated from inspection error is used. Decision Matrix Method enables to include the rework centers in candidate work centers for improvement. In calculation of cumulative totally variable costs for work centers to determine the levels for the totally variable cost criterion, the yield rates of rework units, probability of sending an item to rework unit and rework costs are considered. The constraint work center is identified depending on the ideal product mix instead of the period's product mix. Calculation of share in production values are also based on the ideal product mix. In determination of the relationship values, AHP's absolute mode is used.

Results of the proposed method obtained under different experimental conditions with different weight sets are compared with the results of T-L Method which selects the work center that gives the maximum T-L value by its improvement for the planning period under consideration. Effect of methods used in choice of levels and usage of the ideal product mix in construction of the decision matrix on the performance of the method are analyzed, as well. It is seen that results obtained by choosing the levels of GC and Cpm in absolute scale and levels of the other criteria relatively are better than the results obtained when relative scale is used for level determination for all of the criteria. Using the current period's product mix instead of the ideal product mix does not generate difference in the results but since in extreme cases the ideal product mix enables recognizing better improvement opportunities usage of the ideal product mix is suggested. The determined weight set implies that the most effective criterion in selection of work center for improvement is Cpm. LC is the second important criterion in the decision. GC, TVC and closeness to constraint have relatively small effects on the decision.

Deviation of Decision Matrix Method from T-L Method is 29.05% on the average. Although T-L Method gives better results than our method in almost all of the cases, Decision Matrix have the advantage of simplicity. On the other hand, the selection made by T-L Method may not be the best choice in multiperiod case. For this reason, a method which evaluates the effect of the selections for more than one period is needed. Such a method entails determination of the appropriate number of periods.

In this study raw material costs and labor costs are considered as totally variable costs and it is assumed that workers are paid on hourly basis. If it is not the case and if the labor cost does not change by the volume of production it is not included in the totally variable costs. Similarly, any costs that increase as a direct result of increased level of production can be taken as totally variable costs. One other assumption is 100% inspection. Generally 100% inspection cannot be applied and some sampling techniques are developed. On the other hand, rework operations may not be handled separately from the processing unit. These assumptions do not generate any restriction for the applicability of the method, but the weight set determination and examination of the performance of the method is performed on an example problem where these assumptions are satisfied. Therefore, the analyses are valid for such a manufacturing environment.

One of the assumptions is independence of quality characteristics. This may not be the case in a manufacturing environment. Multivariate capability indices and loss functions may be helpful in such instances. Improving the method to handle the cases where quality characteristics are dependent and/or work centers are producing more than one quality characteristic can be a new area of research.

In order to use Decision Matrix Method in non-manufacturing environment, new criteria suitable for a non-manufacturing environment should be determined and this opens a new area of research.

In determination of relationship values scores under criteria are aggregated additively. Aggregation rule and scale values affect the performance of the method. Determination of the most accurate type of aggregation and scale values needs further study.

In order to handle more general cases and obtain more accurate solutions, extensive analyses on cost terms, customer aspects, measures related to the work centers and the relationships among them should be performed. The decision matrix may be insufficient to consider more complex manufacturing environments. A more flexible decision support tool that can evaluate the situation in detail is needed to deal with the problem adequately.

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APPENDIX A

COMPARISON MATRICES

Cpm	low	medium	high
low	1	5	9
medium	1/5	1	2
high	1/9	1/2	1

LC	low	medium	high
Low	1	1/5	1/9
medium	5	1	1/2
high	9	2	1

TVC	low	medium	high
Low	1	1/5	1/9
medium	5	1	1/2
high	9	2	1

closeness to constraint	at/next	far
at/next	1	9
far	1/9	1

GC	low low	low medium	medium low	medium medium	low high	high low	medium high	high medium	high high
low low	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9

(Priorities of the ratings for gage capability criterion is obtained from the first raw of the comparison matrix.)

