ABSTRACT

AN INTEGRATED QFD APPROACH TO DETERMINE QUALITY IMPROVEMENT PRIORITIES IN MANUFACTURING

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In this study, a tool is developed for determining priorities of quality improvement activities for manufacturing operations, for the purposes of both quality and throughput improvement. This tool utilizes Quality Function Deployment (QFD), Theory of Constraints (TOC), Statistical Process Control (SPC) and Failure Mode and Effects Analysis (FMEA) methodologies. The use of the tool is demonstrated on an example problem. The results obtained under different experimental conditions are compared with solutions of more popular, simple decision-making measures, and the optimal solutions obtained from a mathematical model. The analysis shows that the proposed tool gives close solutions to optimal, and it can easily be applied in a typical manufacturing setting. This study also demonstrates how various different methodologies can be integrated for the purposes of quality and throughput improvement in shorter times.

Key words: Quality Improvement, TOC, QFD, FMEA, SPC

ÖZ

ÜRETİMDE KALİTE İYLEŞTİRME FAALİYETLERİNİN ÖNCELİKLERİNİN BELİRLENMESİNDE BÜTÜNLEŞİK KFG YAKLAŞIMI

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Bu çalışmada hem kalite hem de satış hızının iyileştirilmesi amacıyla imalat operasyonlarındaki kalite iyileştirme (Kİ) aktivitelerinin önceliklerini belirlemek için bir yöntem geliştirilmiştir. Bu yöntem Kalite Fonksiyon Göçerimi (KFG), Kısıtlar Teorisi (KT), İstatistiksel Proses Kontrol (İPK) ve Hata Türü ve Etkileri Analizi (HTEA) metotlarından yararlanmaktadır. Yöntemin kullanılışı örnek bir problem üzerinde gösterilmektedir. Farklı deney koşulları altında elde edilen sonuçlar daha çok bilinen basit karar verme ölçütleriyle ve matematiksel modelden elde dilen optimal sonuçlarla karşılaştırılmaktadır.Analiz önerilen yöntemin sonuçlarının optimale yakın olduğunu ve kolaylıkla tipik bir imalat ortamında uygulanabileceğini göstermektedir.Bu çalışma aynı zamanda kısa sürede kalite ve satış hızının iyileştirilmesi amacıyla nasıl entegre olabileceğini göstermektedir.

Anahtar Kelimeler:Kalite İyileştirme, KT, KFG, HTEA, İPK

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CHAPTER 1

INTRODUCTION

Many quality improvement (QI) programs fail to achieve satisfactory quality, productivity and financial results. A major reason of this failure is considered as lack of focus on results. It is a valid question how a company should determine its quality improvement priorities, if several processes are in need of improvement. The literature suggests somewhat indirectly the use of many approaches to determine these priorities. Quality Function Deployment (QFD), Theory of Constraints (TOC), Statistical Process Control (SPC), and Failure Modes and Effects Analysis (FMEA) are among the most relevant approaches. On the other hand, there are a few attempts to develop an integrated use of them for better results.

Application of QFD to an existing product requires determination of critical operations to focus on at some stage of the deployment of customer requirements into product/process characteristics. On the other hand, traditional SPC approach suggests the use of process capability indexes to determine which process is in more need of improvement. FMEA approach further improves this measure by also considering severity and detectability of failures occurring at processes. Recently TOC has challenged them by claiming what matters after all is the throughput, inventory and operating expenses; hence such priorities should be determined so as to optimize them.

Köksal and Karşılıklı (2002) have shown how misleading TOC can be, if QI activities are prioritized by ignoring long term effects on customer satisfaction. They have developed a mathematical model that considers both throughput and customer satisfaction to prioritize QI activities. However, this model is not practical to use for many.

On the other hand, QFD presents a comprehensive framework of how customer satisfaction should be taken into account. This framework involves many aspects of SPC and FMEA as well. However, based on the literature on QFD and our experience with it, we have not seen a QFD tool that combines TOC, SPC and FMEA measures to suggest a vital few operations to focus on for quality improvement.

In this study, we propose an integrated tool that utilizes QFD, TOC, SPC and FMEA methodologies for prioritizing QI activities in a manufacturing setting. The integrated approach developed determines which work center is to be improved first by considering product mix, process capability, customer satisfaction and cost terms.

The thesis is organized under three headings. The second chapter gives the basics of the research carried out and definitions necessary to comprehend the work. In the third chapter, the methods that are developed for determining quality improvement priorities are explained and the proposed integrated method is introduced. Additionally, the use of this tool for selecting the manufacturing operations for improvement is demonstrated on an example problem by using different sets of parameters. Discussions on the method are carried out in the last section of the third chapter. The final chapter is a conclusion about the work done and it provides some hints on the future research directions.

CHAPTER 2

LITERATURE REVIEW

2.1 IMPROVEMENT PARADOX

For the last twenty years an increasing interest is projected on the quality improvement issue. Nearly all customers of all products have a feeling of quality in their decision making criteria, which affects their decision to buy a certain product. This interest grew in such acceleration that, quality, once known as a competitive weapon, from now on, is critical to corporate survival (Dettmer 1995). It is currently accepted as the price of admission just to play the game, it is a necessary condition not a discriminating one.

However, real life situations are more demanding when you decide to apply a quality improvement program. There is a tendency of not reaching a convincing rate of success among firms who apply such programs. One study reveals that 73% of 300 electronics firms had a QI program on the way, but fewer than 37% had achieved a defect reduction of 10% or more (Schaffer and Thomson 1992). Harrari (1993) adds another contradiction by stating only about 20% of all QI programs, observed to obtain tangible results in terms of quality, productivity or financial improvements.

There are many debates in the literature as to whether or not the QI programs are valuable. When viewed with an objective position, the idea behind the QI programs and their necessity cannot be denied. So, there should be something other than their existence in the common failures caused in QI programs. Some studies indicate that the reason is a lack of focus on results. (Schaffer and Thomson, 1992, Myers and Ashkenas, 1993). Many companies dived deep into changing the corporate culture with continuous education and training activities, so that main objective of obtaining tangible results within the shortest time is somewhat forgotten. All members of the program become frustrated, since they do not see any benefits, improvement is very slow and there is continuous change in the day-to-day operations. Results are a costly education program which fails to give short term results, diminishing resources and loss of credibility for keeping the QI program working. Another case applies when all improvement possibilities are treated independently, with an approach to combine the improvements afterwards for a global improvement. However, rather than the synergetic effects, contradictory improvements in different departments are frequently forgotten and results are more or less the same with an education dominated QI. Solution to such problems is given as taking the system as a whole (Dettmer 1995) and develop a way to focus on improvements that are proved to yield global success results (like bottom line in the balance sheet) (Atwater and Chakravorty (1995)). There is a vast variety of tools in the literature that are also used for the same purposes. These will be mentioned briefly in the next section.

2.2 SELECTED TOOLS FOR IMPROVEMENT

Table 2.1, is a finite list of tools used for improvement in general. Nearly all of the tools are competent in a specific aspect of a system improvement process and all have some disadvantages because of this specialization. These tools are selected as they appear to be used vastly in the industry and are complementary to each other.

Table 2.1 Improvement Tools

Approach	**Performance Criteria**	**Focusing Approach**	**Advantages**	**Disadvantages**
House of quality (Cohen 1998)	Priority weights of technical properties	Customer requests are implemented in production and process design. After priority weights for these properties are assigned, customer requests that will be focused and related technical details are decided by weights.	-Inter-functional team work -Understanding customer requests -Extensive analysis	-Long term data analysis and results -Scales used are questionable

Table 2.1 (cont'd)

Value Engineering (VE) (Dell'sola 1974)	Value Index (Total Cost of part / total value assigned to the critical functions of the part), cost/value ratio, cost, acceptability ratios of functions	Different approaches are used. Cost and acceptability ratios are assigned to functions. Information is evaluated using focusing criteria. In cases where inconsistency between cost and value (where cost is higher than the value) improvement process is focused.	-Function, cost and value relationship is constructed	-Assignment procedure differs by human judgment -Variable approaches to the problem - No creative approach
Total Productive Maintenance (TPM) (Robinson and Ginder 1995)	Average Machine Effectiveness (AME) = availability× performance effectiveness ×quality ratio	TPM, tries to minimise the loss in the three performance criteria given in AME. Processes where AME is small are selected as the areas for improvement.	-Works independently from other focusing tools -Neutral focusing criteria	-Preparation and implementation steps take too long
Theory of Constraints (Goldratt and Cox 1992)	Throughput, Inventory and Operating Expense	Uses as a five step procedure. Bottleneck resource is found using the capacity insufficiency. Bottleneck is elevated in a way that improves the focusing criteria. All parts of the system are adjusted to this decision. Bottleneck is then elevated. Step one is returned but inertia is not allowed.	-Neutral focusing criteria -Powerful creative approaches (Logical trees) -Wide area of useability -Can be used with other approaches	-Uses criteria against all usual criteria
Failure Mode and Effects Analysis (FMEA) (Kanji and Asher 1993)	Risk Priority Indicator = Failure Seizing Ratio × failure cost ratio × failure forming ratio	Risk Priority Indicators are calculated for products and processes. Areas with high Risk Priority Indicator points to the areas to be improved.	-Effective in removing failures.	-Assignment procedure differs by human judgement No creative approach

Table 2.1 (cont'd)

Statistical Process Control (SPC) (Kolarik 1995)	Process run tests, run length, process capability	Processes are analysed for improvement according to run lengths	-Prevents the failure before it happens	-Processes should be selected beforehand. -No evaluation for cost. - No creative approach -Complex statistics usage
Robust Design (RD) (Kolarik 1995)	Loss Function, variance, average	Products and processes that have high variation are improved.	-Cost of improvement is low.	- No creative approach -Complex statistics usage -It is not always possible to decrease the variation.
Learning Management Systems (Doğrusöz et al. 1999)	There are no special criteria. Criteria are generated from scratch for the process	Performance criteria are reported in a designed format. Performance is discussed in Performance Evaluation Committees. Problems are identified, and high priority improvements are determined.	Interactive performance evaluation of all parties	Difficulties in managing Performance Evaluation Committees
System Dynamics (Hidaka 1998)	System ratios	After drawing the system dynamics diagram and analysis of the tendency of the ratios, cases which are not appropriate are improved.	-Probability to estimate the future	-Long preparation -High structural failure ratio -Complex structure and results that cannot be easily interpreted No creative approach

Table 2.1 (cont'd)

Other	Questionnaire results for customer satisfaction, customer complaints, defective ratios, scrap rates	Areas where complaints or scrap rates are high are focused.	Points to quality improvement necessities	-It may not maximize profitability - Problems in designing and evaluating questionnaires -Weak structure to take precautions for the failures

Motivation in constructing Table 2.1 is to provide a basic understanding into the improvement processes, and to give the reader a notion of advantages and disadvantages of the tools used. Each tool can be used separately which will also reduce the probability of success.

As seen from Table 2.1 most of the approaches use their own performance criteria. Most of the time performance criteria are compared with predetermined values. In the cases where the criteria fail, it becomes impossible to give a direction for the improvement. Some of the criteria include human senses and impressions (FMEA, QFD), and sometimes they include independent observations from individuals, and yield identical results at every given instance (SPC, RD). Human interaction is used when customer wants and needs are important and should be understood widely, which causes error share in judgments to increase. Human factors are variable in nature and an agreement is settled within a long period of time. Instances where human factor is not utilized are definite, takes little time to give specific answers, but may be incomprehensible by the stakeholders.

Another observation from the Table 2.1 is that, there exists inability to focus on the starting point for most of the approaches. The impact of change of any local improvement on the system as a whole is generally missed, at the initial period when a specific tool is thought to be used. This is the case when small parts of the system is improved, and then combined to obtain system wide improvements.

These disadvantages are claimed to overcome by Theory of Constraints understanding. Main concern should be predicting the system performance increase for a specific improvement and point all the efforts into the direction when the gain is maximized.

Theory of Constraints neither defies any tool, nor promotes its usage in the improvement process. Theory of Constraints can help improvement approaches at some points:

- Help in selection of the improvement approach, guiding for improvement (or focusing), screening and evaluating with independent and global performance criteria.
- Help to improve the deficiency of creativity in all processes with the help of logic trees.
- Help the processes with alternative criteria, when their own criteria fail to point any logical direction.

2.3 REVIEW OF THEORY OF CONSTRAINTS

Common for all Theory of Constraints applications is the simple five steps of continuous improvement process (Goldratt 1988):

1) Identify the system constraints,
2) Decide how to exploit the system constraints,
3) Subordinate everything else to the above decision,
4) Elevate the system constraints,
5) If, in the previous steps, the constraints have been violated, go back to Step 1, but do not let inertia become the system constraint. Often improvement process is understood as a matter of production (physical constraints), but far too often constraints could be found from policy and paradigm levels (intangible constraints) (Dettmer (1997), Corbett (1998): 138-156). Also common to all Theory of Constraints applications is the definition of the particular company's goal (Goldratt 1990): "To make money now and in the future." It is really easy to make money now, but increasing profits continuously in the future is harder to achieve. So under Theory of Constraints principles, a company is seen as “a money making machine”. According to Goldratt (1990: 12-13) it is important to make a distinction between the goal, necessary conditions and the means. For example, customer service, product quality, employee satisfaction, responsibility of society and responsibility of environment are often necessities, sometimes even representing the means of organization’s performance. However, these never represent organization’s goal, because in the end company should serve its shareholders.

Theory of Constraints represents a tremendous change in direction for most manufacturing companies (Stein 1997). Theory of Constraints introduces fundamental principles upon which to build a profitable foundation for any company, regardless of industry, including:

- A process of continuous improvement
- A fundamental decision process focusing on global rather than local issues
- A new method for analyzing the relationships between resources and determining where to focus efforts
- A new measuring system
- New insights into how to use the traditional TQM tools to maximize profitability
- New methods for scheduling the workplace
- New methods for analyzing policy problems and arriving at simple solutions.

These changes are summarized in three different levels (APICS FAQ):
Production Management – Initial Theory of Constraints level applied to solve problems of bottlenecks, scheduling, and inventory reduction.
Throughput Analysis – application of Theory of Constraints with a shift from cost-based decision making based on continuous improvement of processes in which system throughput, system constraints, and statistically determined protective capacities at critical points are key elements
Theory of Constraints Logical Processes - This third level is the general application of Theory of Constraints reasoning to attack a variety of process problems within organizations. Theory of Constraints logic is applied to identify what factors are limiting an organization from achieving its goals, developing a solution to the problem, and getting the individuals in the process to invent the requisite changes for themselves.

Part of Goldratt's Theory of Constraints paradigm is a set of global measures designed specifically to enable local managers to make decisions, confident in the knowledge that their decision will have the desired systemic effect, namely Throughput (T), Inventory or Investment (I), and Operating Expense(OE), (Goldratt 1992) .

Throughput is defined as the rate at which a system generates money through sales, mathematically sales minus raw material inventory content of the sales. Inventory is all the money that the system has invested in purchasing things that it intends to sell, which includes items like buildings, machinery and such under its heading. Operating Expense is defined as all the money the system spends in order to turn inventory into throughput, it includes wages, overhead costs, maintenance and depreciation.

These definitions are specially designed by Goldratt to get rid of the problems caused by the traditional definitions used for these terms. Throughput is defined as such to eliminate the value added notion used to define the worth of the goods. Throughput is only achieved when a product is sold, thus building up inventories to balance work loads, to decrease fixed costs per unit while generating value added is not a realistic approach. Without generating throughput a product can only be valued by the raw material used to produce it, thus it has no value added in it. Because of this new approach of creating value, inventory definition should also be changed. Goldratt used the definition of inventory to strengthen the throughput concept and create a solid medium to evaluate the inventory at hand without dealing with the value added concept. Thirdly, operating expense is defined to support the first two definitions. Operating expense in this case is somewhat a fixed item in the overall process. We do not have much control to reduce operating expenses as they have a minimum level to support for the throughput. Operating expenses in this definition are not allocated to goods as they are thought to be fixed whether we produce or we do not produce (like wages, depreciation). This definition is useful, as there exists no need to build up inventories (which do not have any value added if they are not sold) or allocation of costs which is used for accounting purposes. This definition of operating expenses does not carry after sales costs which can be the only disadvantage when relating customer perspective into the environment.

TOC accommodates a technique called drum buffer rope. *Drum buffer rope* methodology is a technique for developing a smooth, obtainable schedule for the plant from a global perspective (Stein 1997). It determines relationships among resources to create a smooth flow of product and process.

Drum: Drum is the schedule for the system's constraint and represents a portion of exploitation phase of the five-step improvement process of Goldratt. It is used to maximize the available time of constraint. Schedule is done so that:

- Enough protection is available to meet due dates
- No conflicts exist between orders attempting to occupy the same space at the same time.

Buffer: It is a time mechanism to get rid of effects of things that may go wrong. It is simply an amount of unprocessed product waiting to be processed. It is equal to processing time plus setup time and an aggregated amount of protective capacity. It is required at three locations:

- Shipping buffer, to deliver parts on time
- Constraint buffer, to maximize its utilization
- Assembly buffer, where one leg is fed by constraint, so that parts leaving bottleneck will not wait.

Rope: Rope is the synchronization mechanism for the other resources and consists of the release schedule for all gating operations. Technically the rope is equal to the constraint schedule date minus the buffer time.

Goldratt developed a Drum Buffer Software package called Disaster (Goldratt (1990)) that gives reliable due-date performance, effective exploitation of constraint and short response times that uses concepts of drum, buffer and rope. In Haystack Syndorme Goldratt defines resources under three categories (Goldratt (1990)):

- Bottleneck: Any resource whose capacity is less than the demand placed on it. This is a system constraint
- Non-bottleneck : A resource whose capacity is greater than the capacity placed on it.
- Capacity-Constrained Resource: A resource whose capacity is close to the demand placed on it. A capacity-constrained resource can easily become a bottleneck if it is not scheduled properly.

Another tool presented by TOC is the thinking processes. The objective of Theory of Constraints thinking process is to define the actions necessary to improve a company, and improve its current situation which may not be so obvious to reach. It defines "what to change", "what to change to" and "how to cause the change".

Theory of Constraints thinking process is the five tools as defined in the It's not Luck (Goldratt 1995):

- *Current reality tree*: used to find the core cause or causes from undesirable effects (UDEs)
- *Evaporating cloud*: assumption model-used to model the assumptions that block the creation of a breakthrough solution

- *Future reality tree*: used to model the changes created after defining breakthrough changes from the evaporating cloud
- *Prerequisite tree*: used to uncover and solve intermediate obstacles to achieving the goal
- *Transition tree*: used to define those actions necessary to achieve the goal.

<u>History of TOC</u>

Management philosophy today named as Theory of Constraints (TOC), earlier known as optimized production technology (OPT) and in the beginning named as optimized production timetables (OPT), has changed thinking about production and operations management in practice, and also in the academic field (Jacobs l984; Goldratt 1988; Spencer and Cox 1995). The two terms, Theory of Constraints and OPT, are used somewhat interchangeably when discussing production planning and control. In 1984, Goldratt and Cox (1984) presented the basic performance measurement principles and logic of Theory of Constraints in the form of a novel and a series of illustrations. Later, Goldratt and Fox (1986) developed the production planning and control techniques further, and identified that component of Theory of Constraints as drum-buffer-rope. These planning and control techniques were further developed into buffer management as described by Schragenheim and Ronen (1990,1991). The success of the planning and control techniques rests upon a unique performance measurement system that is treated as a separate component of Theory of Constraints.

Jacobs (1983) reports the first examination of OPT software, and concludes it would work best in high volume, large batch-size environments with few production operations. He concludes that economic justification of OPT is difficult. Jacobs (1984) claims 'OPT represents a new approach to the problem of operations planning and material control. The concepts in the set of rules Creative Output, Inc. has developed are relevant and could be applied to many production environments, with or without the use of the OPT software package'. Meleton (1986) reports on OPT results and concludes, 'the description of how OPT operates and the philosophy that drives it leads to the conclusion that OPT would be most beneficial in scheduling a traditional job shop and in modeling and simulation'. Vollum (1986) describes how OPT is used to enhance a Computer Integrated Manufacturing (CIM) application for which MRP cannot synchronize production because of Material Requirements Planning (MRP) assumptions. Tobis (1990) and Pence et al. (1990) compare the critical nature of managing a production bottleneck to achievement of organizational goals. Ptak(1991) views the OPT philosophy as embracing the precepts of Just-in-Time and builds upon the requirements of MRP. Fawcett and Pearson (1991) support Ptak's view as does Reimer (1991) who reports on a case study concerning MRP and Theory of Constraints used in combination that supports Ptak's conclusions. It appears that the success of OPT-Theory of Constraints is determined to a large degree by the relative success of the performance measurement system and its underpinning philosophy. This observation is further supported by the first survey results concerning the OPT software by Fry et al. (1992), although the focus of the survey is on implementation issues rather than performance measurement results.

As the former names of Theory of Constraints indicate, its methodologies were developed first in production management, called as drum-buffer-rope, and were under research interest in the 1980's (e.g. Jacobs 1984; Aggarwal 1985). In the 1990's interest turned into throughput accounting, which is cost accounting method of Theory of Constraints (e.g. Luebbe and Firch 1992; Goldratt 1999). In the latter part of the 1990's systems thinking applied to more intangible areas using developed thinking process tools (Goldratt 1994; Dettmer 1997; Lepore and Cohen 1999: 121-148), but also ordinary project management methods were challenged by critical chain approach (Goldratt 1997; Newbold 1998; Hoel and Taylor 1999). Research has not found any fatal problems in the use of Theory of Constraints principles in different contexts, generally Theory of Constraints has been seen at least as well-designed approach for certain situations. (Aggarwal 1985; Luebbe et al 1992; Patterson 1992; Noreen, Smith Mackey 1995; Balderstone and Mabin 2000, Coman and Ronen 2000). However some remarks are also made, including the cases where multiple constraints exist in the system, and basic five step procedure of Theory of Constraints is proved to yield infeasible results(Fredendall and Lea 1997; Hsu and Chung 1998). In such cases improved algorithms are developed, mainly for the product mix selection problem.

Additional research focuses on the implementation of Theory of Constraints scheduling methods into existing production planning and control systems. Spencer (1991), Fawcett and Pearson(1991), and Reimer (1991) examine how Theory of Constraints can be used in an MRP system, while Lockamy and Cox (1991) examine V-A-T analysis to facilitate JIT implementation. V-A-T analysis is a constraint management procedure for determining the general flow of parts and products from raw materials to finished products within a manufacturing facility. Once the general parts flow is determined, control points can be identified and managed (Cox et al. 1995).

In many cases, Theory of Constraints is used as an alternative to the existing decision making methodology (Patterson (1992); Luebbe et al (1992); Lee and Plenert (1993); Chakravorty and Atwater (1995); Atwater and Gagne (1997); Kee and Schmidt (2000)).

Patterson (1992) and Lee and Plenert (1993) examine the effect of Theory of Constraints measurement on the product selection and mix decisions. Luebbe and Finch (1992) use Theory of Constraints and linear programming to make product mix decisions. In all instances, Theory of Constraints is proved to be superior to alternative management tools, with a given set of assumptions and experimental conditions. They also highlight the global nature as a philosophy versus LP's role as a single optimizing technique. Fry (1992) and Spencer (1994) show how Theory of Constraint's performance measurement system is valid within the context of economic theory. Spencer (1994) also showed, using a case study, how Theory of Constraints-based product mix decisions are used successfully when traditional cost accounting would have led to a different product decision. Umble (1992) applies Theory of Constraints measurements more broadly in analysing a set of manufacturing problems. Lockamy (1993) also examine Theory of Constraints principles more broadly using a case study.

However, some articles also mention the complementing nature of Theory of Constraints to other management techniques (Ruhl (1997); Kee and Schmidt (2000); Atwater and Gagne (1997)). This complementary nature comes into discussion when the length of decision-making period is extended. Theory of Constraints is often suggested as a short-sighted tool (Kee and Schmidt (2000); Atwater and Gagne (1997)). Because most of its usage is limited with finding an optimal product mix with performance criteria supplied by Theory of Constraints for a single period, for such instances. Suggestions are using Theory of Constraints in the short term, and supplementing it with other tools like ABC or Contribution Margin Analysis for long-term decisions.

Goldratt (1993) has written the first article moving Theory of Constraints away from production planning and control to a general examination of managerial problem solving. Gardiner et al. (1994) trace the development of Theory of Constraints by citing several successful implementations, and explore the use of Theory of Constraints methods, such as the five step focusing process and buffer management, for developing a continuous improvement process. They further compare the Theory of Constraints scheduling methods with Kanban, concluding that Theory of Constraints methods are more suitable for multi-product environments. Ennis (1996) also demonstrate the continuous improvement nature of

Theory of Constraints using a simulation technique. Dettmer (1995) collate many of the problem solving methods used by Goldratt in his text examining Theory of Constraints as a continuous improvement management system. Spencer and Cox (1995) trace the evolution of Theory of Constraints from OPT and create a classification system consisting of (1) a logistics branch, (2) a problem solving branch, and (3) a performance measurement branch to facilitate further research.

2.3.1 Theory of Constraints and TQM

All companies running a QI program should never forget the fact that goal of any business and any change pertaining to the business is to create wealth. Since customers place good quality as a requirement for all the companies, firms should provide good quality at an acceptable price, or they will not spend money for the products or services. However, firms cannot guarantee a sales increase, no matter how big their quality increase is. In order to create wealth either sales must go up or operating expense and inventory level should go down, which is improvement in profitability. Even when quality is defined in its broadest terms, once it is achieved, it only increases potential for sales, not revenue itself. For companies to be successful at implementing QI programs, they should make the connection between the measures used for improvement, such as reliability, complaint reduction and processing time, and their impact on return on assets. It must be understood that in order for profits to improve, companies must improve the right things. Otherwise notion known as "Improvement Paradox" will apply. Measurements and focusing mechanisms used to determine what needs to be improved should lead them to a corresponding increase in profit. So QI methodology should be improved, leading to a system where all improvements are strongly linked to tangible outcomes like profit increase. Such a system should have some basic principles to be applied (Stein 1997):

1. Quality is a necessary condition: This item defines quality as a condition that should be met before most people wants to buy a certain product. Otherwise any decrease in the quality level will result in decrease is sales thus decline of profitability.
2. Every solution will serve to invalidate itself over time: All systems are chains of events. A particular solution for a part may prove to be valid for some time, but any other improvement at some other part of the system may cause the initial solution to be invalid. An example is the flat tire problem. An initial solution will be to use a spare tire but one cannot go on searching for spare tires unless there is way to fix the flat ones.

3. Throughput of the system is determined by its constraints: Systems are chain of events and there's always the weakest link. It is that link that determines the system output or strength (or amount of money generated)
4. Value of an activity is determined by the limitations of the system: An activity should be valued according to its location in system, links to the other parts and whether it is a bottleneck or not. An improvement in an activity with excess capacity will not result in an increase in profit and may actually decrease as a result of mis-utilization of resources.
5. In a chain of events, the utilization of any resource may be determined by any other resource in the chain: Demand and forecasts determine the extent of utilization of resources. As all resources are interconnected, the resource which cannot supply all its link's resources will cause them to starve, so its utilization should be changed accordingly.
6. The level of inventory and operating expense is determined by attributes of the non-constraints: The output of the system is connected to one resource, the bottleneck one. If it produces less, than the overall output will be less or vice versa. Non-constraint resources provide a protection mechanism for the bottleneck machine. It should never starve for resource, otherwise output will decrease. So utilization of the non-constraints will determine the level of stock in front of bottleneck to process or the level of flow will determine if overtime is necessary. In both cases inventory and operating expense increase.
7. Resources are to be not merely activated, but utilized in the creation or protection of Throughput: Increasing inventory in order to catch up with good utilization figures is not an appreciated thing to do. Such an approach will increase inventory levels such that lead times are extended, and therefore throughput decreases.

The key to getting to the point of success in TQM programs is the common observation: "TQM/Quality/Productivity cannot lead to more business unless it first/also leads to more total system capacity, and to new additional capabilities for attacking an existing or new market". Many "successful" quality/productivity efforts are spread around the business, implementing improvements all along the chain of processes that make up the business. The only problem is that only one of the links of that chain is the "weakest link" -- the process that is constraining the business from doing more business. As long as the constraint is internal to the business' processes and as long as that constraint gets only "average" attention along with all the other processes, one can only get "average" improvement in capacity of the system as a whole. Throw in the cost-world thinking that requires lean processes, and company will lose not only additional capacity achieved in the constraint, but also the protective capacity embedded in the other processes. An effective strategy for application of TQM/Quality/Productivity efforts involves 1) identifying the current constraint, 2) squeezing the most out of it through common sense as well as through TQM tools and techniques, 3) making sure the rest of the system doesn't get in the way of its output (the appropriate use of TQM tools/techniques on non-constraints), then only if necessary, 4) buying more capacity in that constraint. When the constraint is sufficiently elevated in capacity, that is, when it may no longer be the system's constraint, you 5) repeat the cycle with the next constraint. As you can see, this provides not only a mechanism for focusing management and TQM efforts where it counts-on the constraint of the system, but also provides a true process of on-going improvement that doesn't waste effort improving only the individual processes, as if they were stand-alone processes, and improves the total output of the entire system/organization/business. However buying capacity may not be always possible and the first three steps are adequate enough to develop a consistent improvement tool. Squeezing most out of the constraint is a way of optimizing the current system according to performance criteria suggested by Theory of Constraints over the known set of constraints which is briefly introduced in section 2.4

Sooner or later, the constraint shifts from an internal process to outside the system, very often to the market. The responsibility of management to both shareholders (who rightfully expect higher profitability) and employees (who rightfully expect a secure and satisfying workplace) is to act in long term so that when working on the internal constraining processes, they are aware that when they are elevated, the market constraint can be attacked with new offers that can capitalize on the new capacity/capability. Evidence of external constraints are beyond the scope of the analysis but mentioned to give a complete overview.

2.4 PRODUCT MIX PROBLEMS

For many firms, the most important decisions relating to production are those that determine the product mix for a given period of time. There may be a number of products that the company could produce and sell in the period and the problem is to decide how much of each product to schedule. The objective is to utilize limited resources to maximize value of the output. Following features characterize a product mix problem:

1. Maximization of contribution to value.
2. Constraints resulting from resource limitations.

3. Bound constraints on planned production.

Most of the time product mix problems are modeled as a linear programming model. Let :

X_i = quantity of product i, i= 1,2,…,n produced in the period

b_k = amount of resource k, k= 1,2,…,K available during period

a_{ik} = number of units of resource k required to produce one unit of product i.

U_i = maximum sales potential of product i in the period.

r_i = revenue from selling one unit of product i,

c_i = cost of producing one unit of product i.

Our objective will be to maximize,

$$Z= \sum_{i=1}^{n}(r_i - c_i)X_i$$

Subject to,

$$\sum_{i=1}^{n} a_{ik}X_i \le b_k \qquad k= 1,2,\ldots,K$$

$$X_i \le U_i,$$

$$X_i \ge 0, \qquad i= 1,2,\ldots,n$$

The first constraint is the resource constraint, second and third ones are the bound constraints on planned production.

Although neatly designed, the model does not belong to reality says Goldratt (1990). Such a model emphasizes the profit of the product and allocates available capacity among product types according to decreasing amount of unit profits. This methodology focuses on products rather than available constraints at hand. Goldratt suggests using Throughput as the maximisation criterion and selecting the product mix according to decreasing ratio of Throughput per constraint hour. By this way money generation through the bottleneck is maximized, thus the output of the system is improved. Throughput is given by the following formula:

$$T_i = r_i - \sum_{j=1}^{m}(M_j * p_j), \text{ where}$$

T_i = Throughput value of the product,

M_j = the quantity of raw material j used to produce product i, j= 1,...,m
p_j = the purchase price of raw material j used in product i, j= 1,...,m

and the final objective function will be of the form: $Z=\sum_{i=1}^{n} T_i * X_i$.

In Goal (Goldratt 1990), Atwater and Chakravorty (1995), Lee (1993) a heuristic, based on Theory of Constraints, is used in product mix selection problem. This heuristic finds throughput per constraint hour figures, sort them in descending order and allocate resources starting from the end of the list, till any one of the resources is diminished. The resource fully utilized is the bottleneck resource and heuristic guarantees to find optimal solution when a single bottleneck exists. This heuristic will be called the "constraint elevation heuristic" in the analysis. Use of a LP enhanced version of Theory of Constraints has many advantages over the usual heuristic method (Balakrishnan (1999), Balakrishnan and Cheng (2000)). Firstly the cases where multiple constraints, which occur regularly (Plenert (1993)), exists cannot be solved by the usual heuristic methodology (Balakrishnan (1999); Hsu and Chung (1998); Fredendall and Lea (1997)). Either an improved heuristic should be used (Hsu and Chung (1998); Fredendall and Lea (1997)) or an LP embedded analysis should be performed (Balakrishnan 1999). This method does not only guarantee a best solution but may help the user with sensitivity analysis to check for the optimality boundaries. However, it should be realized that Theory of Constraints and LP are not identical (Balakrishnan 1999). Theory of Constraints is a management philosophy whereas LP is a tool and should only represent the Theory of Constraints methodology in a similar application.

On the other hand, the management accounting system influences the product mix decision by calculating the product cost and the product's contribution margin (i.e., the difference between the selling price and the product cost). If the calculated product cost is not correct, whenever the demand is greater than a firm's production capacity, it is possible that a product mix decision will result in the less profitable product in demand being manufactured, while a more profitable product that is in demand is not manufactured. The traditional cost accounting system originated in the early 1900s when direct labor and materials were the predominant factors of production, technology was stable, overhead activities supported the production process, and the range of products was limited (Bakke and Hellberg, 1991;Brimson, 1991; Kaplan, 1991). The traditional accounting system allocated overhead to product cost using volume-sensitive cost drivers, such as direct labor. This allocation of overhead was a reasonable assumption during the mass production era, but because of the use of automation and technology, the actual overhead costs may not have been incurred in proportion to product volume, so the allocation of overhead cost used in traditional costing could distort the product cost (Horngren and Foster, 1991; Kaplan, 1991;O'Guin, 1991).

George Staubus introduced Activity Based Costing (ABC) in 1971 in response to increased overhead from automation and technology usage, more product varieties, decreased labor, and lowered inventories. The ABC system assumed that all activities existed to support the production and delivery of goods and services were product costs.

The throughput accounting system was introduced in the late 1980s (Galloway and Waldron, 1988; Goldratt and Cox, 1992; Waldron and Galloway, 1988, 1989a, b; Wouters, 1994). Supporters of throughput accounting argue that traditional costing became obsolete not only because it uses direct labor to allocate overhead, but also it does allocate costs to products Corbett, 1998). These supporters of throughput accounting contend that overhead is a corporate cost and not a product cost because there is no feasible method of accurately tracing overhead to products. Furthermore, they have argued that since companies cannot actually eliminate overhead, why do they need to trace it to products? Therefore, throughput accounting calculates product costs as the sum of the truly variable costs of production (usually only raw material costs are considered) (Corbett, 1998,p.30). All other costs are treated as operating expenses during the period they occurred (Goldratt and Cox, 1992).

Spencer (1994) analyzed traditional costing and throughput accounting with microeconomics theory and suggested that throughput accounting could be effective. Low (1992) and Corbett (1998) used simple numerical examples to compare traditional costing, activity based accounting, and throughput accounting and concluded that throughput accounting maximized profit. Dugdale and Jones (1996a, b) indicated that firms increased their profits when using throughput accounting. However, they compared the use of a traditional cost system in an MRP environment to the use of throughput accounting in a TOC environment. It is not clear whether the reported profit differences were due to the management accounting system or the manufacturing system. Lea's (1998) study indicated that throughput accounting did not perform adequately when there were significant overhead, labor costs, and automation involved in the manufacturing process. Kee and Schmidt (2000) identified conditions where throughput accounting or ABC was appropriate for product mix decisions. They concluded that the relative performance of throughput accounting and ABC accounting in terms of the product mix decision depended on the extent of management's control over labor and overhead within the specified planning horizon. Bakke and Hellberg (1991) suggest the possibility that a series of product mix decisions that create the highest profit in the short term may not generate the highest profit in the long term. Lea and Fredendall (2002) have examined how various types of management accounting systems and two methods to determine product mix interact in both the short term and the long term to affect the manufacturing performance of two shops – one with a flat and the other with a deep product structure – in a highly automated industry that has a significantly high overhead content where environmental uncertainty creates fluctuations. They have agreed on the conclusion that the manager should determine which performance measures are the most important to their competitive success when making a decision about selecting or changing a management accounting system, product mix algorithm, or product structure.

2.5 QUALITY FUNCTION DEPLOYMENT (QFD)

Quality Function Deployment (QFD) is a concept and mechanism that translates the customer aspects which is called 'voice of customer', through the various stages of product planning, engineering and manufacturing into a final product. QFD approach has been used as a tool for defining new products, as well as for diagnosing and improving existing products to ensure the improvement of quality and productivity.