APPENDIX B

RELATIONSHIP VALUES

Table B.1 Relationship values

Gage Capability		Process Capability Index (Cpm)	Loss Coefficient	Totally Variable Cost	Closeness to Constraint	Relationship Value
P/T	σ_M^2/σ_T^2					
low	low	low	low	low	at/next	0.55
low	low	low	low	low	far	0.51
low	low	low	low	medium	at/next	0.57
low	low	low	low	medium	far	0.53
low	low	low	low	high	at/next	0.60
low	low	low	low	high	far	0.55
low	low	low	medium	low	at/next	0.72
low	low	low	medium	low	far	0.67
low	low	low	medium	medium	at/next	0.74
low	low	low	medium	medium	far	0.69
low	low	low	medium	high	at/next	0.76
low	low	low	medium	high	far	0.72
low	low	low	high	low	at/next	0.91
low	low	low	high	low	far	0.87
low	low	low	high	medium	at/next	0.93
low	low	low	high	medium	far	0.89
low	low	low	high	high	at/next	0.96
low	low	low	high	high	far	0.91
low	low	medium	low	low	at/next	0.20
low	low	medium	low	low	far	0.15
low	low	medium	low	medium	at/next	0.22
low	low	medium	low	medium	far	0.17
low	low	medium	low	high	at/next	0.24
low	low	medium	low	high	far	0.20
low	low	medium	medium	low	at/next	0.36
low	low	medium	medium	low	far	0.32
low	low	medium	medium	medium	at/next	0.38
low	low	medium	medium	medium	far	0.34
low	low	medium	medium	high	at/next	0.41
low	low	medium	medium	high	far	0.36
low	low	medium	high	low	at/next	0.55
low	low	medium	high	low	far	0.51
low	low	medium	high	medium	at/next	0.57
low	low	medium	high	medium	far	0.53
low	low	medium	high	high	at/next	0.60

Table B.1 (continued)

Gage Capability		Process Capability Index (Cpm)	Loss Coefficient	Totally Variable Cost	Closeness to Constraint	Relationship Value
P/T	σ_M^2 / σ_T^2					
low	low	medium	high	high	far	0.55
low	low	high	low	low	at/next	0.15
low	low	high	low	low	far	0.11
low	low	high	low	medium	at/next	0.17
low	low	high	low	medium	far	0.13
low	low	high	low	high	at/next	0.20
low	low	high	low	high	far	0.15
low	low	high	medium	low	at/next	0.32
low	low	high	medium	low	far	0.27
low	low	high	medium	medium	at/next	0.34
low	low	high	medium	medium	far	0.29
low	low	high	medium	high	at/next	0.36
low	low	high	medium	high	far	0.32
low	low	high	high	low	at/next	0.51
low	low	high	high	low	far	0.46
low	low	high	high	medium	at/next	0.53
low	low	high	high	medium	far	0.49
low	low	high	high	high	at/next	0.55
low	low	high	high	high	far	0.51
low	medium	low	low	low	at/next	0.56
low	medium	low	low	low	far	0.51
low	medium	low	low	medium	at/next	0.58
low	medium	low	low	medium	far	0.54
low	medium	low	low	high	at/next	0.60
low	medium	low	low	high	far	0.56
low	medium	low	medium	low	at/next	0.72
low	medium	low	medium	low	far	0.68
low	medium	low	medium	medium	at/next	0.74
low	medium	low	medium	medium	far	0.70
low	medium	low	medium	high	at/next	0.77
low	medium	low	medium	high	far	0.72
low	medium	low	high	low	at/next	0.92
low	medium	low	high	low	far	0.87
low	medium	low	high	medium	at/next	0.94
low	medium	low	high	medium	far	0.89
low	medium	low	high	high	at/next	0.96
low	medium	low	high	high	far	0.92
low	medium	medium	low	low	at/next	0.20
low	medium	medium	low	low	far	0.16
low	medium	medium	low	medium	at/next	0.22
low	medium	medium	low	medium	far	0.18
low	medium	medium	low	high	at/next	0.25
low	medium	medium	low	high	far	0.20

Table B.1 (continued)

Gage Capability		Process Capability Index (Cpm)	Loss Coefficient	Totally Variable Cost	Closeness to Constraint	Relationship Value
P/T	σ_M^2 / σ_T^2					
low	medium	medium	medium	low	at/next	0.37
low	medium	medium	medium	low	far	0.32
low	medium	medium	medium	medium	at/next	0.39
low	medium	medium	medium	medium	far	0.34
low	medium	medium	medium	high	at/next	0.41
low	medium	medium	medium	high	far	0.37
low	medium	medium	high	low	at/next	0.56
low	medium	medium	high	low	far	0.52
low	medium	medium	high	medium	at/next	0.58
low	medium	medium	high	medium	far	0.54
low	medium	medium	high	high	at/next	0.60
low	medium	medium	high	high	far	0.56
low	medium	high	low	low	at/next	0.16
low	medium	high	low	low	far	0.11
low	medium	high	low	medium	at/next	0.18
low	medium	high	low	medium	far	0.13
low	medium	high	low	high	at/next	0.20
low	medium	high	low	high	far	0.16
low	medium	high	medium	low	at/next	0.32
low	medium	high	medium	low	far	0.28
low	medium	high	medium	medium	at/next	0.34
low	medium	high	medium	medium	far	0.30
low	medium	high	medium	high	at/next	0.37
low	medium	high	medium	high	far	0.32
low	medium	high	high	low	at/next	0.51
low	medium	high	high	low	far	0.47
low	medium	high	high	medium	at/next	0.54
low	medium	high	high	medium	far	0.49
low	medium	high	high	high	at/next	0.56
low	medium	high	high	high	far	0.51
low	high	low	low	low	at/next	0.58
low	high	low	low	low	far	0.53
low	high	low	low	medium	at/next	0.60
low	high	low	low	medium	far	0.55
low	high	low	low	high	at/next	0.62
low	high	low	low	high	far	0.58
low	high	low	medium	low	at/next	0.74
low	high	low	medium	low	far	0.70
low	high	low	medium	medium	at/next	0.76
low	high	low	medium	medium	far	0.72
low	high	low	medium	high	at/next	0.79
low	high	low	medium	high	far	0.74
low	high	low	high	low	at/next	0.93