QFD was first conceptualized in the late 1960s (Akao, 1997) when the importance of design quality became apparent, after World War II. A few years later, in 1972, QFD was implemented at the Kobe shipyards of Mitsubishi Heavy Industries Ltd. Even though its application was followed by successful implementations throughout Japan, e.g. at Toyota, it remained a Japanese tool until the early 1980s. Following the article by Kogure and Akao (1983) and through Ford Motor Company and the Cambridge Corporation, QFD has entered the borders of the US and has started to play an important role at companies.

The basic concept of QFD is to translate the desires of customers, i.e. the voice of customer, into product technical requirements (PTRs) or engineering characteristics, and subsequently into parts characteristics, process plans and production requirements. In order to establish these relationships QFD usually requires four matrices: product planning, parts planning, process planning, and production planning matrices, respectively. Product planning matrix translates customer needs into product design requirements; part planning matrix translates important design requirements into product/part characteristics; process planning matrix translates important product/part characteristics into manufacturing operations; production/operation planning matrix translates important manufacturing operations into day-to-day operations and controls. These four matrices form the four phase of QFD (See

Figure 2.1) and each translation use a similar matrix called the house of quality (HOQ) (See Figure 2.2)

In addition to four phase of QFD, a multiple matrix is developed by Akao that incorporates many disciplines into a less structured format consisting of a matrix of matrices (Shillito, 1994).

There has been some research on quantifying the planning issues in HOQ within the past decade, mainly focusing on customer needs. Chan, Kao, Ng, and Wu (1999) and Khoo and Ho (1996) employ fuzzy set theory for rating the customer needs. Other researchers use the analytic hierarchy process (AHP) to determine the degree of importance of the customer needs (Lu, Madu, Kuei, & Winokur, 1994; Park & Kim, 1998).

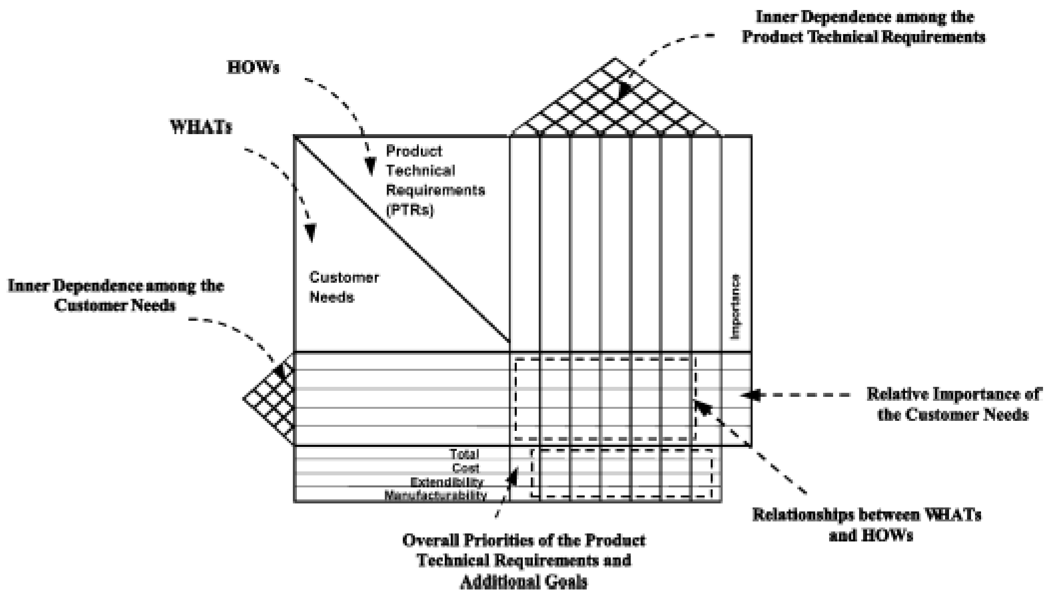


Figure 2.1 House of Quality (Source : Karsak et al. (2002))

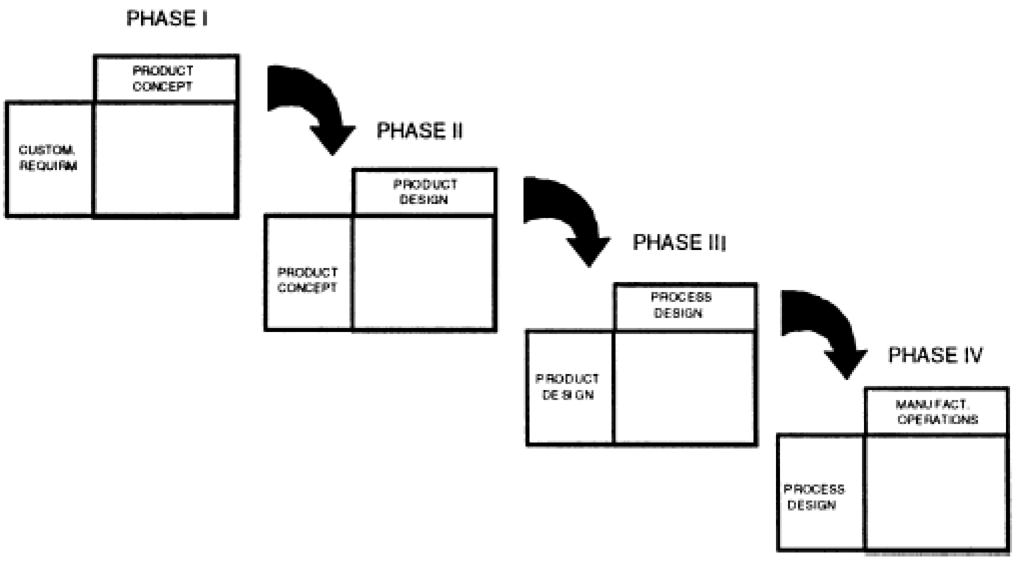


Figure 2.2 Four Phase QFD (Source: American Supplier Institute)

<u>The house of quality</u>

In today's competitive environment, the HOQ is a key strategic tool to aid companies in developing products that satisfy customer needs. According to Hauser and Clausing (1988), the HOQ is a kind of conceptual map that provides the means for interfunctional planning and communications. The seven elements of the HOQ shown in Fig. 1.1 can be described as follows;

(1) Customer needs (WHATs): They are also known as voice of the customer, customer attributes, customer requirements or demanded quality.
Affinity diagram, which is a method used to gather large amounts of qualitative data and to organize them into sub groupings based on the similarities between them, can be used for gathering the WHATs (Cohen, 1998). Cluster analysis can also be used to form and structure customer needs (Griffin & Hauser, 1993).
(2) PTRs (HOWs): PTRs are also known as design requirements, product features, engineering attributes, engineering characteristics or substitute quality characteristics. Karsak et al (2002) have proposed to use analytic network process for selecting the PTR's and determining the dependencies.
(3) Relative importance of the customer needs: companies should trade off one benefit against another, and work on the most important needs while disregarding relatively unimportant ones according to the importance of the customer needs.

(4) Relationships between WHATs and HOWs : The relationship matrix indicates how much each PTR affects each customer need. The relations can either be presented in numbers or symbols.
(5) Inner dependence among the customer needs: In general, customer needs have inner dependence among them that can be identified by a correlation matrix emphasizing necessary trade-offs.
(6) Inner dependence among the PTRs : The HOQ's roof matrix is used to specify the various PTRs that have to be improved collaterally, providing a basis to calculate to what extent a change in one feature will affect other features.
7) Overall priorities of the PTRs and additional goals: Here the results obtained from preceding steps are used to calculate a final rank order of HOWs, also called PTR ratings. Additional design metrics such as cost, extendibility, manufacturability, etc. can also be incorporated into the analysis at this step (Shillito, 1994). Karsak et al.(2002) have proposed an analytical procedure that takes multi objective nature of the problem and incorporates these goals of cost ,extendibility and manufacturability of PTR's by zero-one goal programming methodology.
According to PTR ratings of HOQ, one decision is to determine target levels for manufacturing characteristics. After Kim et al (1994) who have developed a fuzzy multi objective model to choose target levels for engineering characteristics, Moskowitz and Kwang(1997) have performed a mathematical programming for obtaining target engineering characteristic values.

Although QFD matrices are mostly focused on product development and design, they are equally applicable to the development of decisions or strategy implementation. Erol and Ferrell (2003) have presented a methodology to assist decision makers in selecting from a finite number of alternatives when there is more than one objective. Their proposed methodology uses fuzzy QFD to convert qualitative information into quantitative parameters and then combines this data with other quantitative data to parameterize a multi-objective mathematical programming model.

Using QFD as a decision making tool allows the company to allocate resources and take decisions based on the importance ratios given by the decision makers therefore it reduces and avoids the mid-project changes and corrections. Besides, that taking the decisions in the systematic order of QFD matrices is time consuming and making things easier for decision makers.

2.6 FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

The FMEA methodology was developed and implemented as a reliability evaluation technique to determine the effects of the system and equipment failures firstly in 1949 by the United States Army. In the 1970s, thanks to its characteristics of strength and validity, its application area extended to aerospace and automotive industry, then to general manufacturing (SVRP, 1997).

Proper use of FMEA technique can provide a manufacturer company such benefits of high product reliability, less design modification, lower manufacturing cost, continuous improvement in product and process design, better competitiveness, improve system safety and reliability.

Terminology in FMEA

Failure mode: Failure modes are sometimes described as categories of failure. A potential failure mode describes the way in which a product or process could fail to perform its desired function (design intent or performance requirements) as described by the needs, wants, and expectations of the internal and external customers/users. Examples of failure modes are: fatigue, collapse, cracked, performance deterioration, deformed, stripped, worn (prematurely), corroded, binding, seized, buckled, sag, loose, misalign, leaking, falls off, vibrating, burnt, etc.

Potential cause(s) of failure: This is a list conceivable potential cause(s) of failure assignable to each failure mode. The causes listed should be concise and as complete as possible. Typical causes of failure are: incorrect material used, poor weld, corrosion, assembly error, error in dimension, over stressing, too hot, too cold, bad maintenance, damage, error in heat treat, material impure, forming of cracks, out of balance, tooling marks, eccentric, etc.

Effect. An effect is an adverse consequence that the customer/user might experience. The customer/user could be the next operation, subsequent operations, or the end user.

Severity: Severity is an assessment of how serious the effect of the potential failure mode is on the customer/user.

Applying FMEA to a production process means following a series of successive steps: analysis of the process/product in every single part, list of identified potential failures, evaluation of their frequency, severity (in terms of effects of the failure to the process and to the surroundings) and detection technique, global evaluation of the problem and identification of the corrective actions and control plans that could eliminate or reduce the chance of the potential failures. (See Figure 2.3)

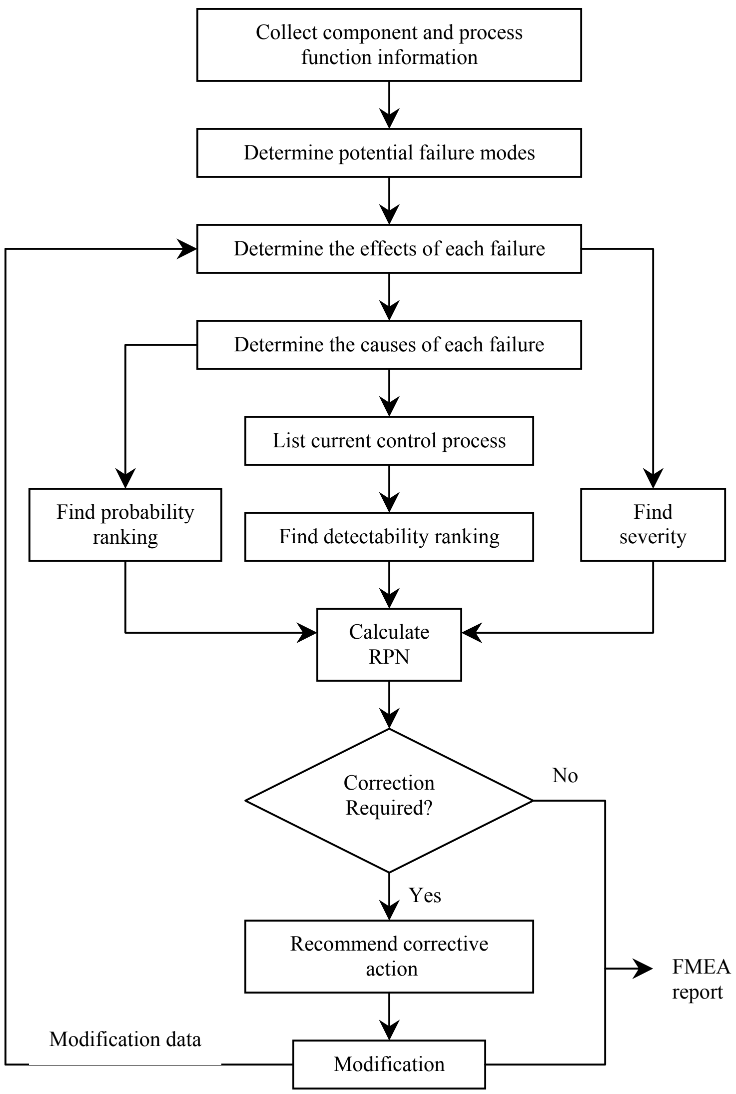


Fig 2.3 FMEA procedure (Copied from Pillay and Wang 2003)

The most important aspect of FMEA is the evaluation of the risk level of potential failures defined for every sub-system or component. The global value of the damages caused on the function or on the surroundings by every failure is indicated with the risk priority number(RPN). This number is an index obtained from the multiplication of three risk parameters, which are:

• Severity of the worst potential resulting outcome due to the failure in terms of safety and system functionality (Severity).

• Relative probability that the failure will occur (Occurrence).

• Probability that the failure mode will be detected and/or corrected by the applicable controls installed on the production lines (Detection).

The RPN is obtained by finding the multiplication of three factors, which are the probability of failure (S_f), the severity of the failure (S) and the probability of not detecting the failure (S_d).

$$RPN = S_f \times S \times S_d$$

According to Ben Daya et al (1993) the most critically disadvantage of the traditional FMEA is that various sets of S_f , S and S_d may produce an identical value of RPN, however, the risk implication may be totally different. Therefore, Pillay & Wang (2003) have proposed to use a fuzzy rule base to rank the potential causes identifed within the FMEA, which would have identical RPN values but different risk implications. The approach then extends the analysis to include weighting factors for S_f , S and S_d using defuzzified linguistic terms and grey relation analysis.

2.7 LOSS FUNCTION

Although quality of products and services may be evaluated in different ways, many companies traditionally have measured quality in terms of the number of rejects or the defect rate. This view of quality had a major impact on how companies implemented quality control activities and on how they evaluated the cost of quality. For example, the idea that inspection can identify defective materials and products is based on classifying units into conforming and nonconforming categories.

The traditional view of quality suggests that all products with actual measurements occurring between the lower and upper specification limits are "quality" products, while those products not falling between the specification limits are defects. This method for evaluating quality leads to the belief that no losses related to poor quality are incurred when the products conform to specifications. Conversely, a loss (in the form of rework, or warranty replacement) occurs, if the product's actual measurement exceeds the upper specification limit or is below the lower specification limit.

This traditional view of quality has been called the goalpost view (Ross 1988), because it defines success whether a ball goes between the uprights of the goalpost. The same success is applicable whether the ball is centred between the uprights or it is only inches away from a goalpost upright. Thus, a wide tolerance exists in what is acceptable, and one could argue that all attempts that result in success are of high quality, and those that do not are defective. Companies apply this same logic when conformance to specification is the criterion used to classify products as acceptable or defective.

The goalpost view provides the basis for many current quality measures, including the traditional quality cost model (Campanella (1990)). There is an upward sloping line showing higher prevention, and appraisal costs are associated with a greater percentage of products conforming to specifications. A downward sloping line shows that failure costs decrease as the percentage conforming becomes larger. The total quality cost curve is minimized at a level of conformance where the marginal cost of prevention plus appraisal equals the marginal cost of failure (Campanella (1990)). Since the cost functions depend on the percentage of products conforming to specifications, this view of quality relies on the dichotomous classification of products into conforming and nonconforming categories.

Taguchi disagrees with the traditional goal-post view (Taguchi 1989). His quality loss function is based on the premise that all products falling between specification limits are not of equal quality. Taguchi's philosophy about quality and its cost has been summarized in four statements:

- We cannot reduce cost without affecting quality.
- We can improve quality without increasing cost.
- We can reduce cost by improving quality.
- We can reduce cost by reducing variation. When we do so, performance and quality will automatically improve (Campanella (1990)).

The importance of variation as a quality concept has been supported by other quality professionals. For example, Phadke (1989) observe that the fraction of defective products is often a misleading performance measure because the deterioration of product performance occurs along a continuum and is not easily placed into discrete categories. Furthermore, he notes that as a crucial quality characteristic deviates further from a target value, the quality becomes progressively worse. Therefore, all products that occur within the bounds of the upper and lower engineering specification limits are not equally good.

In the Taguchi approach, quality is defined as the avoidance of financial loss to society after a product is shipped (Barker 1990). This loss does not depend on whether the product confirms to specification limits, but rather on how the product affects the consumer and the society.

Taguchi's view of loss to society extends beyond the factory walls to include customer ill will and warranty claims, both of which can result in loss of market share (Campanella 1990). Many types of Quality Loss Functions (QLF) exist; the nature of each type depends on the shape of the loss function and how the target value is determined. In all types, the loss is assessed by evaluating the variation from a target specification. Three general functions that express the Taguchi philosophy about the relationship between quality and variability are the following cases:

- Nominal is the best.
- Smaller is better.
- Larger is better.

<u>Nominal is the best</u>: The nominal-is-the best case refers to a distribution in which the target value is a nominal value. In these cases, the actual product characteristic can be greater than or less than the nominal value. The loss function for this case is quadratic, which is when the deviation from a target value doubles, the loss incurred quadruples. For the nominal is the best case, the unit loss function L(y) is calculated using the formula.

$L(y) = k\,(y-T)^2$ Equation 2.1

where y = actual value of characteristic

T = target value of characteristic

k = proportionality constant that depends on the cost structure of the process or organization.