Table B.1 (continued)

Gage Capability		Process Capability Index (Cpm)	Loss Coefficient	Totally Variable Cost	Closeness to Constraint	Relationship Value
P/T	σ_M^2 / σ_T^2					
low	high	low	high	low	far	0.89
low	high	low	high	medium	at/next	0.95
low	high	low	high	medium	far	0.91
low	high	low	high	high	at/next	0.98
low	high	low	high	high	far	0.93
low	high	medium	low	low	at/next	0.22
low	high	medium	low	low	far	0.17
low	high	medium	low	medium	at/next	0.24
low	high	medium	low	medium	far	0.20
low	high	medium	low	high	at/next	0.26
low	high	medium	low	high	far	0.22
low	high	medium	medium	low	at/next	0.38
low	high	medium	medium	low	far	0.34
low	high	medium	medium	medium	at/next	0.40
low	high	medium	medium	medium	far	0.36
low	high	medium	medium	high	at/next	0.43
low	high	medium	medium	high	far	0.38
low	high	medium	high	low	at/next	0.58
low	high	medium	high	low	far	0.53
low	high	medium	high	medium	at/next	0.60
low	high	medium	high	medium	far	0.55
low	high	medium	high	high	at/next	0.62
low	high	medium	high	high	far	0.58
low	high	high	low	low	at/next	0.17
low	high	high	low	low	far	0.13
low	high	high	low	medium	at/next	0.19
low	high	high	low	medium	far	0.15
low	high	high	low	high	at/next	0.22
low	high	high	low	high	far	0.17
low	high	high	medium	low	at/next	0.34
low	high	high	medium	low	far	0.29
low	high	high	medium	medium	at/next	0.36
low	high	high	medium	medium	far	0.31
low	high	high	medium	high	at/next	0.38
low	high	high	medium	high	far	0.34
low	high	high	high	low	at/next	0.53
low	high	high	high	low	far	0.49
low	high	high	high	medium	at/next	0.55
low	high	high	high	medium	far	0.51
low	high	high	high	high	at/next	0.58
low	high	high	high	high	far	0.53
medium	low	low	low	low	at/next	0.56
medium	low	low	low	low	far	0.52

Table B.1 (continued)

Gage Capability		Process Capability Index (Cpm)	Loss Coefficient	Totally Variable Cost	Closeness to Constraint	Relationship Value
P/T	σ_M^2 / σ_T^2					
medium	low	low	low	medium	at/next	0.59
medium	low	low	low	medium	far	0.54
medium	low	low	low	high	at/next	0.61
medium	low	low	low	high	far	0.57
medium	low	low	medium	low	at/next	0.73
medium	low	Low	medium	low	far	0.68
medium	low	Low	medium	medium	at/next	0.75
medium	low	Low	medium	medium	far	0.71
medium	low	low	medium	high	at/next	0.77
medium	low	low	medium	high	far	0.73
medium	low	low	high	low	at/next	0.92
medium	low	low	high	low	far	0.88
medium	low	low	high	medium	at/next	0.94
medium	low	low	high	medium	far	0.90
medium	low	low	high	high	at/next	0.97
medium	low	low	high	high	far	0.92
medium	low	medium	low	low	at/next	0.21
medium	low	medium	low	low	far	0.16
medium	low	medium	low	medium	at/next	0.23
medium	low	medium	low	medium	far	0.18
medium	low	medium	low	high	at/next	0.25
medium	low	medium	low	high	far	0.21
medium	low	medium	medium	low	at/next	0.37
medium	low	medium	medium	low	far	0.33
medium	low	medium	medium	medium	at/next	0.39
medium	low	medium	medium	medium	far	0.35
medium	low	medium	medium	high	at/next	0.42
medium	low	medium	medium	high	far	0.37
medium	low	medium	high	low	at/next	0.57
medium	low	medium	high	low	far	0.52
medium	low	medium	high	medium	at/next	0.59
medium	low	medium	high	medium	far	0.54
medium	low	medium	high	high	at/next	0.61
medium	low	medium	high	high	far	0.57
medium	low	high	low	low	at/next	0.16
medium	low	high	low	low	far	0.12
medium	low	high	low	medium	at/next	0.18
medium	low	high	low	medium	far	0.14
medium	low	high	low	high	at/next	0.21
medium	low	high	low	high	far	0.16
medium	low	high	medium	low	at/next	0.33
medium	low	high	medium	low	far	0.28
medium	low	high	medium	medium	at/next	0.35

Table B.1 (continued)

Gage Capability		Process Capability Index (Cpm)	Loss Coefficient	Totally Variable Cost	Closeness to Constraint	Relationship Value
P/T	σ_M^2 / σ_T^2					
medium	low	high	medium	medium	far	0.30
medium	low	high	medium	high	at/next	0.37
medium	low	high	medium	high	far	0.33
medium	low	high	high	low	at/next	0.52
medium	low	high	high	low	far	0.48
medium	low	high	high	medium	at/next	0.54
medium	low	high	high	medium	far	0.50
medium	low	high	high	high	at/next	0.56
medium	low	high	high	high	far	0.52
medium	medium	low	low	low	at/next	0.57
medium	medium	low	low	low	far	0.53
medium	medium	low	low	medium	at/next	0.59
medium	medium	low	low	medium	far	0.55
medium	medium	low	low	high	at/next	0.62
medium	medium	low	low	high	far	0.57
medium	medium	low	medium	low	at/next	0.73
medium	medium	low	medium	low	far	0.69
medium	medium	low	medium	medium	at/next	0.76
medium	medium	low	medium	medium	far	0.71
medium	medium	low	medium	high	at/next	0.78
medium	medium	low	medium	high	far	0.74
medium	medium	low	high	low	at/next	0.93
medium	medium	low	high	low	far	0.88
medium	medium	low	high	medium	at/next	0.95
medium	medium	low	high	medium	far	0.90
medium	medium	low	high	high	at/next	0.97
medium	medium	low	high	high	far	0.93
medium	medium	medium	low	low	at/next	0.21
medium	medium	medium	low	low	far	0.17
medium	medium	medium	low	medium	at/next	0.23
medium	medium	medium	low	medium	far	0.19
medium	medium	medium	low	high	at/next	0.26
medium	medium	medium	low	high	far	0.21
medium	medium	medium	medium	low	at/next	0.38
medium	medium	medium	medium	low	far	0.33
medium	medium	medium	medium	medium	at/next	0.40
medium	medium	medium	medium	medium	far	0.35
medium	medium	medium	medium	high	at/next	0.42
medium	medium	medium	medium	high	far	0.38
medium	medium	medium	high	low	at/next	0.57
medium	medium	medium	high	low	far	0.53
medium	medium	medium	high	medium	at/next	0.59
medium	medium	medium	high	medium	far	0.55

Table B.1 (continued)

Gage Capability		Process Capability Index (Cpm)	Loss Coefficient	Totally Variable Cost	Closeness to Constraint	Relationship Value
P/T	σ_M^2 / σ_T^2					
medium	medium	medium	high	high	at/next	0.62
medium	medium	medium	high	high	far	0.57
medium	medium	high	low	low	at/next	0.17
medium	medium	high	low	low	far	0.12
medium	medium	high	low	medium	at/next	0.19
medium	medium	high	low	medium	far	0.14
medium	medium	high	low	high	at/next	0.21
medium	medium	high	low	high	far	0.17
medium	medium	high	medium	low	at/next	0.33
medium	medium	high	medium	low	far	0.29
medium	medium	high	medium	medium	at/next	0.35
medium	medium	high	medium	medium	far	0.31
medium	medium	high	medium	high	at/next	0.38
medium	medium	high	medium	high	far	0.33
medium	medium	high	high	low	at/next	0.53
medium	medium	high	high	low	far	0.48
medium	medium	high	high	medium	at/next	0.55
medium	medium	high	high	medium	far	0.50
medium	medium	high	high	high	at/next	0.57
medium	medium	high	high	high	far	0.53
medium	high	low	low	low	at/next	0.59
medium	high	low	low	low	far	0.54
medium	high	low	low	medium	at/next	0.61
medium	high	low	low	medium	far	0.56
medium	high	low	low	high	at/next	0.63
medium	high	low	low	high	far	0.59
medium	high	low	medium	low	at/next	0.75
medium	high	low	medium	low	far	0.71
medium	high	low	medium	medium	at/next	0.77
medium	high	low	medium	medium	far	0.73
medium	high	low	medium	high	at/next	0.80
medium	high	low	medium	high	far	0.75
medium	high	low	high	low	at/next	0.94
medium	high	low	high	low	far	0.90
medium	high	low	high	medium	at/next	0.96
medium	high	low	high	medium	far	0.92
medium	high	low	high	high	at/next	0.99
medium	high	low	high	high	far	0.94
medium	high	medium	low	low	at/next	0.23
medium	high	medium	low	low	far	0.19
medium	high	medium	low	medium	at/next	0.25
medium	high	medium	low	medium	far	0.21
medium	high	medium	low	high	at/next	0.28