Taguchi derives loss function from a Taylor Theorem expansion about the target value (Barker 1990). He notes that the use of a quadratic function is found extensively in the statistical and control theory (Taguchi et al 1989). Equation 2.1 expresses the loss for a particular unit. An average loss per unit can be calculated as follows:

$L\ (avg) = k\ [s^2 + (\bar{y} - T)^2\ ]$ Equation 2.2

Where,

s^2= variance around the average, $\bar{y}$

$\bar{y}$ = average value of y

k and T are as defined previously

The value of k in equations 2.1 and 2.2 depends on the loss for a specific unit. The value is often based on the loss incurred for a unit at a specification limit. The value of k is calculated as:

$$k = \frac{L}{d^2}$$

where L= loss for a unit at the specification limit.

d= distance from the target value to the specification limit

<u>Smaller is better</u>: The smaller is better QLF exists when smaller values of a characteristic are desirable. Examples are fuel consumption and number of warranty claims. The unit loss function and average loss is given as:

Unit Loss Function , $L(y) = k\ (y)^2$

Average loss , $L(avg) = k\ [s^2 + (\bar{y})^2\ ]$

<u>Larger is better</u>: A larger is better QLF exists when large values of a characteristic are desirable. Examples are weld strength, customer acceptance rate. The unit loss function and average loss is given as:

Unit Loss Function , $L(y) = \frac{k}{y^2}$

Average loss , $L(avg) = \frac{k}{\bar{y}^2}\left[1 + \frac{3s^2}{\bar{y}^2}\right]$

The conventional method of computing the cost of quality is based on the number of parts rejected and reworked. This method of quality evaluation is incapable of distinguishing between two samples, that are both within the specification limits, but with different distributions of targeted properties.

The following figure illustrates the difference between the conventional method and Taguchi's view of the loss function:

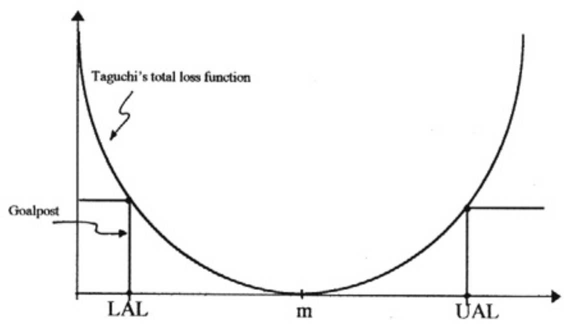


Figure 2.4 Taguchi Loss Function compared with traditional approach

The graph depicts the loss function as a function of deviation from an ideal, or the target value of a given design parameter. Here m represents the target value, or the most desirable value, of the parameter under consideration. This parameter may be critical dimension, color of the product, surface finish or any other characteristics that contributes to the customer's conception of quality.

UAL and LAL in the figure represent upper and lower acceptable limits of a design parameter, respectively. Normally, the product is functionally acceptable if the value of the specified parameter is within the range between the UAL and LAL limits. No societal loss is assumed to occur and the product is accepted for further processing. However, if the product lies outside these limits, it is either discarded or subjected to salvage operations. Every attempt is made to control the manufacturing process to maintain the product within these limits.

However, according to Taguchi, there is no sharp cut-off in the real world. Performance begins to gradually deteriorate as the design parameter deviates from its optimum value.

Therefore, he proposed that the loss function be measured by the deviation from the ideal value. The above figure pictures the nominal the best case. This figure can also help in defining the ways to approximate the loss function coefficient k. Taguchi uses the mathematical equation 2.1 to estimate for the k value. When a product exceeds the limits then it is scrapped by a certain cost of C. Then finding k value is trivial (Ross (1988)):

$$k = \frac{C}{(LAL - m)^2}$$, when the product is scrapped due to lower limit, or:

$$k = \frac{C}{(UAL - m)^2}$$, when the product is scrapped due to upper limit.

On the other hand, the loss function in Equation 2.1 is almost restricted to the shipment time of a product and ignores the degradation effect of usage over time on quality performance. By considering the effect of product deterioration on quality performance, Teran et al. (1996) introduced the present worth of expected quality loss (PWL) as a quality performance measure. They modeled the expected quality loss from the standpoint of a discounted cash flow, which considers the time value of money.

As stated before, L(y) relates to the deviation of the quality characteristic y from its ideal target at an arbitrary time. However, as a consequence of product use, such a deviation may change over time, and so can its quality loss. Thus, y is also a function of time that is denoted by y(t), and the corresponding loss function can be expressed as L(y; t). The average loss L(y; t) can be considered as a cash flow stream that occurs during a planning horizon (0, T) and can be written as;

$$L(avg,t) = k\,[s^2(t) + (\bar{y}(t) - T(t))^2]$$ Teran et al(1996)

where $\bar{y}(t)$ represents the mean of y at time t, and $s^2(t)$ denotes its variance (also as a function of time). Taguchi's quality loss function takes into account only one characteristic. A process may be characterized by m correlated characteristics. If m individual loss functions are independently employed to evaluate the m correlated characteristics, the correlation of the *m* characteristics is neglected and, consequently, the evaluation result will be distorted. Kapur and Cho (1996) extended the concept of Taguchi's loss function and developed the multivariate loss function to describe the relationship between the m correlated characteristics and the associated societal losses.

Suppose $y_1, y_2, ..., y_m$ are m responses from the same unit of a product, each having an NTB type of characteristic, and $T_1, T_2, ..., T_m$ are the target values for $y_1, y_2, ..., y_m$, respectively. Using Taylor's expansion and ignoring the higher-order terms, the multivariate loss function can be expressed as;

$$L(y_1, y_2, ...y_m) = \sum_{i=1}^{m}\sum_{j=1}^{i} k_{ij}(y_i - T_i)(y_j - T_j) \text{ (Kapur and Cho (1989))}$$

where $k_{ij} = k_{ji}$ is the proportionality constant depending on the losses at the specification limits can be determined by using a regression method (Chen and Kapur(1989), Neter, Wasserman and Kutner (1983)). Chou and Chen (2001) have incorporated multiple quality loss function and its present worth in their analysis. Additionally Fawzan and Rahim (2001) have considered the optimal determination of the length of the production run and the initial setting of a process that exhibits a linear drift that can start at a random point of time including quadratic off-target costs and time based costs of maintenance and salvage value.

Although Loss functions are widely used to measure physical characteristics of a manufactured product, there have been other application areas such as Quigley and McNamara (1992) and Snow (1993) implemented Taguchi's loss function to evaluate product quality as an aid in selection of suppliers Another application of forming real estate selection model using a methodological ranking procedure of Taguchi loss function, is presented by Kethley, Waller and Festervand (2002).

2.8 PROCESS CAPABILITY ANALYSIS

Process capability analysis is an engineering study to estimate process capability by quantifying the current and expected future common cause variation. Easiest way of estimating the capability is through the use of Process Capability Ratio (PCR or C_p) which only indicates out the potential capability. While the process is off centered, C_p values cannot detect this. To ease that problem C_{pk} value is used. By comparing C_p with C_{pk}, one can judge whether the process is centered or not (Montgomery (1997) pg 444). However C_{pk} values do not tell anything about the location of the mean in the interval from Lower specification Limit (LSL) to Upper Specification Limit (USL). Formulas for C_p and C_{pk} is given below:

$$C_p = \frac{USL - LSL}{6\sigma}$$

$$C_{pk} = \min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right)$$

One way to address this difficulty is to use a process-capability ratio that is better indicator of centering. One such ratio is

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

Boyles (1991) has provided a definitive analysis of C_{pkm} and its usefulness. Boyles shows that C_{pkm} is bounded by the PCR value of the process. Thus a given value of C_{pkm} places a constraint on the difference between μ and the target value T.

The relationship between of C_{pkm} and Squared Error Loss is defined by Johnson(1992). This analysis suggests that use of C_{pkm} reduces the information required to use a loss function and gives an interpretation of the index of C_{pkm} in terms of percentage loss.

In addition to these measures mentioned above, Stoumbos (2000) has presented a number of process capability indices and their estimators such as C_p,C_p^*,CPL,CPU,C_{pm}^*,etc.
As stated before, the index C_{pk} takes into account the magnitude of process variation as well as the degree of process centering, which measures process performance based on yield(proportion of conformities).For a normally distributed process with a fixed value of C_{pk} ,the bounds on process yield, %yield , are given by, $2\varphi(3C_{pk})-1 \leq \%\ \text{Yield} < \varphi(3C_{pk})$, where $\varphi(.)$ is the cumulative distribution function of N(0,1), the standard normal distribution. Since Boyles(1994) has noted that the index C_{pk} only provides an approximate rather than exact measure of process yield, he has considered a yield index, referred to as S_{pk}, for normally distributed processes which is defined as:

$$S_{pk} = \frac{1}{3}\varphi^{-1}\left[\frac{1}{2}\varphi\left(\frac{USL - \mu}{\sigma}\right) + \frac{1}{2}\varphi\left(\frac{\mu - LSL}{\sigma}\right)\right]$$

Where φ^{-1} is the inverse function of φ .

For processes with multiple characteristics, Bothe (1992) has considered a simple measure by taking the minimum measure of each single characteristic. Then Chen, Pearn and Lin(2003) have proposed the following overall capability index, referred to as S^T_{pk};

$$S^T_{pk} = \frac{1}{3}\varphi^{-1}\left[\left(\prod_{j=1}^{v}(2\varphi*(3S_{pkj})-1)+1\right)/2\right]$$

where S_{pkj} denotes the S_{pk} value of the j^{th} characteristic for j = 1, 2, . . . , v and v is the number of characteristics. The new index, S^T_{pk}, may be viewed as a generalization of the single characteristic yield index, S_{pk}, considered by Boyles.

In literature, several process capability indices have been proposed for use with non-normal populations, most notably those of Clements (1989) and Johnson–Kotz–Pearn (JKP)(1994). Wu et al(1999) have developed non normality-based indices based on the weighted variance control charting method.

Johnson, Kotz, and Pearn (1994) have developed a ‘flexible’ index to consider the possible differences in variability above and below the target value (T), while the weighted variance-based indices are based upon the concept of dividing a skewed or asymmetric distribution into two normal distributions from its mean (μ).Flaig (1997) has suggested a capability index which is one to one correspondence with the process nonconforming fraction and simple inferential procedures under a Bayesian perspective are developed by Borges and Ho(2001) to facilitate its use in industrial applications which is also applicable to non-normal processes.

Six Sigma Methodology

Six Sigma measurement is utilized to identify customer-critical characteristics, evaluate performance at any given process step, calculate process capability to determine the probability of success and improvement in terms of sigma level. For any given sigma level, an unacceptable level of performance, which can adversely affect profitability, exists. The main purpose of the measurement system is to quantify performance and its impact on profitability. If performance significantly affects profitability adversely, a project can be implemented to solve the problem.

To determine performance, the process defect rate is normalized per the process output, called a unit. A unit is a discrete measure of output that can be counted, verified and measured. A unit is used to estimate the quality of the process output in terms of defects per unit, percent yield or the first pass yield.

Defects per unit (DPU) is defined as a ratio of the total number of defects observed in the inspected or verified units over the total number of units processed or built.

DPU = Total number of defects/Total number of units verified

Defects per million Opportunities (DPMO) is the mostly used measurement of six sigma methodology that normalizes the reject rate based on opportunities instead of units. (Montgomery 1997:23)

$$\text{DPMO} = \frac{\text{Total number of defects x 1,000,000}}{\text{Total number of units verified * Average number of opportunities in a unit}}$$

To understand the relationship between DPU and DPMO, the formula above can be restated as:

$$\text{DPMO} = \frac{\text{DPU x 1,000,000}}{\text{Average number of opportunities in a unit}}$$

DPMO measure forms a meaningful process capability index that is applicable for both to the attribute type quality characteristics and non normal processes

CHAPTER 3

AN INTEGRATED APPROACH DEVELOPED AND A NUMERICAL EXAMPLE PROBLEM

3.1 INTRODUCTION

In our Century, most of the manufacturing firms have believed that continuous improvement should be considered as the key weapon towards the increasing competition. Certainly, the basic source for this improvement is the system itself.

In order to guide continuous improvement, any system has to be well defined and investigated. A typical production system, including sub-systems and their interactions is demonstrated in Figure 3.1

Shaded boxes in Figure 3.1 represent functions in close relationship with manufacturing operations. In some environments, the functions of inventory control and procurement can be considered as sub-systems of production planning function. Therefore, Production Planning is the first stage before production, which requires the inputs; such as policies, market research solutions, forecasts, resource plans, capacities and economic indices in order to determine the outputs of resource allocations; such as schedules of routing, machines, labors and materials.

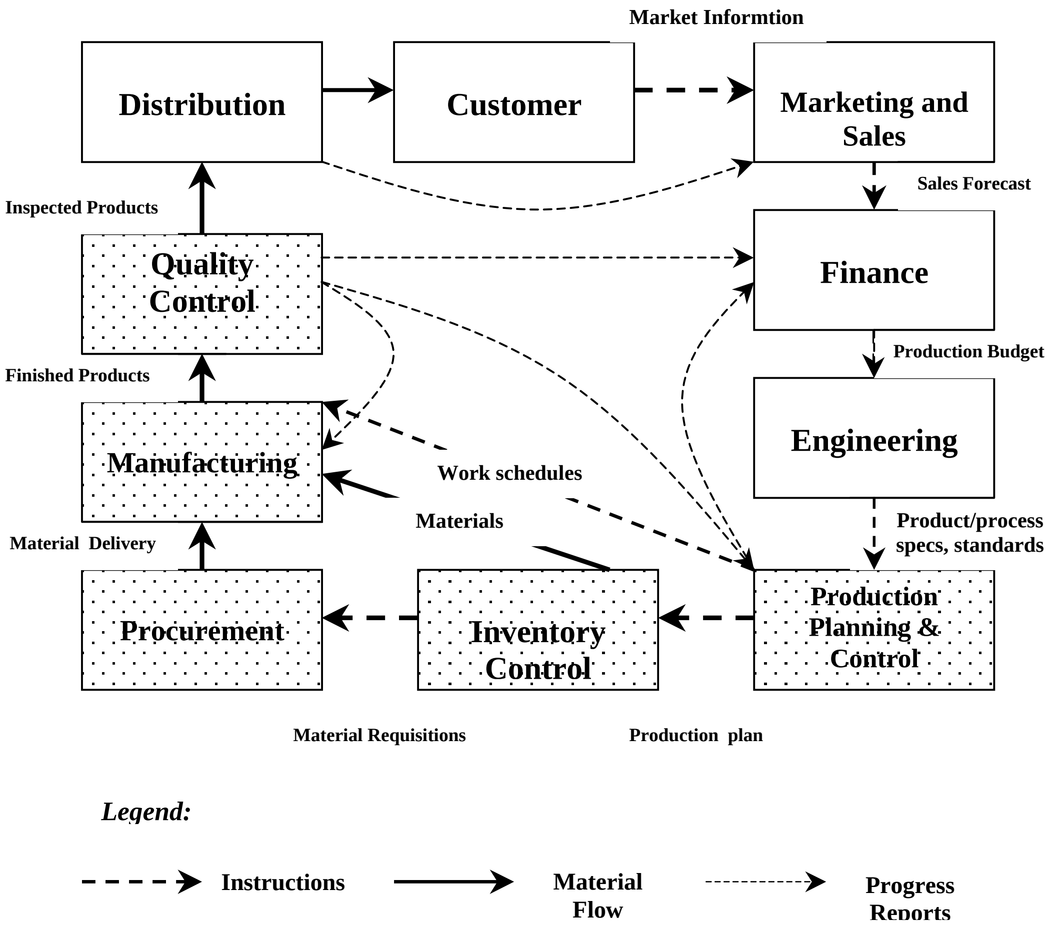


Figure 3.1 Cycle of production functions (Adapted from Riggs 1987: 48)

One other important output of production planning is the product mix decision that determines the amount of the production in a period when there are several products being processed at the same work centers.

Figure 3.2 demonstrates the importance of quality as a production responsibility which requires total organizational support. Quality decisions must ensure that quality is built into the production in all stages of operations: setting standards, equipment designed, people trainee and the product or service inspection for quality to result.

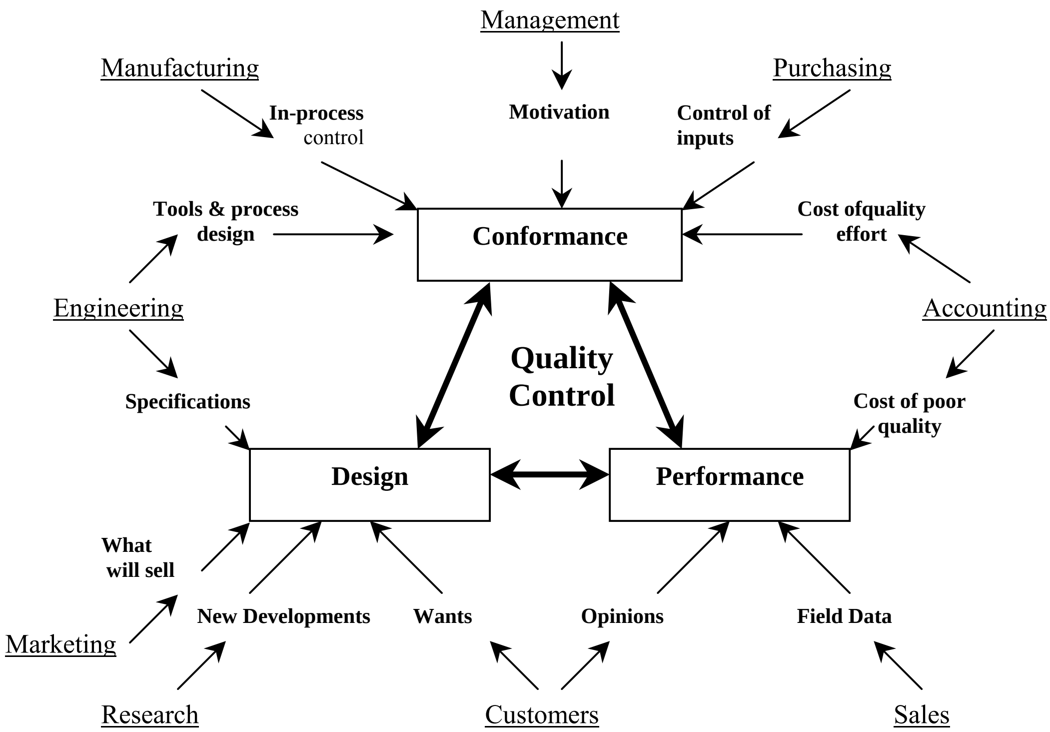


Figure 3.2 Concept of quality within the total production system (Source: Riggs 1987:582)

Production quality starts with a process capable of producing to the design specifications and continues with an inspection program that ascertains whether the standards are being met. Quality should be taken as a dynamic process that needs to be improved continually in order to survive in the global market place.