Table B.1 (continued)

Gage Capability		Process Capability Index (Cpm)	Loss Coefficient	Totally Variable Cost	Closeness to Constraint	Relationship Value
P/T	σ_M^2 / σ_T^2					
medium	high	medium	low	high	far	0.23
medium	high	medium	medium	low	at/next	0.39
medium	high	medium	medium	low	far	0.35
medium	high	medium	medium	medium	at/next	0.42
medium	high	medium	medium	medium	far	0.37
medium	high	medium	medium	high	at/next	0.44
medium	high	medium	medium	high	far	0.39
medium	high	medium	high	low	at/next	0.59
medium	high	medium	high	low	far	0.54
medium	high	medium	high	medium	at/next	0.61
medium	high	medium	high	medium	far	0.56
medium	high	medium	high	high	at/next	0.63
medium	high	medium	high	high	far	0.59
medium	high	high	low	low	at/next	0.19
medium	high	high	low	low	far	0.14
medium	high	high	low	medium	at/next	0.21
medium	high	high	low	medium	far	0.16
medium	high	high	low	high	at/next	0.23
medium	high	high	low	high	far	0.19
medium	high	high	medium	low	at/next	0.35
medium	high	high	medium	low	far	0.31
medium	high	high	medium	medium	at/next	0.37
medium	high	high	medium	medium	far	0.33
medium	high	high	medium	high	at/next	0.39
medium	high	high	medium	high	far	0.35
medium	high	high	high	low	at/next	0.54
medium	high	high	high	low	far	0.50
medium	high	high	high	medium	at/next	0.56
medium	high	high	high	medium	far	0.52
medium	high	high	high	high	at/next	0.59
medium	high	high	high	high	far	0.54
high	low	low	low	low	at/next	0.58
high	low	low	low	low	far	0.54
high	low	low	low	medium	at/next	0.60
high	low	low	low	medium	far	0.56
high	low	low	low	high	at/next	0.63
high	low	low	low	high	far	0.58
high	low	low	medium	low	at/next	0.75
high	low	low	medium	low	far	0.70
high	low	low	medium	medium	at/next	0.77
high	low	low	medium	medium	far	0.72
high	low	low	medium	high	at/next	0.79
high	low	low	medium	high	far	0.75

Table B.1 (continued)

Gage Capability		Process Capability Index (Cpm)	Loss Coefficient	Totally Variable Cost	Closeness to Constraint	Relationship Value
P/T	σ_M^2 / σ_T^2					
high	low	low	high	low	at/next	0.94
high	low	low	high	low	far	0.89
high	low	low	high	medium	at/next	0.96
high	low	low	high	medium	far	0.91
high	low	low	high	high	at/next	0.98
high	low	low	high	high	far	0.94
high	low	medium	low	low	at/next	0.22
high	low	medium	low	low	far	0.18
high	low	medium	low	medium	at/next	0.25
high	low	medium	low	medium	far	0.20
high	low	medium	low	high	at/next	0.27
high	low	medium	low	high	far	0.23
high	low	medium	medium	low	at/next	0.39
high	low	medium	medium	low	far	0.34
high	low	medium	medium	medium	at/next	0.41
high	low	medium	medium	medium	far	0.37
high	low	medium	medium	high	at/next	0.43
high	low	medium	medium	high	far	0.39
high	low	medium	high	low	at/next	0.58
high	low	medium	high	low	far	0.54
high	low	medium	high	medium	at/next	0.60
high	low	medium	high	medium	far	0.56
high	low	medium	high	high	at/next	0.63
high	low	medium	high	high	far	0.58
high	low	high	low	low	at/next	0.18
high	low	high	low	low	far	0.14
high	low	high	low	medium	at/next	0.20
high	low	high	low	medium	far	0.16
high	low	high	low	high	at/next	0.22
high	low	high	low	high	far	0.18
high	low	high	medium	low	at/next	0.34
high	low	high	medium	low	far	0.30
high	low	high	medium	medium	at/next	0.36
high	low	high	medium	medium	far	0.32
high	low	high	medium	high	at/next	0.39
high	low	high	medium	high	far	0.34
high	low	high	high	low	at/next	0.54
high	low	high	high	low	far	0.49
high	low	high	high	medium	at/next	0.56
high	low	high	high	medium	far	0.51
high	low	high	high	high	at/next	0.58
high	low	high	high	high	far	0.54
high	medium	low	low	low	at/next	0.59

Table B.1 (continued)

Gage Capability		Process Capability Index (Cpm)	Loss Coefficient	Totally Variable Cost	Closeness to Constraint	Relationship Value
P/T	σ_M^2 / σ_T^2					
high	medium	low	low	low	far	0.55
high	medium	low	low	medium	at/next	0.61
high	medium	low	low	medium	far	0.57
high	medium	low	low	high	at/next	0.64
high	medium	low	low	high	far	0.59
high	medium	low	medium	low	at/next	0.76
high	medium	low	medium	low	far	0.71
high	medium	low	medium	medium	at/next	0.78
high	medium	low	medium	medium	far	0.73
high	medium	low	medium	high	at/next	0.80
high	medium	low	medium	high	far	0.76
high	medium	low	high	low	at/next	0.95
high	medium	low	high	low	far	0.91
high	medium	low	high	medium	at/next	0.97
high	medium	low	high	medium	far	0.93
high	medium	low	high	high	at/next	0.99
high	medium	low	high	high	far	0.95
high	medium	medium	low	low	at/next	0.24
high	medium	medium	low	low	far	0.19
high	medium	medium	low	medium	at/next	0.26
high	medium	medium	low	medium	far	0.21
high	medium	medium	low	high	at/next	0.28
high	medium	medium	low	high	far	0.24
high	medium	medium	medium	low	at/next	0.40
high	medium	medium	medium	low	far	0.36
high	medium	medium	medium	medium	at/next	0.42
high	medium	medium	medium	medium	far	0.38
high	medium	medium	medium	high	at/next	0.44
high	medium	medium	medium	high	far	0.40
high	medium	medium	high	low	at/next	0.59
high	medium	medium	high	low	far	0.55
high	medium	medium	high	medium	at/next	0.61
high	medium	medium	high	medium	far	0.57
high	medium	medium	high	high	at/next	0.64
high	medium	medium	high	high	far	0.59
high	medium	high	low	low	at/next	0.19
high	medium	high	low	low	far	0.15
high	medium	high	low	medium	at/next	0.21
high	medium	high	low	medium	far	0.17
high	medium	high	low	high	at/next	0.24
high	medium	high	low	high	far	0.19
high	medium	high	medium	low	at/next	0.36
high	medium	high	medium	low	far	0.31

Table B.1 (continued)

Gage Capability		Process Capability Index (Cpm)	Loss Coefficient	Totally Variable Cost	Closeness to Constraint	Relationship Value
P/T	σ_M^2 / σ_T^2					
high	medium	high	medium	medium	at/next	0.38
high	medium	high	medium	medium	far	0.33
high	medium	high	medium	high	at/next	0.40
high	medium	high	medium	high	far	0.36
high	medium	high	high	low	at/next	0.55
high	medium	high	high	low	far	0.50
high	medium	high	high	medium	at/next	0.57
high	medium	high	high	medium	far	0.52
high	medium	high	high	high	at/next	0.59
high	medium	high	high	high	far	0.55
high	high	low	low	low	at/next	0.60
high	high	low	low	low	far	0.55
high	high	low	low	medium	at/next	0.62
high	high	low	low	medium	far	0.57
high	high	low	low	high	at/next	0.64
high	high	low	low	high	far	0.60
high	high	low	medium	low	at/next	0.76
high	high	low	medium	low	far	0.72
high	high	low	medium	medium	at/next	0.78
high	high	low	medium	medium	far	0.74
high	high	low	medium	high	at/next	0.81
high	high	low	medium	high	far	0.76
high	high	low	high	low	at/next	0.96
high	high	low	high	low	far	0.91
high	high	low	high	medium	at/next	0.98
high	high	low	high	medium	far	0.93
high	high	low	high	high	at/next	1.00
high	high	low	high	high	far	0.96
high	high	medium	low	low	at/next	0.24
high	high	medium	low	low	far	0.20
high	high	medium	low	medium	at/next	0.26
high	high	medium	low	medium	far	0.22
high	high	medium	low	high	at/next	0.29
high	high	medium	low	high	far	0.24
high	high	medium	medium	low	at/next	0.41
high	high	medium	medium	low	far	0.36
high	high	medium	medium	medium	at/next	0.43
high	high	medium	medium	medium	far	0.38
high	high	medium	medium	high	at/next	0.45
high	high	medium	medium	high	far	0.41
high	high	medium	high	low	at/next	0.60
high	high	medium	high	low	far	0.55
high	high	medium	high	medium	at/next	0.62