3.2 PROBLEM DEFINITION

In recent times, since quality has become the prior criterion for the customers to buy the product, Quality Improvement (QI) has been taken as a major concern for manufacturing companies. Therefore, QI efforts such as projects and programs have been developed almost for every stage of production operations. However, coping with numerous projects or programs leads to the problem of determining the right projects which will help to achieve objectives of the company.

Atwater and Chakravorty (1995) have developed an argument that questions the value of QI programs after stating low value of returns of the programs, although they are very popular and widely applied. This argument simply states that many QI efforts fail due to their lack of focus on results (Schaffer and Thomson 1992, Myers and Ashkenas 1993). Their claim is that most of the firms focus on education and changing of the corporate culture in QI programs and expectations of returns are limited by a five or more years period. A focused program should help in speeding up the implementation period and expose evident successes that will help in getting rid of the frustration of the change in the corporation. Additionally, such a program should help in cutting implementation costs by educating only the focused group of people and exposing tangible benefits that will be used by the program by utilizing these benefits for other projects. According to them, one such tool, for determining the improvements that have high value of returns, is Theory of Constraints (TOC).

If we focus on a typical manufacturing environment (consists of products, product lines, processes, work centers, etc.), one possibly proposed project among various QI alternatives, is the improvement of processes or namely; the work centers where processes are held on. Improvement of a work center can be explained as taking any action that decreases its scrap rate in order to achieve higher productivity. However, generally it is not possible to improve all work centers at the same time. Therefore, the decision maker who is in charge of manufacturing operations confronts the problem of selecting the work center which has highest requirement for quality improvement relative to the objectives such as minimization of cost , maximization of profit or throughput (which is TOC's measure) or maximization of customer satisfaction.

According to TOC philosophy, anything, that limits the performance of a system relative to its goal, is defined as a 'constraint' for the system. The obvious prerequisite of the TOC approach for improvement is that the constraint must be identified. In such an environment, each work center could be considered as a constraint for the system and what the decision maker intends to do is to identify the primary constraint (work center) that has the greatest negative impact (which has the highest quality improvement requirement) on achieving systems objectives. Therefore, TOC methodology is being utilized here in building the main logical behavior of the decision maker.

Figure 3.3 demonstrates the basic variables, measures and constraints that could be taken as inputs for the decision making process of determining the work center for improvement. Moreover, there exist different methodologies (which are stated in the following paragraphs) that would be possible to guide the decision maker in his/her decision making process.

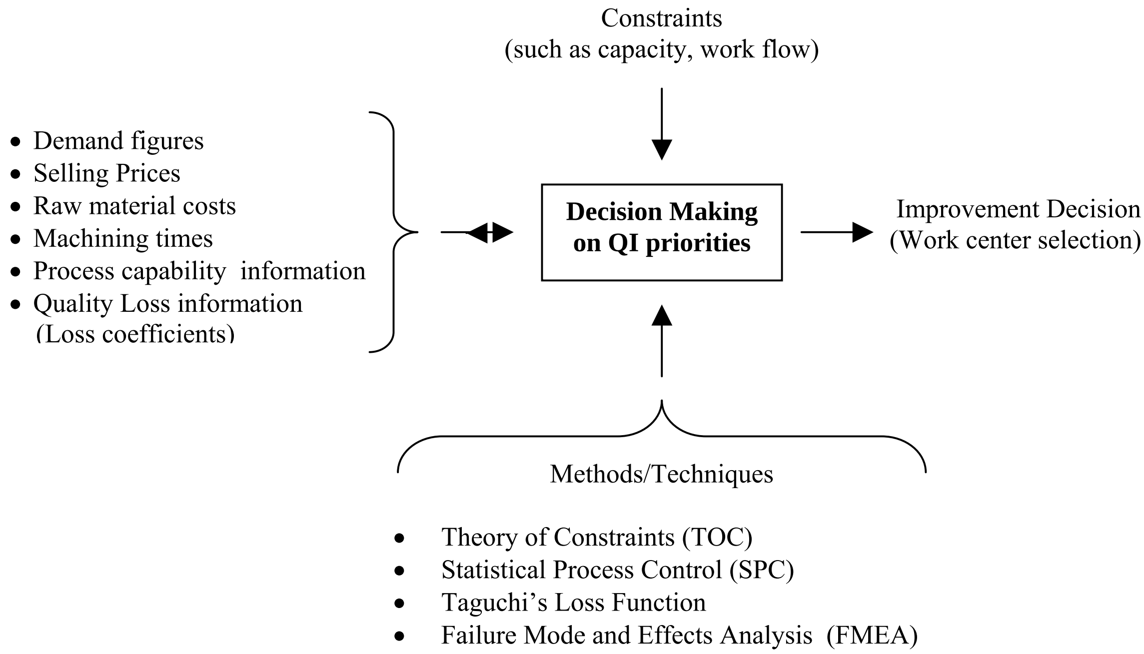


Figure 3.3 Decision Making Process on QI priorities

As mentioned in the literature review chapter, one unique aspect of TOC is to increase throughput rather than decreasing cost. Under the TOC approach, throughput is defined as the revenue generated by the system which is the difference between the selling prices and the raw material costs of the products representing the money generated within the company by its manufacturing operations. TOC methodology emphasizes on two key points; first one is that an unsold product does not generate any revenue, so products built for inventory do not count as throughput under TOC. Secondly, advocates of TOC find the traditional cost accounting improper by the way that it uses direct labor to allocate overhead costs. TOC supporters contend that overhead is a corporate cost since there is no feasible allocation system to trace it to products. They define product cost as the sum of truly variable costs of production which is usually only raw material costs. Costs other than raw material are treated as the operating expenses for the period.

In case of applying TOC procedure, first step is to identify the constraint. Any source, whose capacity is less than the demand placed on it, is defined as a 'bottleneck' source and considered to be the system's primary constraint and needs to be eliminated. Goldratt (1992) has pointed out the impact of bottleneck source on achieving TOC's goal of increasing throughput.

In such a manufacturing setting, Atwater and Chackravorty (1995) have utilized TOC methodology as a decision making tool while determining the work center for quality improvement. Firstly, they have determined the ‘constraint’, namely ‘bottleneck’ work center whose capacity is inadequate to satisfy the demand. Afterwards, in order to ‘exploit’ the constraint, the most profitable product mix has been computed by using a heuristic method that fully utilizes the constraint of bottleneck work center. However, the product mix depends on the yield rates which is the ratio of the conforming products to the total amount of the products produced. Furthermore, if the quality of a work center is improved, it results in an increase in the yield rate of that work center. Atwater and Chakravorty (1995) have proposed a solution algorithm that computes expected yield rates after each improvement one by one. According to this algorithm the work center that allows the system reaching the highest throughput, if improved, is selected as the first one to improve. And their results claim that this is bottleneck work center and is not necessarily the one with the highest scrap rate.

Although TOC offers a reasonable method of elimination of constraints to increase the throughput, it has a short term memory and may not be efficient for long term decision making, since some products that are most profitable in the short term may generate low profit in the long term. On the other hand, customer satisfaction is a long term issue which is not included in the short term planning. Therefore, by applying TOC procedure alone, any company may lose all its competitiveness, thus, ability to make profit (or throughput) as it does not take into account the customer aspects (such as loss of goodwill) or process related measures such as scrap rates or capability measures.

Using Statistical Process Control (SPC) measures such as control charts, run tests or process capability indexes is widely accepted decision making criteria for comparing processes and judging their need for improvement. Besides, SPC helps decision maker to evaluate processes by using variation, scrap rate figures and process capability measures such as C_p, C_{pk} or DPMO, etc. However, there is no apparent immediate basis for the optimal values of these process capability measures and that the managers and engineers can not comprehend the significance of their values. (e.g What is the actual quality improvement when C_p changes from 0.95 to 1.05?). Besides, it does not take cost extend and customer evaluations into decision making process. Based on these reasons Taguchi (1987) has introduced a monetary evaluation called loss function to evaluate the quality of the products or processes. However, deciding via using quality loss measure only takes into account the quality performance and customer satisfaction while ignoring the process performance issues such as the capability or scrap rates of the processes.

Failure Mode Effects Analysis (FMEA) is an effective methodology that improves operational performance of the production cycles and reduces their overall risk level by means of identifying and taking preventive action to the system's potential failures while increasing customer satisfaction. A potential failure mode is described as the way in which a product or process could fail to perform its desired function. So as to evaluate the risk level of each potential failure, FMEA produces Risk Priority Numbers (RPN) by multiplying its specific terms of 'occurrence of the failure', 'severity of the failure effect' and 'detectability of the failure' for each failure modes. In such a manufacturing setting, failure modes could be referred as work centers. As in SPC, FMEA results in numerical solutions so that decision making would be easy. Moreover, in FMEA 'severity of failure effect' term resembles Taguchi's loss function in the sense that the steeper is the loss function, the more severe is the failure effect, and vice versa. However FMEA severity determination is based on human judgment while loss values are evaluated by the using a mathematical function of Taguchi. In addition, calculation of Risk priority numbers and judging according to them does not take into direct consideration of any costs or cycle time of a process.

On the other hand, as Atwater and Chackravorty (1995) have mentioned in their study, amount of products produced at the work centers are highly affected by the yield ratios and have a direct impact on the system's revenue. Therefore, product mix information should also be taken into consideration while determining the quality improvement priorities.

None of the techniques stated above tackles the problem in the desired multi-perspective manner if they are employed separately. Therefore, different integrated methodologies should be developed to determine QI priorities.

Hence, the objective of this study is to develop a practical approach to determining which work center should be improved first in a typical manufacturing shop floor, that increases throughput in the short and long runs

3.3 PROPOSED METHODS FOR THE PROBLEM

Despite the deficiencies stated in the previous section, one of the widely used traditional methods that can not be neglected is the process capability method in which process improvement priorities are determined based on process capability measures.

'Throughput-Loss' Method is developed by utilizing the Linear Programming method that Köksal and Karşılıklı (2002) have proposed, in order to compensate for the misleading parts of TOC for determining the work center to improve first and the product mix decisions. Likely Atwater and Chackravorty (1995), Köksal and Karşılıklı (2002) have solved the problems of determining the product mix and quality improvement priorities together which requires higher integration of quality control, production planning and manufacturing sub-systems. The method that will be explained in Section 3.5, gives optimal results but have some disadvantages in application. It is not easy to determine the model parameter values and solve the model in practice. Moreover, it requires higher integration of the sub-systems which could possibly lead to confusion to gather model parameters accurately. By taking these deficiencies as a main starting point, an integrated method is proposed using Quality Function Deployment (QFD) methodology which is explained in detail in the following sections.

The following is a list of basic assumptions that are made for our analysis. Actually, first and second items have already been assumed by Atwater and Chackravorty (1995) while items 3 and 4 have been added by Köksal and Karşılıklı (2002). Further assumptions are appended to the list as items 5, 6 and 7.

1) All of the products produced are sold immediately. Because of this, overall demand can be taken as an amount that is much larger than the production amounts.
2) Cost of reducing scrap is negligibly different or the same for all work centers which can be relaxed.
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 ($T=\mu$) for the sake of simplicity.
4) Labor or overhead costs are assumed to be insignificant compared to raw material costs. Therefore, only raw material costs are taken into the consideration.

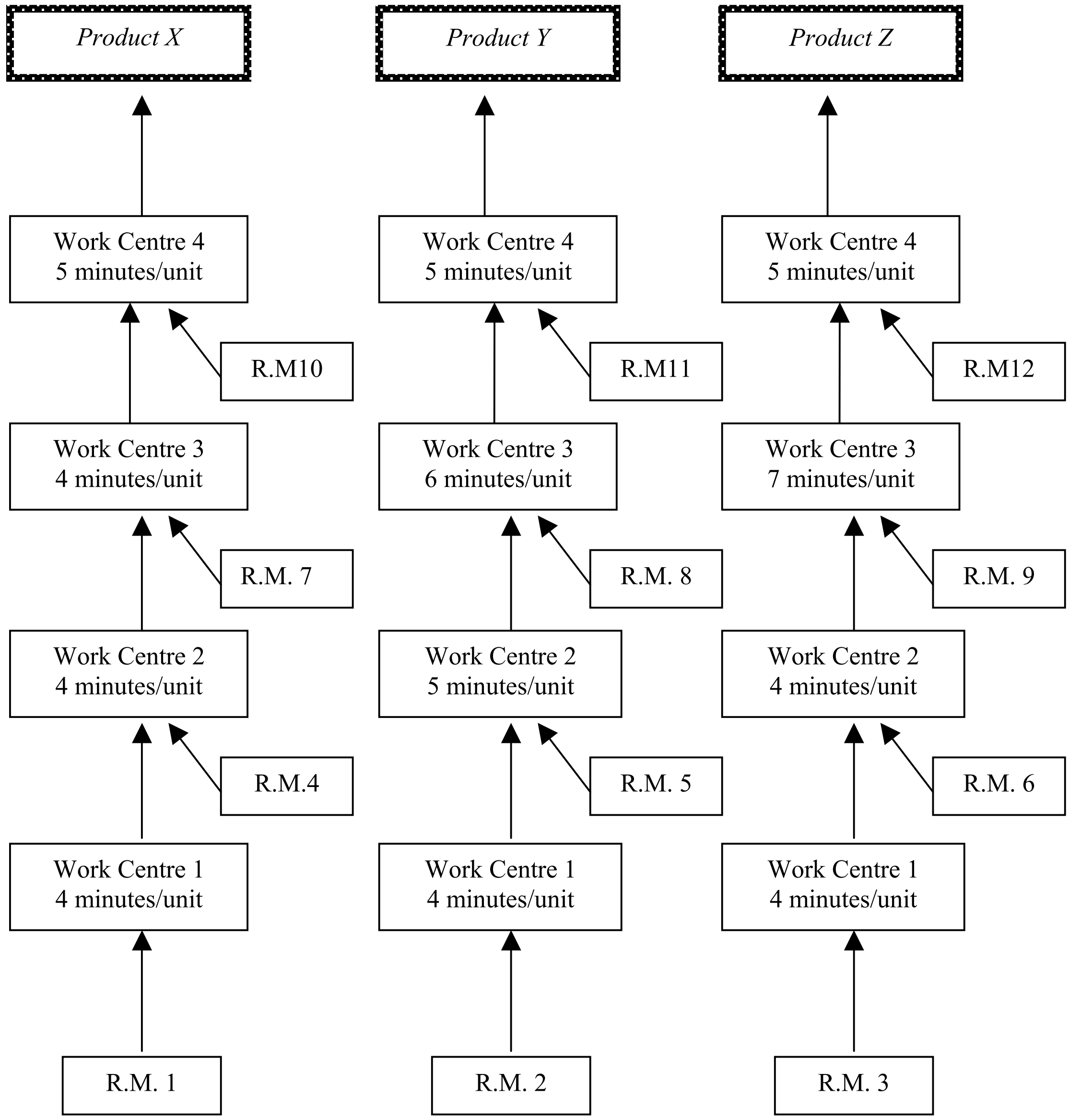
5) Inspection and detectability are assumed as 100% which means that each product comes to inspection points after each operation. After detection, the parts that do not conform to the specifications are not allowed to pass screening. It is also assumed that defective products are not repaired (or reworked) but they are scrapped.
6) For the sake of simplicity work center selected for improvement at this period is assumed to be improved to the desired stage at the end of the period.

3.4 NUMERICAL EXAMPLE PROBLEM

In order to utilize TOC in manufacturing operations, Atwater and Chackravorty (1995) have developed an imaginative production environment, consisting of three products (X,Y,Z), each with different product lines and all are processed at the same four work centers (1,2,3,4). Products to be produced have different raw material requirements, machining times, selling prices and constant demands in a given period. On the other hand, the work centers have constant yield rates which apply to all of the products and the production environment is designed in such a way that, meeting all the demand figures is infeasible due to the capacity constraints. This layout forms the basics of our analysis as well in order to illustrate the proposed methods for determining the work center for improvement. Moreover, other given parameters are the related loss coefficients of the products at each work center (as a quality loss measure) and the C_p indices of the work centers (as a process capability measure). Figure 3.4 demonstrates the manufacturing setting for our case problem that is similar to the problem in Atwater and Chackravorty's (1995) case with some modifications.

The problem of determining the work center for QI is solved by applying three methods namely 'Throughput-Loss', 'Process Capability' and 'Integrated QFD'. However, in order to compare the performances of these methods on consecutive periods, we assume three consecutive planning periods each of which is four months long. Improvement decisions are needed to be made at the beginning of the first and second periods.

On the other hand, scrap of the work center is assumed to be halved after improvement. In fact, this assumption has been made by Köksal and Karşılıklı (2002) in their analysis for computational purposes. The assumption does not form a limitation for the methods but has been added just for collecting parameters for the methods.
In the following sections the numerical example problem is solved by utilizing each proposed method, so as to express the methods in more understandable way.



Information:

- Plant operates
  8 hrs/shift , 2 shifts/day , 5 days/week , 4 weeks/month
  4 months planning period (76800 minutes)
- Each work centre has only one resource
- R.M : Raw material

Figure 3.4 Process Flow of the numerical problem

(Adapted from Atwater and Chackravorty (1995) case)

Notation used :

D_i = Number of demanded units for product i

SP_i = Selling price for product i

CA_k = Capacity available for work centre k

t_{ik} = Production time per unit at work centre k for product i

C_{pk} = Process capability index of work center k.

A_{ik} = Loss coefficient for the major characteristic of product i on work centre k (Further explanation of the coefficient is given in section 3.5.1)

P_{ik} = Total raw material cost for processing one unit of product i at work center k

H_{ik} = Range of upper or lower specification limit for the characteristic of product i from its target value at work center k.

3.4.1 Parameter Values of Numerical Example Problem

Table 3.1 Demand and selling price figures

	Products		
	X(1)	Y(2)	Z(3)
D_i	4200	2500	3200
SP_i	4000	5400	4500

Table 3.2 Process capability indices for work centers

	Work center 4	Work center 3	Work center 2	Work center 1
C_{pk}	1.5	0.56	0.45	0.3

Table 3.3 Loss coefficients

A_{ik}	Work center 4	Work center 3	Work center 2	Work center 1
Product X	96	3500	1800	50
Product Y	1650	2200	650	19
Product Z	50	5600	2700	71

Table 3.4 Raw Material Costs

P_{ik}	Work center 4	Work center 3	Work center 2	Work center 1
Product X	5	15	45	10
Product Y	10	25	19	2
Product Z	10	35	15	8

Table 3.5 Table of H_{ik} values

H_{ik}	Work center 4	Work center 3	Work center 2	Work center 1
Product X	0.6862429	0.876521	1.356076	1.560445
Product Y	0.7517414	0.939964	1.286486	1.452695
Product Z	0.7197376	0.960181	1.187373	1.34637

Other parameter values of t_{ik} and CA_k (which is 76800 minutes for all work centers) are demonstrated in Figure 3.4.