Table B.1 (continued)

Gage Capability		Process Capability Index (Cpm)	Loss Coefficient	Totally Variable Cost	Closeness to Constraint	Relationship Value
P/T	σ_M^2 / σ_T^2					
high	high	medium	high	medium	far	0.57
high	high	medium	high	high	at/next	0.64
high	high	medium	high	high	far	0.60
high	high	high	low	low	at/next	0.20
high	high	high	low	low	far	0.15
high	high	high	low	medium	at/next	0.22
high	high	high	low	medium	far	0.17
high	high	high	low	high	at/next	0.24
high	high	high	low	high	far	0.20
high	high	high	medium	low	at/next	0.36
high	high	high	medium	low	far	0.32
high	high	high	medium	medium	at/next	0.38
high	high	high	medium	medium	far	0.34
high	high	high	medium	high	at/next	0.41
high	high	high	medium	high	far	0.36
high	high	high	high	low	at/next	0.55
high	high	high	high	low	far	0.51
high	high	high	high	medium	at/next	0.57
high	high	high	high	medium	far	0.53
high	high	high	high	high	at/next	0.60
high	high	high	high	high	far	0.55

APPENDIX C

WEIGHT SETS

Cpm	**LC**	**GC**	**TVC**	**CC**
0.8	0.05	0.05	0.05	0.05
0.45	0.4	0.05	0.05	0.05
0.45	0.05	0.4	0.05	0.05
0.45	0.05	0.05	0.4	0.05
0.45	0.05	0.05	0.05	0.4
0.1	0.75	0.05	0.05	0.05
0.1	0.4	0.4	0.05	0.05
0.1	0.4	0.05	0.4	0.05
0.1	0.4	0.05	0.05	0.4
0.1	0.05	0.75	0.05	0.05
0.1	0.05	0.4	0.4	0.05
0.1	0.05	0.4	0.05	0.4
0.1	0.05	0.05	0.75	0.05
0.1	0.05	0.05	0.4	0.4
0.1	0.05	0.05	0.05	0.75
0.24	0.19	0.19	0.19	0.19
0.52	0.12	0.12	0.12	0.12
0.17	0.47	0.12	0.12	0.12
0.17	0.12	0.47	0.12	0.12
0.17	0.12	0.12	0.47	0.12
0.17	0.12	0.12	0.12	0.47

APPENDIX D

DECISION MATRICES FOR THE EXAMPLE PROBLEM

Process Capability Index (Cpm)

Table D.1 Process capability index (Cpm) values for period 1

Cpm	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	0.7071	0.7071	0.7071	0.7071	1.3333	1.3333	1.3333	1.3333
Product 2	0.7071	0.7071	0.7071	0.7071	1.3333	1.3333	1.3333	1.3333
Product 3	0.7071	0.7071	0.7071	0.7071	1.3333	1.3333	1.3333	1.3333

Cpm is labeled as 'Low' if $Cpm_{ij} \leq 1$

'Medium' if $1 < Cpm_{ij} \leq 1.33$

'High' if $Cpm_{ij} > 1.33$

Table D.2 Labeled Cpm values for period 1

Cpm	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	Low	Low	Low	Low	High	High	High	High
Product 2	Low	Low	Low	Low	High	High	High	High
Product 3	Low	Low	Low	Low	High	High	High	High

Gage Capability

Table D.3 P/T values for period 1

P/T	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Product 2	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Product 3	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

Table D.4 (σ_M^2 / σ_T^2) values for period 1

	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	0.059	0.059	0.059	0.059	0.1	0.1	0.1	0.1
Product 2	0.059	0.059	0.059	0.059	0.1	0.1	0.1	0.1
Product 3	0.059	0.059	0.059	0.059	0.1	0.1	0.1	0.1

P/T is labeled as 'Low' if $P/T_{ij} \leq 0.1$

'Medium' if $0.1 < P/T_{ij} \leq 0.3$

'High' if $P/T_{ij} > 0.3$

σ_M^2 / σ_T^2 is labeled as 'Low' if $(\sigma_M^2 / \sigma_T^2)_{ij} \leq 0.1$

'Medium' if $0.1 < (\sigma_M^2 / \sigma_T^2)_{ij} \leq 0.3$

'High' if $(\sigma_M^2 / \sigma_T^2)_{ij} > 0.3$

Applying these procedures yields the following table.