3.5 THROUGHPUT-LOSS METHOD

In order to solve the problem of selecting quality improvement activities to focus on and determining the product mix, Köksal and Karşılıklı (2002) have developed a mathematical model which is utilized for Throughput-Loss Method.

3.5.1 LP Formulation

LP formulation of the problem has been constructed with additional corrections to the model proposed by Köksal and Karşılıklı (2002).

According to the formulation; production amounts of each product at each work centre are selected as the decision variables and the objective function is to maximize 'Throughput-Loss' value.

T_i = Throughput value 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 work centre k to satisfy production requirements of product i.

Y_k = Yield ratio of work centre k

$U_{ik} = U_{i,k+1} / Y_k$,

C_k = Capacity required for work center k to satisfy the demand for all products

m = Total number of products

n = Total number of work centers

$$C_k = \sum_{i=1}^{m} U_{ik} * t_{ik}$$

Loss function concept is used to assess quality loss in terms of monetary values. It has been incorporated into analysis in order to compensate for TOC's ignorance about impact of customer dissatisfaction on sales. Since selling of the future products may be affected by the quality loss such as that demand may decrease due to poor quality and may result in decrease in throughput.

Loss to the society or loss of goodwill is hard to quantify, but for comparison purposes it can be considered as repair and replacement cost at the specification limits.

The Loss Function for a variable quality characteristic can be reduced to L= $A\sigma^2$ when the quality characteristic is distributed with mean at the target (T=μ). (See Section 2.7)

L_{ik} =Average loss incurred per product i due to its processing on machine k

B_{ik} = Loss caused by the major quality characteristic of product i at work center k when it is at its specification limits. (monetary units)

B_i = Total loss associated to the product i caused by work centers.

$$B_i = \sum_{k=1}^{n} B_{ik}$$

The value of B_{ik} could be any after sales cost that can be expressed in monetary terms of customer dissatisfaction, warranty expenses, possible complaints, repair, replacement or adjustment costs in case of the product is brought back by the customer when the product is at its limit of nonconformance (at specification limit).

$$A_{ik} = \frac{B_{ik}}{H_{ik}^2}$$

σ_{ik}^2 = Variance of the quality characteristic of product i at work centre k

$L_{ik} = A_{ik} \times \sigma_{ik}^2$

Instead of σ_{ik}^2 which is used by Köksal and Karşılıklı (2002), σ_{aik}^2 should be used since detection of failures and inspection are assumed to be 100 percent.

σ_{aik}^2 = Variance of the quality characteristic of product i that has passed screening, at work centre k.

Further explanation and computation of σ_{aik}^2 is mentioned in the following section.

Therefore the corrected formulation should be ;

$L_{ik} = A_{ik} \times \sigma_{aik}^2$

W_k = Total loss (total amount of after sales cost) caused by work center k

$W_k = \sum_{i=1}^{m} (U_{ik} \times L_{ik})$ (Köksal and Karşılıklı, 2002)

As mentioned before, a product has to reach to a customer in order to incur some loss. U_{ik} is the total number of parts to be processed at work centre k, however at the end of the line only S_i units will be produced and shipped to the customers. Hence, S_i should replace U_{ik} in the correct formulation.

$$W_k = \sum_{i=1}^{m} (S_i \times L_{ik})$$

Using TOC methodology, W_k, which is an after-sales cost (including repair, replacement and loss of goodwill costs), has been considered as a "negative throughput" or another objective function to be minimized in the model.

As a result the following model is formulated for the problem of determining the product mix under capacity, demand constraints and for given yield ratios of work centers.

$$\text{Max } F = \sum_{i=1}^{m} [(SP_i \text{ x } S_i) - \sum_{k=1}^{n} (U_{ik} \text{ x } P_{ik})] - \sum_{k=1}^{n}\sum_{i=1}^{m}(S_i \text{ x } A_{ik} \text{ x } \sigma_{aik}{}^2)$$

Subject to ;

$U_{ik} = U_{i,k+1} / Y_k \quad , \ i = 1,...,m \ , \ k = 1,...,n$

$U_{i,,n+1} = S_i \quad , \ i = 1,...,m$

$$\sum_{i=1}^{m}(U_{ik} \text{ x } t_{ik}) \leq CA_k \quad , \ k = 1,...,n$$

$U_{i,n+1} \leq D_i \quad , \ i = 1,...,m$

$0 \leq U_{ik} \quad , \ i = 1,...,m \quad k=1,...,n+1$

3.5.2 Application of LP Formulation

As in the example problem, if process capability indexes of work centers are known, then the parameters of the model; such as yield rates and variances can be obtained.

$$C_{pk} = \frac{USL_{ik} - LSL_{ik}}{6\sqrt{\sigma_{ik}{}^2 + (\mu_{ik} - T_{ik})^2}} \quad \text{(Montgomery 1997)}$$

As USL = -LSL (symmetric specification limits) and $\mu = T$ (nominal the best case) the formula reduces to:

$$C_{pk} = \frac{USL_{ik}}{3\sigma_{ik}}$$

Scrap rate is defined as the ratio of products beyond the specification limits (Upper Specification Limit, Lower Specification Limit) to the whole which is simply the area under the distribution function beyond USL and LSL points.

Since improvement scenarios are constructed by 50% reduction in scrap rates, that is $1-Y_k$ values are reduced by half, the formulation requires finding new variance values after the improvement to calculate the relevant loss function value.

As the distribution is assumed to be normal (thus symmetrical), Φ represents the distribution function of standard normal distribution, where Φ^{-1} is the inverse of the standard normal distribution.

$$\frac{(USL_{ik} - \mu_{ik})}{\sigma_{ik}} = \Phi^{-1}\left(1 - \frac{1 - Y_k}{2}\right), \text{ or } (USL_{ik} - \mu_{ik}) = H_{ik}.$$

In the analysis, recall that we take $\mu = T$, then for any work centre k and product i,

if $H_{ik} = \frac{(USL_{ik} - LSL_{ik})}{2}$ is given as in our case problem , then

$C_{pk} = \frac{USL_{ik}}{3\sigma_{ik}}$ will turn into $C_{pk} = \frac{H_{ik}}{3\sigma_{ik}}$

So as to obtain initial variance information and yield ratios, following equations are used:

$$\sigma_{ik}^{2} = \left(\frac{H_{ik}}{3 * C_{pk}}\right)^{2}$$

$$\left(1 - \frac{1 - Y_k}{2}\right) = \Phi\left(\frac{H_{ik}}{\sigma_{ik}}\right)$$

To find the improved variances (σ'_{ik}) and improved yield rates (Y'_k) following equations are used:

$$\frac{H_{ik}}{\sigma'_{ik}} = \Phi^{-1}\left(1 - \frac{1 - Y_k'}{2}\right)$$

Here, the only unknown is σ'_{ik}, where $1 - \frac{1 - Y_k'}{2}$ values are half the original.

According to the assumption that both inspection and detection of the defective products are 100%, the parts that are not between specification limits (as shown by the hatched area in Figure 3.5) can not pass screening. As these defective parts are assumed not to be repaired but scrapped, within spec parts that have shipped to customer are expected to form different distribution and have different variance: σ_{aik}^{2}.

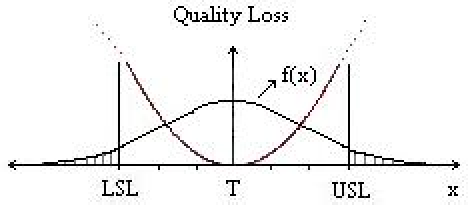


Figure 3.5 Quality loss with screening

Let $f_{ik}(x)$ be the density function of the normal distribution of the major characteristic of product i at work center k , which is given by

$$f_{ik}(\mathrm{x}) = \frac{1}{\sqrt{2\pi}\sigma_{ik}} \mathrm{e}^{(-1/2)((\mathrm{x} - \mu_{\mathrm{ik}})/\sigma_{ik}{}^{2}))} \qquad -\infty < \mathrm{x} < \infty$$

The probability density function of the items that have passed the screening (acceptable items) is given by dividing the probability density function by yield rate $\mathrm{Y_k}$, the proportion of acceptable items which is simply the area between spec limits.
(Taguchi and Elyased 1989:20-22)

$$f_{accepted\_i\,k}(\mathrm{x}) = f_{aik}(\mathrm{x}) = \frac{f_{ik}(\mathrm{x})}{\mathrm{Y_k}} \qquad \mathrm{LSL_{ik}} \leq \mathrm{x} \leq \mathrm{USL_{ik}}$$

$$\mathrm{Y_k} = \int_{\mathrm{LSL_{ik}}}^{\mathrm{USL_{ik}}} f_{ik}(\mathrm{x})\mathrm{dx}$$

Therefore the variance of the passed items;

$$\sigma_{aik}{}^{2} = \int_{\mathrm{LSL_{ik}}}^{\mathrm{USL_{ik}}} (\mathrm{x} - \mu_{\mathrm{ik}})^{2} f_{aik}(\mathrm{x})\mathrm{dx}$$

After the calculations and integration by parts which can be seen in Appendix A, the final solution is generated as;

$$\sigma_{aik}^{2} = \sigma_{ik}^{2}\left(1 - \frac{2H_{ik}\, e^{(-1/2)(H_{ik}/\sigma_{ik})^2}}{Y_k \sigma_{ik}\sqrt{2\pi}}\right)$$

As stated before, each work center gives one characteristic to the product. At the end of the assembly line the distribution of the shipped product to the customer with respect to any characteristic is assumed to be remained similar with the distribution of the product at the related work center after inspection. This means the following:

Assume characteristic k is given by work center k and $f_k(x)$ is the density function of the normal distribution of the characteristic k.

$$f_{\text{shipped items of characteristic k}}(x) = \frac{f_k(x)}{Y_k}$$

σ'_{aik} , which is the variance of the characteristic of the product after improvement could be generated using the same computations.

$$\sigma'^{2}_{aik} = \sigma'^{2}_{ik}\left(1 - \frac{2H_{ik}\, e^{(-1/2)(H_{ik}/\sigma'_{ik})^2}}{Y'_k \sigma'_{ik}\sqrt{2\pi}}\right)$$

3.5.3 Throughput-Loss Algorithm

Throughput-Loss Algorithm is based on the mathematical model developed by Köksal and Karşılıklı (2002). The Algorithm verifies the optimal solution and optimal product mix. As mentioned before, three planning periods are assumed in a year and at the end of each period the work center selected for improvement is assumed to be improved to the desired level (scrap is halved).

Steps of the Algorithm :

STEP 1. For the current period; determine the optimal product mix for this period's production by solving the T-L Model.

STEP 2. If it is desired to continue improvement, go to step3, if not, stop improvement projects.

STEP 3. In order to determine the work center to be improved in the current period, for each work center; find the optimal product mix and the associated F value by solving T-L Model using the next period's demand, selling price, raw material cost, processing time, capacity, loss figures, yield rates and variances, assuming that the work center under consideration has already been improved as much as anticipated. (The other work centers are not improved at this time.) Repeat same procedure for all work centers. Decide to improve the work center in the current period, which has highest objective function F value. Start the improvement project at the chosen work center. Move to the next period. Go back to Step 1.

Improvement decision:

According to the assumption that the work center chosen for improvement will be entirely improved at the end of the current period as much as anticipated, next period's F value is computed by assuming the work center have been improved. The procedure below is repeated for each work center to find the one that should be the first to improve.

1. Scrap rate of the work center is decreased to half of its original value
2. LP formulation is constructed by using improved yield rates and standard deviation values.
3. Model is solved and the objective value F is saved.

After applying the procedure for each work center, one, which gives the highest objective value (F) is chosen for improvement project.

3.5.4 Application of T-L Method on the Example Problem

An example problem is generated to clarify the algorithm and its application in practice.
Input parameters of the problem are stated in Section 3.4.
The related calculations for obtaining model parameters are demonstrated in Appendix B.

Application of the Algorithm

Period 1

No improvement case (current conditions)

LP model is constructed with the current period's figures. The model is solved.

Product mix : (S_1=4200, S_2=2500 , S_3=2356)

Objective function value = F_1(4200, 2500, 2356) = Throughput $_1$ – Loss $_1$= $26,635,871

The work center which gives the highest F value for the next period is chosen for improvement project.

If Work Center 4 is improved; F = $26,643,712

If Work Center 3 is improved; F = $27,585,494

If Work Center 2 is improved; F = $27,599,410

If Work Center 1 is improved; F = $26,700,952

Work Center 2 is selected for improvement project. At the end of this period:

F_1 (4200, 2500, 2356) = Throughput $_1$ – Loss $_1$= $26,635,871

Period 2

Work Center 2 has been improved.

Product mix : (S_1=4200, S_2=2500 , S_3=3200)

Improvement decision:

If Work Center 4 is improved; F = $29,594,698

If Work Center 3 is improved; F = $30,677,625

If Work Center 2 is improved again; F = $30,528,711 (see the remark in Appendix B)

If Work Center 1 is improved; F = $29,555,718

Work Center 3 is selected for improvement project. At the end of the period:

F_2 (4200, 2500, 3200) = Throughput $_2$ – Loss $_2$= $29,586,791

Period 3

Work Center 3 has been improved

Product mix : (S_1=4200, S_2=2500 , S_3=3200)

Stop improvement projects for the demonstration purposes. At the end of the period ;

F_3 (4200, 2500, 3200) = Throughput $_3$ – Loss $_3$= $30,677,625

Total F $_{T-L}$ = F_1+F_2+F_3

= $86,900,287

3.6 INTEGRATED QFD METHOD

QFD is an effective approach in focusing efforts for customer satisfaction and profitability. It guides product development efforts by suggesting a series of deployment tools for understanding customer requirements and translating them into product and process characteristics. Among these tools widely known and used ones include matrix diagrams. These matrices help store relevant information at a stage of deployment, and they typically study relations between important parameters of the problem at that stage. Different types of matrices can be used to analyze failure modes and effects, process capability, and so on (Akao 1990, King 1989). Hence, QFD approach incorporates to a certain extend with other quality tools such as FMEA, and utilizes information collected through SPC. There are studies that incorporate TOC with QFD as well (such as Zultner 1998). However, looking at QFD from a wider perspective, we observe the particular tools suggested for use by QFD practitioners can further be improved for better focusing, and eventually for more customer satisfaction and profitability.

We aim to develop a QFD tool that can be used in analyzing the relations between various different products of the company and the manufacturing operations (work centers in our case), and help focus on the most important operations for customer satisfaction and profitability.

3.6.1 Criteria Selection

TOC defines a ‘constraint’ that prevents and limits the performance of the system as a bottleneck resource which should be released first. In their analysis, Atwater and Chackravorty (1995) have claimed the effect of improving bottleneck work center on the system and concluded that the succeeding work center of the bottleneck work center according to the production sequence, have considerable impact on the system as well. Due to the dependency between the bottleneck and the next work center, eliminating scrap at the next work center results in a reduction in the amount of materials that must be processed at the bottleneck work center. Since the bottleneck work center would become to process less material to compensate for the scrap of the following work centers, the capacity of the bottleneck resource is relaxed. Actually, the impact of improving a successor work center decreases while its distance to the bottleneck resource increases. Integrated QFD method takes this relationship into account as ‘closeness to bottleneck’ criteria. The bottleneck and first successor work center are given higher importance than the other work centers.

According to TOC reasoning the 'throughput' (which is the difference between selling income and raw material expenses) has to be taken as the major measure. Furthermore, an unsold product does not generate any revenue. However, if the product is scrapped, it is considered to result in loss at the throughput because of its raw material expenses. On the other hand, in our analysis other costs are assumed to be negligible when compared to raw material costs. Therefore only raw material costs of the products at each work center are taken into consideration as criteria in integrated QFD method. Otherwise, we would consider labor and utility costs as well in the analysis.

Moreover, while evaluating processes, SPC typically suggests use of different capability measures; such as 'Process Capability Index' (C_p), which is the basic general measure used by more practitioners. Therefore, C_p measure is labeled as criteria in integrated QFD method as well.

Furthermore, one other effective method in measuring customer aspects and quality levels of the product is to utilize the loss function. Therefore, loss coefficients of the products at the work centers are taken as 'Loss Coefficient' measure.

Process FMEA, on the other hand, concentrates on failure modes of processes, their effects and causes. It suggests, for each potential cause of a failure, calculation of Risk Priority Number (RPN) = (Severity of hazard the failure will result in) × (Likelihood of occurrence of the failure) × (the ease with which the failure may be detected) (Stamatis, 1995). Likelihood of occurrence of the failure can be determined using the process capability index values. One may concentrate on the operations according to these RPN values. Besides, associated loss coefficients of the products at work centers seem to be positively correlated with severity of hazard a failure of the product will result in.

3.6.2 Relationship values

As explained in the previous section, major indicators of the various approaches can be evaluated together to determine the work center (manufacturing operation) to be improved first. However, combining these indicators under QFD matrix calls for utilizing a tool, such as to define 'relationship values' which reflect the improvement requirement of the product at the work center. The steps in obtaining relationship values are summarized below;

1) Each criterion is categorized into levels of low and high. However, the process capability index criterion is determined as the most effective factor on the improvement decisions. Therefore, classifying the criteria into two levels is found to be inadequate in prioritizing the operations and it is categorized in to three levels which are low, medium and high.

2)After analyzing various different cases, relationship values are allocated according to their importance in decision making, when arranged from the most effective to least is 'Process Capability Index' (such as C_p), 'Loss Coefficient', 'Closeness to Constraint' (Bottleneck) and 'Raw material cost'. This ranking is reflected to relationship values and Table 3.6 is constructed. Furthermore, Table 3.7 shows an agreement between of our proposed relationship values and RPN values which is the main indicator of FMEA methodology.