Table D.5 Gage capability levels for period 1

GC	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	Medium Low	Medium Low	Medium Low	Medium Low	Medium Low	Medium Low	Medium Low	Medium Low
Product 2	Medium Low	Medium Low	Medium Low	Medium Low	Medium Low	Medium Low	Medium Low	Medium Low
Product 3	Medium Low	Medium Low	Medium Low	Medium Low	Medium Low	Medium Low	Medium Low	Medium Low

Loss Coefficient

Range=R=400-10=390

Loss coefficient is labeled as 'Low' if $A_{ij} < 140$

'Medium' if $140 \leq A_{ij} < 270$

'High' if $270 \leq A_{ij}$

Table D.6 Levels of loss coefficients for period 1

LC	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	Low	Medium	Medium	High	Low	Medium	Medium	High
Product 2	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Product 3	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium

Closeness to Constraint

Work center 3 uses all of its capacity to produce the ideal product mix and it is the constraint work center. Therefore, work centers 3, 4 and 7 (rework unit of the processing unit 3) are labeled as ‘At/Next’ and the other work centers are labeled as ‘Far’.

Table D.7 Closeness to constraint levels for period 1

CC	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	Far	Far	At/Next	At/Next	Far	Far	At/Next	Far
Product 2	Far	Far	At/Next	At/Next	Far	Far	At/Next	Far
Product 3	Far	Far	At/Next	At/Next	Far	Far	At/Next	Far

Totally Variable Costs

Table D.8 Cumulative totally variable costs for period 1

CTVC	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	300	603.5	907.1	1210.8	450	753.5	1057.1	1360.8
Product 2	375	754.4	1133.9	1513.5	562.5	942	1321.4	1701
Product 3	450	905.4	1360.8	1816.3	675	1130.4	1585.8	2041.3

Range=R=2041.3-300=1741.3

Totally variable cost is labeled as ‘Low’ if $CTVC_{ij} < 880.43$

‘Medium’ if $880.43 \leq CTVC_{ij} < 1460.87$

‘High’ if $1460.87 \leq CTVC_{ij}$

Table D.9 Totally variable cost levels for period 1

TVC	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8
Product 1	Low	Low	Medium	Medium	Low	Low	Medium	Medium
Product 2	Low	Low	Medium	High	Low	Medium	Medium	High
Product 3	Low	Medium	Medium	High	Low	Medium	High	High

According to determined levels relationship values are chosen from the table given in Appendix B and the decision matrix is filled.

Table D.10 Decision matrix for period 1

WC Product	1	2	3	4	5	6	7	8	SR
1	0.52	0.68	0.75	0.94	0.12	0.28	0.35	0.5	0.4444
2	0.68	0.68	0.75	0.77	0.28	0.3	0.35	0.33	0.3333
3	0.68	0.71	0.75	0.77	0.28	0.3	0.37	0.33	0.2222
IW	0.609	0.687	0.750	**0.845**	0.209	0.291	0.354	0.406	

The forth work center has the highest importance weight. Hence, it is selected for improvement.

Table D.11 Decision matrix for period 2

WC Product	1	2	3	4	5	6	7	8	SR
1	0.52	0.68	0.75	0.53	0.12	0.28	0.35	0.5	0.4444
2	0.68	0.68	0.75	0.36	0.28	0.3	0.35	0.33	0.3333
3	0.68	0.71	0.75	0.36	0.28	0.3	0.37	0.33	0.2222
IW	0.609	0.687	**0.750**	0436	0.209	0.291	0.354	0.406	

Table D.12 Decision matrix for period 3

WC Product	1	2	3	4	5	6	7	8	SR
1	0.52	0.68	0.34	0.53	0.12	0.28	0.35	0.5	0.4444
2	0.68	0.68	0.34	0.36	0.28	0.3	0.35	0.33	0.3333
3	0.68	0.71	0.34	0.36	0.28	0.3	0.37	0.33	0.2222
IW	0.609	**0.687**	0.340	0436	0.209	0.291	0.354	0.406	