Table 3.6 Relationship values for QFD matrix

Process Capability Index (such as C_p)	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
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

Table 3.7 Risk priority numbers (RPN)

Process Capability Index	Loss coefficient	RPN
High	Low	1 (lowest)
Medium	Low	2
Low	Low	3
High	High	4
Medium	High	5
Low	High	6 (highest)

Generating Levels

Different approaches are used in deciding on the levels of the criteria;

Process Capability Index (C_{pk})

1. In a given set of C_{pk} values, calculate the range.
   Range=R=max$\{C_{pk}\}$-min $\{C_{pk}\}$

2. For each C_{pk} value; k=1,..,n
   C_{pk} is labeled as 'Low' ; if $C_{pk} \leq \min\{C_{pk}\}+R*0.15$
   'Medium' ; if $\min\{C_{pk}\}+R*0.15 < C_{pk} \leq \min\{C_{pk}\}+R*0.75$
   'High'; if $\min\{C_{pk}\}+R*0.75 < C_{pk} \leq \max\{C_{pk}\}$

Loss Coefficient (A_{ik})

1. In a given set of A_{ik} values, calculate the overall and specific average values associated to each product

$$\text{Product Average} = PA_i = \frac{1}{n}\sum_{k=1}^{n} A_{ik}$$

$$\text{Overall Average} = OA = \frac{1}{mn}\sum_{i=1}^{m}\sum_{k=1}^{n} A_{ik}$$

2. For each A_{ik} value; i=1,…,m , k=1,…,n

A_{ik} is labeled as 'High'; if $[(A_{ik} \geq PA_i)$ and $(A_{ik} \geq OA)]$

'Low'; otherwise

Closeness to Constraint

According to TOC, the work center whose capacity is insufficient to satisfy the demand placed on it, is called as bottleneck work center and forms a constraint and should be relaxed. Bottleneck work center is determined by computing the work loads of the work centers for satisfying the demand placed on them (which is actually the product mix for the periods). The work center that is loaded very close to (which means differing at most 1% from the capacity limit) or at its capacity limit, is defined as the 'bottleneck'.

$S_i = U_{i,,n+1}^*$ = Optimal number of units of product i to be produced within the specified time frame.

U_{ik}^* = Optimal amount of total parts to be processed at work centre k to satisfy production requirements of product i (units).

$U_{ik}^* = U_{i,k+1}^* / Y_k$, k=1,..,n

$$C_k = \sum_{i=1}^{m} t_{ik} * U_{ik}^*$$

For k=1,..,n

If $(CA_k - C_k \leq CA_k * 0.01)$ then the work center k is considered to be bottleneck.

As mentioned before, since the impact of improving any successor work center increases while its distance to the bottleneck resource decreases ,the bottleneck (k) and its successor work center (k+1) are leveled as 'At/Next' while 'Far' is assigned to other work centers.

Raw material cost

As the raw material value of the product at any work center is expressed as the total cost of all raw material requirements of the product till the current process, cumulative raw material costs associated with each product at each work center, should be computed.

1. In a given set of P_{ik} values, calculate cumulative raw material costs.

CP_{ik}=Cumulative raw material cost of product i at work center k

For i=1,…,m k=1,…,n

$$CP_{ik} = \sum_{k=1}^{k} P_{ik}$$

After forming the CP_{ik} table, the overall and average values associated with each product are calculated.

Product Average= $PA_i = \frac{1}{n}\sum_{k=1}^{n} CP_{ik}$

Overall Average=OA= $\frac{1}{mn}\sum_{i=1}^{m}\sum_{k=1}^{n} CP_{ik}$

2. For each CP_{ik} value; i=1,…,m, k=1,…,n

CP_{ik} is labeled as 'High '; if [$(CP_{ik} \geq PA_i)$ and $(CP_{ik} \geq OA)$]

'Low' ; otherwise

3.6.3 Constructing the QFD Matrix

Table 3.8 demonstrates the proposed House of Quality matrix of QFD which is utilized for selecting the process for improvement.

Table 3.8 The proposed QFD matrix

	Operations (Work Centers)				
Products	n	….	2	1	Share in production (SR_i)
1	R_{1n}	….	R_{12}	R_{11}	SR_1
2	R_{2n}	….	R_{22}	R_{21}	SR_2
….	….	….	….	….	….
m	R_{mn}	….	R_{m2}	R_{m1}	SR_m
Importance weight(IW_k)	IW_4	….	IW_2	IW_1	

Share in production values are computed by using the amounts of products to be produced in the period (which is the product mix information). Actually, this task is generally done by production planners by solving a typical product mix problem. Hence, the QFD method we propose, takes the product mix as given rather than finding it together with the improvement priorities as done by the Throughput-Loss method. Here:

R_{ik}=Relationship value assigned to product i at work center k

SR_i= The ratio of amount of product ito the total number of items to be produced.

$$SR_i = \frac{S_i}{\sum_{i=1}^{m} S_i} \qquad \text{(Equation 3.1)}$$

IW_k=Importance Weight of the work center k (which shows the improvement requirement of work center k)

$$IW_k = \sum_{i=1}^{m} SR_i * R_{ik} \qquad \text{(Equation 3.2)}$$

3.6.4. The QFD Algorithm

STEP 1 For the period under consideration, determine the optimal product mix based on demand, selling price, raw material cost, processing time, capacity, and scrap rate figures of products and work centers. This is typically performed by production planners using an algorithm such as the one given by Johnson and Montgomery (1974). LP model that is used to generate the product mix is shown below.

STEP 2 Fill in the QFD matrix of Table 3.8 with suitable relationship values using Table 3.6, and the current product mix determined at Step 1.

If loss coefficients are not known, but FMEA is carried out for the processes, then process capability and loss coefficient columns of Table 3.6 can be replaced with RPN column of Table 3.7

STEP 3 Perform the matrix analysis; decide to improve the work center that has the highest importance weight. Start the improvement project at the chosen work center. If decide to continue improvement then move to the next period and go back to Step 1, otherwise; stop improvement projects.

As mentioned in Step 1, a typical product mix problem either aims to maximize profit or minimize cost. Although, the model shown below resembles to ‘Throughput-Loss’ model, it differs in easiness of application since it does not take quality loss into account.

The notations used are the same as in defined in Sections 3.4 and 3.5.

$$\text{Max } F = \sum_{i=1}^{m} [(SP_i \text{ x } S_i) - \sum_{k=1}^{n} (U_{ik} \text{ x } P_{ik})]$$

Subject to

$$U_{ik} = U_{i,k+1} / Y_k \quad , \; i = 1,...,m \;, \; k = 1,...,n$$

$$U_{i,n+1} = S_i \quad , \; i = 1,...,m$$

$$\sum_{i=1}^{m} (U_{ik} \text{ x } t_{ik}) \leq CA_k \quad , \; k = 1,...,n$$

$$U_{i,n+1} \leq D_i \quad , \; i = 1,...,m$$

$$0 \leq U_{ik} \quad , \; i = 1,...,m \;, k=1,....n$$

3.6.5 Application of the QFD Method on the Example Problem

So as to clarify the proposed method, QFD algorithm is applied on the same example problem which is introduced in Section 3.4.

Application of the Algorithm

Period 1

No improvement case (current conditions)

Typical LP model is constructed with the current period's figures and the model given in Section 3.6.4 is solved.

Product mix : (S_1=3356, S_2=2500, S_3=3200)

Improvement decision:

Classify the variables into levels of low, medium or high by using the algorithms defined in the Section 3.6.2. Detailed calculations can be seen in Appendix C. Fill in the QFD matrix with suitable relationship values by using Table 3.6.

The relationship values that are assigned to the products at each work center are determined based on the levels of the criteria. Suppose that, if the relationship value of product 1 at work center 3 is to be computed; levels of each criteria are gathered; such as 'M' for C_p criterion, 'H' for Loss Coefficient criterion, 'H' for Raw Material Cost criterion and 'At/Next' for constraint criterion. And the related relationship value of M-H-At/Next-H is found from Table 3.6 as '6.5' and written on the QFD matrix. Each relationship value is assigned in the same manner. Share in production values and importance weights are calculated by using Equations 3.1 and 3.2 in Section 3.6.3.

Table 3.9 QFD matrix at Period 1 for the example problem

	Operations (Work Centers)(k)				
Products (i)	4	3	2	1	Share in production (SR_i)
X(1)	2	5.5	9	6	0.370
Y(2)	4.5	5.5	6	6	0.276
Z(3)	2	5.5	8	6	0.353
Importance weight (IW_k)	2.688	5.5	***7.81***	6	

According to this analysis, work center 2, which has the highest importance weight, is selected for improvement.

In order to compare the results with 'Throughput-Loss' method, F value is calculated.

At the end of the period;

F_1 (3356, 2500, 3200) =Throughput $_1$ – Loss $_1$= \$26,489,452

Period 2

Work center 2 has been improved.

(Remark: Since an improved work center is expected to have better process capability index and a decreased scrap rate, improved features of the related work center are taken for the following computations. As half way improvement is assumed as performed, improved yield rates and new process capability indices are demonstrated in Appendix B, Table B.2 and Table B.6.

New Product mix : (S_1=4200, S_2=2500, S_3=3200)

Table 3.10. QFD matrix at Period 2 for the example problem

	Operations (Work Centers) (k)				
Products (i)	4	3	2	1	Share in production (SR_i)
X (1)	2	5.5	5.5	5	0.424
Y (2)	4.5	5.5	2.5	5	0.253
Z (3)	2	5.5	5	5	0.323
Importance weight (IW_k)	2.6325	***5.5***	4.5795	5	

Work center 3 is selected for improvement.

F_2(4200,2500,3200)=Throughput $_2$ – Loss $_2$= \$29,586,791

Period 3

WC3 has been improved

Product mix : (S_1=4200, S_2=2500 , S_3=3200)

Stop improvement projects for demonstration purposes.

At the end of the period ;

F_3(4200,2500,3200)=Throughput $_3$ – Loss $_3$= \$30,677,625

Total $F_{QFD} = F_1+F_2+F_3$

= \$86,753,867

3.7 PROCESS CAPABILITY METHOD

Using Process Capability measures; such as C_p indices, is the most general and easiest way of deciding on improvement priorities for many practitioners.

3.7.1 Process Capability Algorithm

STEP 1. For the current period, determine the optimal product mix based on demand, selling price, raw material cost, processing time, capacity, and scrap rate figures by solving typical product mix problem as demonstrated in Section 3.6.4.

STEP2. Decide to improve the work center, which has the smallest C_p value. Start the improvement project at this work center. If it is decided to continue improvements; move to the next period and go back to Step 1; otherwise stop improvement projects.

3.7.2 Application of the Process Capability Method on the Example Problem

Process Capability Algorithm is applied to the same decision problem stated in Section 3.4.

Application of the Algorithm

Period 1

No improvement case (current conditions)

Typical LP model is solved.

Product mix: (S_1=3356, S_2=2500, S_3=3200)

Table 3.11 C_p values at period 1 (no improvement)

	Work center 4	Work center 3	Work center 2	Work center 1
C_{pk}	1.5	0.56	0.45	0.3

Work center 1 is selected for improvement project since it has the smallest C_p value.

So as to measure the performance of the method against the other methods, F value is computed.

At the end of the period;

F_1 (3356, 2500, 3200) =Throughput $_1$ – Loss $_1$= $26,489,451

Period 2

Work center 1 has been improved.

New Product mix: (S_1=4200, S_2=2500, S_3=3200)

Table 3.12 C_p values at period 2 (Work center 1 is improved)

	Work center 4	Work center 3	Work center 2	Work center 1
C_{pk}	1.5	0.56	0.45	0.44

Work center 1 is selected again for improvement project.

F_2 (4200, 2500, 3200) = Throughput $_2$ – Loss $_2$= $28,577,551

Period 3

Work center 1 has been improved again.

Product mix: (S_1=4200, S_2=2500, S_3=3200)

Stop improvement projects.

At the end of the period ;

$F_3(4200,2500,3200)$=Throughput $_3$ – Loss $_3$= \$28,626,415

Total $F_{Cp} = F_1+F_2+F_3$

= \$83,693,417

Solutions of the three methods

Total 'F' values and the improvement decisions made by utilizing each method are summarized on the Table 3.13.

Table 3.13 Solutions of the methods

Method	Work center chosen for improvement		Total F value ($)
	Period 1	Period 2	
Throughput-Loss	2	3	86,900,287
Integrated QFD	2	3	86,753,867
Process Capability	1	1	83,693,417

Table 3.13 indicates that the integrated QFD method is better than the process capability method, and deviates slightly (0,168%) from the Throughput-Loss method where Process Capability method's deviation is much higher (3.69%) from the Throughput-Loss method.

In the following section, the same manufacturing setting is handled with different parameters in order to observe the methods' performance at different conditions as well.

3.8 APPLICATION OF METHODS ON DIFFERENT CASES

3.8.1 Forming Different Settings

In the previous sections, one example problem is created and each method is applied on this decision problem which has resulted in that our proposed method of integrated QFD performs well compared with Throughput-Loss method. However, only one case is not adequate for generalizing the solutions and performance of the QFD algorithm. For this purpose, different experiments are conducted by assigning different parameters to the same manufacturing setting of the example problem defined in section 3.4.

First step is the selection of different experimental settings. Selected experiments should be capable of studying the effect that changes on the problem settings have on the system. The criteria of process capability index, loss coefficient and raw material cost which are used by QFD method, are taken as factors for the experiments. Closeness to constraint criteria is excluded since it is an uncontrollable factor that is being computed under the given experimental conditions. Therefore, four process capability factors: C_{pk} (CP4, CP3, CP2, CP1), twelve loss coefficient factors: A_{ik} (A14, A13, A12, A11, A24,…,A32, A31), 12 raw material cost factors: P_{ik} (P14, P13, P12,…, P32, P31), as a result a total of twenty-eight factors are defined. Each factor is assumed to have two levels.

In order to analyze the results under each levels of each factor, 2^{28} (268,435,456) experiments are required to be examined. One way of studying the effects of the product or process parameters via small number of experiments is to use special matrices, called as 'orthogonal arrays' (Ross, 1988:63). In order to generate different cases L_{32} (2^{31}) orthogonal array is used (see Appendix D). Using L_{32} orthogonal array, only 32 experiments would need to be carried out. First 28 columns of orthogonal array is used for our experimentation while other three columns can be used for error estimation.

Level Generation

Levels of the factors are generated by using the values of L_{32} orthogonal array. The value '1' on the orthogonal array is taken as 'Low' level where '2' is taken as 'High level.

Variable Generation

Variables are generated randomly between the boundaries determined by the factor levels.

X: Random variable

Process Capability Factors

For Level 1; $0.33 \leq X \leq 1.00$

Level 2; $1.00 < X \leq 1.66$

Loss Coefficient Factors

For level 1; $10 \leq X \leq 10^2$

For level 2; $101 \leq X \leq 10^3$

Raw material Cost Factors

For level 1; $0 \le X \le 50$

For level 2; $51 \le X \le 250$

Each row of L_{32} is defined as a different case and these random numbers are used as parameter or factor values for the cases. In order to estimate factor effects better, each case is repeated 20 times by using the same orthogonal array of L_{32}. Part of the data generated is given in Appendix E. Each experiment is solved by applying each method to see the solutions and performance of our proposed QFD method on different case settings.

Table 3.14 demonstrates the selling prices and the demands of the products which are taken as constant variables for all cases.

Table 3.14 Selling price and Demand figures

	X(1)	Y(2)	Z(3)
Demand (units)	6400	4800	3200
Selling Price ($)	2500	3000	3500

3.8.2 Analyzing Solutions

As mentioned before, Throughput -Loss method yields the optimal solution for selecting the work center that maximizes the 'F' value. At the end of the third period, total F values obtained by each method are calculated for all experiments. For comparison purposes, deviation of F values generated by each method (integrated QFD and process capability) from that of the Throughput-Loss method is computed for each experiment e (e=1,…,20) at each case c (c=1,…,32). Product mixes, 'F' values and improvement decisions of some experiments obtained by applying each method is documented in Appendix F.

$Dev_{m,e,c}$ = Percent deviation of method m from Throughput-Loss method at experiment e of case c.

$F_{m,e,c}$ = Total 'F' values of three periods obtained by applying the method m, at experiment e of case c

$$\text{Dev}_{m,e,c} = \left(\frac{F_{T\text{-}L,e,c} - F_{m,e,c}}{F_{T\text{-}L,e,c}} \times 100 \right) \%$$

So as to analyze the solutions statistically, average and standard deviation (σ) figures of method deviations with in 20 experiments are computed for each case. Final solution layout for statistical analysis is formed as in Table 3.14.

Av_m,c= $\overline{\text{Dev}_{m,c}}$ = Average deviation of method m, at case c

$$\overline{\text{Dev}_{m,c}} = \frac{\sum_{e=1}^{20} \text{Dev}_{m,e,c}}{20}$$

St_m,c= $\sigma_{\text{Dev } m,c}$= Standard deviation of method m, at case c

$$\text{St\_m,c} = \sigma_{\text{Dev } m,c} = \sqrt{\frac{\sum_{e=1}^{20} (\text{Dev}_{m,e,c} - \overline{\text{Dev}_{m,c}})^2}{20-1}}$$

Table 3.14 Layout for statistical analysis

Cases (c)	Variables (Factors)	Responses of Experiments ($\text{Dev}_{QFD,c}$, $\text{Dev}_{Cp,c}$)	Av_QFD,c	Av_Cp,c	St_QFD,c	St_Cp,c
	1 2 3 4 ……..27 28	1 2 3 4 ………..20				
1	L_{32} Orthogonal Array					
2						
3						
.						
.						
32						

As can be seen from Table G.1 and Table G.2 in Appendix G, the significant cases where Cp method results in large deviations are listed on the Table 3.15. Although cases 3, 4 and 8 are the ones where both of the methods give their max deviations, QFD method deviates in distinguishable fewer amounts. But in cases 2, 18 and 20, the inadequacy of C_p method is observed both in high average deviation and high standard deviations within experiments. In case 18, the process capability indices of work center 1 and 3 are low while the loss coefficients of other work centers (2 and 4) are high. In this case, Cp algorithm chooses the work center that has the smallest capability index and ignores work centers that have high loss coefficients. On the other hand, it is known that bottleneck and the succeeding work center (which are generally work center 3 or 4 in our cases) have effects on throughput maximization. Hence, that the loss coefficients and the bottleneck work center are not taken into account are the major mistakes of process capability (C_p) algorithm. Another different situation is observed in case 2 where all C_p values and loss coefficients are low. Due to the reason of ignoring high raw material costs, C_p method deviates in large amounts in case 2 as well. Additionally, in case 20, again we observe C_p method's deficiency of ignoring loss coefficients and the bottleneck.

However, QFD method combines these measures for making improvement decisions and results in smaller deviations from the optimal.

Table 3.15 Solutions of the Methods

Av_Cp,c (decreasing order)	Case number (c)	Av_QFD,c	St_Cp,c	St_QFD,c
1.583	2	0.576	1.889	0.863
1.406	4	0.854	1.466	0.919
1.351	8	1.110	1.380	0.047
1.173	3	1.001	1.281	1.167
1.111	18	0.438	1.533	0.636
0.991	20	0.308	1.660	0.745

Table G.1 and G.2 in Appendix G point out the fact that average and standard deviation figures of C_p method's deviations (Av_Cp and St_Cp) are larger compared to the respective QFD deviation figures (Av_QFD and St_QFD).

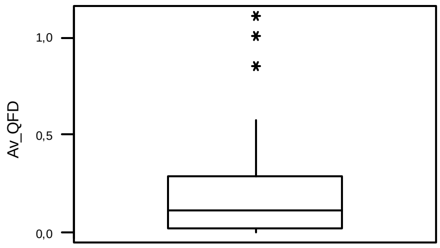


Figure 3.6 Box plot of Av_QFD figures

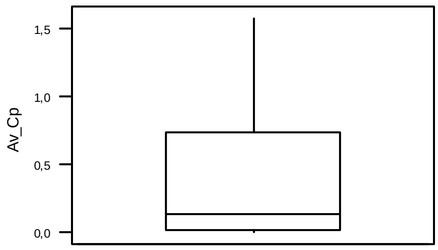


Figure 3.7 Box plot of Av_Cp figures

While comparing Figure 3.6 and Figure 3.7, it can be concluded that Av-QFD deviations are smaller than Av_Cp deviations since up to 75th percentile of the Av_QFD solutions lay between the range 0 and 0.3 while these ranges for Av_Cp is 0 and 0.7 approximately. Excluding outliers, maximum deviation of methods are 0.6 for Av_QFD and 1.6 for Av_Cp approximately.

In order to compare the solutions of the methods, we can perform a paired t test on average deviations of two methods. In such analysis obtained p values represent the smallest level of significance that would lead to rejection of the true null hypothesis. If 95% confidence is selected, p value smaller than 0.05 points out that null hypothesis (H_0) can be rejected (Montgomery 1997:98).

$H_o^a = \mu_{Av\_Cp} - \mu_{Av\_QFD} = 0$

$H_1^a = \mu_{Av\_Cp} - \mu_{Av\_QFD} > 0$

```
Paired T for Av_Cp - Av_QFD

                  N      Mean     StDev   SE Mean
Av_Cp            32    0,3881    0,4938    0,0873
Av_QFD           32    0,2077    0,2924    0,0517
Difference       32    0,1804    0,2893    0,0511

95% lower bound for mean difference: 0,0937
T-Test of mean difference = 0 (vs > 0): T-Value = 3,53  P-Value = 0,001
```

Figure 3.8 Minitab output for paired–t test

Figure 3.8 denotes that there is enough evidence of rejecting the null hypothesis 'H_o^a' with p value of 0.001, respectively. Therefore, the analysis reveals that the average QFD method's deviations (Av_QFD) are significantly less than the deviations of C_p method (Av_Cp).

3.8.3 Applying ANOVA to solutions

As mentioned before, there are 32 different cases with 28 factors that each has 2 levels (low and high). Each factor takes the value '1', if it is at its low level or '2', if it is at its high level. A better way of analyzing our data is to apply 'Analysis of Variance' (ANOVA) procedure.

ANOVA is used to investigate the model and the relationships between a response variable and one or more independent variables by comparing treatment means.

$$Y=\mu+\sum_{i=1}^{28}\tau_i+\varepsilon$$

Y=Response value

μ=overall mean

τ_i=main effect of factor i (i=1(CP4), 2(CP3),…, 28(PZ1))

ε= error term

E(Y)=Expected value of response Y

$$E(Y)=\mu+(\tau_1+\tau_2+\ldots\ldots+\tau_{28})$$

The model is constructed for two response (Y) variables which are 'Average Deviation of method QFD' (Av_QFD) and 'Average Deviation of method C_p' (Av_Cp).
The interaction terms are ignored at this analysis. Confounding between main effects and the interactions can be seen from Alias Table in Appendix H. Since main effects represent almost all possible interaction terms, first order model including only the main effects is formed. On the other hand, our experiment have only three empty columns that may be used for interaction terms. As there are 28 factors in the model, from the combination C (28, 2), 378 different two way interactions exist. Interactions of factors associated to each work center are illustrated as interaction plots in Appendix I.

The following step of the ANOVA procedure is the hypothesis testing for determining the significance of the model and the factors.

H_0=All main effects of the model is zero ($\tau_1 = \tau_2 = \ldots\ldots = \tau_{28} = 0$)
H_1=At least one of the effects listed in H_o is different

$H_o^{'}$=There is no main effect of factor i ($\tau_i = 0$)
$H_1^{'}$= Factor i affects the model ($\tau_i \neq 0$)

Before interpreting the results obtained from ANOVA method, two important assumptions must be satisfied for the model.

1. Error terms (ε) are distributed normally with a mean '0' and a constant variance.
2. All pairs of error terms are uncorrelated.

As can be seen from Appendix J, different graphical tools and statistical tests are applied for checking the validity of these assumptions. First assumption is satisfied by checking the normal probability plots of the residuals. The linear trends of the plots claim that residuals are distributed normally. On the other hand, residual vs. fits graphs indicate that residuals may have equal variances. So as to detect the correlation between residuals, Durbin-Watson test statistic is performed and based on d values of '2.64, 2.70' we can assume uncorrelated errors for all practical purposes. (See figures J.1, J.2, J.3, J.4 and Table J.1in Appendix J)

Table 3.16 Part of Minitab Output of ANOVA Table

Analysis of Variance for Av_QFD

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	28	2,3311	2,3311	0,08325	0,78	**0,700**
Residual Error	3	0,3199	0,3199	0,10662		
Total	31	2,6510				

Analysis of Variance for Av_Cp

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	28	7,3999	7,3999	0,26428	4,95	**0,106**
Residual Error	3	0,1602	0,1602	0,05339		
Total	31	7,5601				

Table 3.16 indicates that, there is large probability (p=0.7) of making a mistake of rejecting the null hypothesis H_0 when ANOVA procedure is applied to the response of Av_QFD. Therefore, H_o should not be rejected. It means that main factors do not affect the model significantly. However, Av_Cp seems to be more affected by the main effects in the model, since the associated p value is '0.106'.

Table 3.17 Part of Minitab output of ANOVA table for Av_Cp

Analysis of Variance for Av_Cp, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
CP 4	1	1,28384	1,28384	1,28384	24,05	**0,016**
CP 3	1	2,43091	2,43091	2,43091	45,53	**0,007**
CP 2	1	0,40233	0,40233	0,40233	7,54	**0,071**
CP 1	1	1,25537	1,25537	1,25537	23,51	**0,017**

According to Table 3.17, related 'p' values of the factors for Av_Cp values: CP4 (p=0.016), CP3 (p=0.007), CP2 (p=0.071), CP1 (p=0.017) point out that all C_p factors are significantly affecting the response of Av_Cp. It is an expected result ,since C_p values are the only criteria used in making improvement decisions based on the C_p method. Complete ANOVA tables, response tables and main effects plots can be seen from Appendices K, L and M.

Moreover, it is concluded that the average deviations of the QFD method (Av_QFD) can not be explained to be resulted from any main effect. This situation is possibly caused by the model's error term which includes various other factors; such as randomness at the factor levels and that the QFD method uses different product mixes than the Throughput-Loss method.

Figure 3.9 demonstrates the relations between the factors and the QFD method's decisions. As can be seen from Figure 3.9, product mix is an important component of QFD matrix in making the improvement decision. Product mix information is utilized in forming the 'Share in Production' column which is used for weighting the relationship values assigned to the work centers. That's why, in some experiments, although QFD gives the same improvement decisions with optimal method, it deviates from the optimal by its total F value due to the different product mixes.

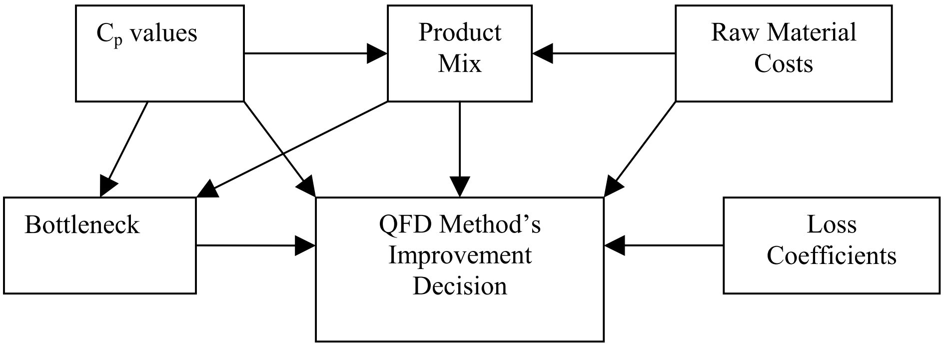


Figure 3.9   Factors that affect the QFD method's decision for improvement.

3.8.4 Applying ANCOVA

The analysis of covariance (ANCOVA) is another technique that is generally useful for improving the precision of an experiment in the cases where any factor can not be controlled by the experimenter but can be observed along with the response. This factor is called as covariate factor. ANCOVA involves adjusting the observed response for the effect of the covariance factor and procedure is a combination of ANOVA and regression analysis. (Montgomery 1997:604,605)

$$Y = \mu + \tau_1 + \tau_2 + \ldots\ldots + \beta\,(X_c - \overline{X_c}) + \varepsilon$$

X_c = Value of the covariate variable

$\overline{X_c}$ = Mean of the X_c values

β = Linear regression coefficient indicating the dependency of the response Y with X_c

In order to apply ANCOVA procedure, the following assumptions should be satisfied.

1) The true relationship between the covariate variable X_c and the response Y is linear.
2) The correlations between all factors are near to 0 and that the covariate variable X_c is not affected by the other factors.
3) Error terms (ε) must be distributed normally with a mean '0' and a constant variance.

In order to analyze the response Av_QFD, ANCOVA procedure is applied by taking the 'product mix' as a covariate factor for the response.
Product mix information is taken into analysis after the following computations;

$Pr_{m,c,e,p}$ = Product mix obtained by using model m, at case c, experiment e and period p.

$Z_{c,e,p}$ = Value of '0' or '1' that indicates whether the product mix obtained with both methods are same or different for the case c, experiment e and period p.

If $Pr_{QFD,c,e,p} = Pr_{T\text{-}L,c,e,p}$ then $Z_{c,e,p}$ is 0, otherwise; 1

$X_{pr,c}$ = Total difference of the product mixes of method QFD from optimal Throughput-Loss method, at case c.

$$X_{pr,c} = \sum_{e=1}^{20}\sum_{p=1}^{3} Z_{c,e,p}$$

According to the first assumption of ANCOVA the relationship between X_{pr} and Y must be linear. However as can be seen from Figure 3.10 there exists a curvilinear relationship between X_{pr} and Y. Therefore, X_{pr}^2 is taken as a covariate factor (See Figure 3.11).

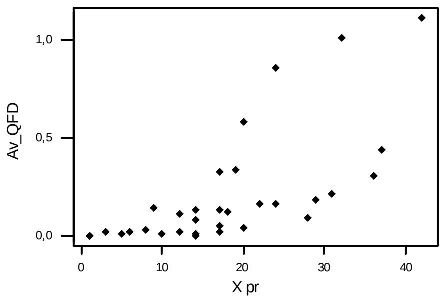


Figure 3.10 X_{pr} versus Av_QFD

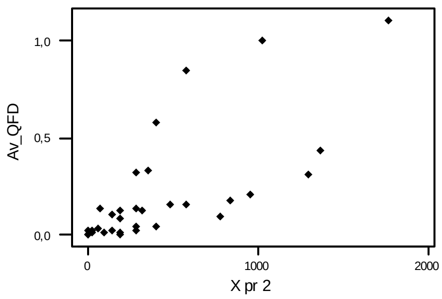


Figure 3.11 X_{pr}^2 versus Av_QFD

On the other hand, according to the second assumption, all factors must be uncorrelated. However, X_{pr}^2 is highly correlated with some factors which are CP1, PY,4 and PY,2 that can be seen from the correlation matrix of Table N.1 in Appendix N. Therefore, these four factors could not exist in the same model. One procedure to deal with these correlated factors is to define principal components which are particular linear combinations of the factors. Principal components depend solely on the correlation matrix of these factors. Figure 3.12 represents the Minitab output of the obtained principal components of the factors CP1, PY4, PY2 and X_{pr}^2.

```
Eigen analysis of the Correlation Matrix

Eigenvalue    1,6215     1,0000     1,0000     0,3785
Proportion     0,405      0,250      0,250      0,095
Cumulative     0,405      0,655      0,905      1,000

Variable         PC1        PC2        PC3        PC4
CP1           -0,474      0,598     -0,439     -0,474
PY4           -0,365     -0,801     -0,304     -0,365
PY2           -0,377      0,022      0,846     -0,377
Xpr2           0,707     -0,000      0,000     -0,707
```

Figure 3.12 Minitab output of principal component analysis

As can be seen from Figure 3.12, principal components are obtained as follows;

PC1= -0.474 CP1 -0.365 PY4 - 0.377PY2 +0.707 X_{pr}^2

PC2= 0.598 CP1 -0.801 PY4 +0.022PY2 -0.000 X_{pr}^2

PC3= -0.439 CP1 -0.304 PY4 +0.846PY2 +0.000 X_{pr}^2

PC4= -0.474 CP1 -0.365 PY4 - 0.377PY2 - 0.707 X_{pr}^2

First principal component (PC1), which explains the largest proportion (0,405) of the total variance, includes all factors with coefficients different than zero and the effect of X_{pr}^2 to the component is significant due to high coefficient value. Therefore, PC1 is taken as a covariate factor for ANCOVA analysis.

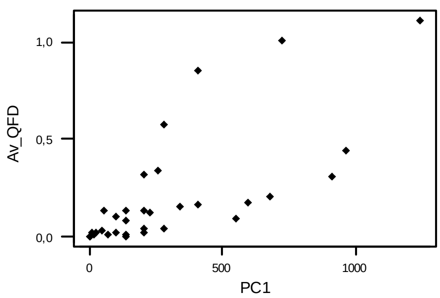


Figure 3.13 PC1 versus Av_QFD

Figure 3.13 demonstrates the linearity between PC1 and Av_QFD, and Table N.2 in Appendix N implies that there are no significant correlations between factors. Therefore, first and second assumptions of ANCOVA are satisfied. However, Figure N.2 in Appendix N points out the heteroscedasticity (unequal variances) between error terms. In literature, in order to remedy such situations, various variance stabilizing transformations have been developed. According to the structure of the residuals of Figure N.2, square root transformation is applied to the response Av_QFD and Figure N.4 is obtained. Hence, all ANCOVA assumptions are satisfied, the final ANCOVA model is constructed as below;

Y= Av_QFD

$$Y^{*}=\sqrt{Y}$$

$$Y^{*}= \mu + \tau_1 + \tau_2 + \ldots\ldots + \beta\,(PC1 - \overline{PC1}) + \varepsilon$$

Table 3.18 Part of Minitab Output of ANCOVA Table

Analysis of Variance for Y*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
PC1	1	0,0138588	0,0059948	0,0059948	15,25	**0,011**
CP4	1	0,0020070	0,0019010	0,0019010	4,84	**0,079**
CP3	1	0,0034739	0,0028907	0,0028907	7,35	**0,042**

According to Table 3.18, ‘p’ values of the factors; CP4 (p=0.079), CP3 (p=0.042) and the covariate PC1(p=0.011) point out that the probability of making an error of rejecting the hypothesis $H_o^{'}$ is very small under 90% confidence assumption and can be rejected. Hence, these factors are significant on the response of Av_QFD. The covariate PC1 is constructed by the factors of CP1, PY,4, PY,2 and X_{pr}^{2} .Therefore, significance of PC1 implies a combined effect of these factors on Av_QFD.

Although it is not possible to separate the effects of these highly correlated factors on the response, product mix seems to have more effect on Av_QFD since it has the highest coefficient value on PC1.

One discussion that Atwater and Chackravorty (1995) have mentioned in their analysis is that the improvement of the last work centers according to the processing sequence seems to have more effect on throughput maximization. In our analysis, same situation may also hold. Since QFD method does not take processing sequence of the work centers into analysis, C_p values of the last work centers (Cp4 and Cp3) may lead to deviations to the QFD method and become significant factors for Av_QFD.

3.9 DISCUSSION

As mentioned earlier, Atwater and Chakravorty (1995) have proposed a quality improvement method for decision making in manufacturing operations by utilizing TOC. They have studied a simple manufacturing system having four work centers and three products as an example case for developing better approaches to quality planning and decision making for process improvements. Köksal and Karşılıklı (2002) have incorporated the loss function concept into the problem and developed an LP formulation. In order to remove the disadvantages of LP formulation, our proposed method of integrated QFD is developed .For the sake of simplicity, this methodology can also be improved by completely or partially relaxing some assumptions as explained below.

According to TOC perspective, all cost terms other than raw material cost (e.g. direct labor, factory overhead) are treated as operating expenses for the period. No allocation system is used to associate these expenses to individual products. This threatens the survival of the firm if throughput for a period does not cover its expenses. However, this approach helps in cutting inventories which is built up to meet operating expenses and overcomes the need for allocating overhead costs which cannot be traced to specific products directly. These two advantages easily invalidate the approach to minimize costs in work environment by building inventories (to decrease the share of fixed cost for each product). Secondly the way inventories are treated is changed, so building up inventories without increasing throughput is not a good alternative. However, by this approach maximization of Throughput is encouraged. (Atwater and Chackravorty (1995))

In our analysis labor and factory costs are assumed to be negligible while compared with raw material costs. However, in some exceptional production environments such as craftsmanship, labor costs may be high or comparable with raw material costs. Then 'raw material cost' criteria can be replaced with 'total cost' criteria for the integrated QFD method.

As mentioned earlier, TOC philosophy defines anything that limits the performance of a system relative to its goal as a 'constraint'. Once the constraint is identified, every effort must be made to ensure that it is fully utilized the system's overall performance. Atwater and Chackravorty (1995) have denoted the impact of the constraint (which is bottleneck and its next operation) on their manufacturing setting. Therefore, proposed QFD method includes bottleneck criteria in decision making for improvement. However, problems may appear when the situation is more complex than the example of Atwater and Chakravorty (1995). In any manufacturing setting, there may exist multiple bottlenecks. One solution could be to decide on the highest priority bottleneck and give more importance on that work center.

According to Crosby (1981), who defines 'Quality' simply as conformance and known with his advocacy of zero defects management advocates that 'Quality is free'. Since Crosby takes quality as conformance to requirements instead of goodness or elegance, quality must be satisfied and nothing can be defined as cost when reaching desired requirements. Partly by utilizing from Crosby's philosophy, improvement budget is assumed to be infinite and costs for improvements are not taken in to decision making process on improvement .On the other hand, in any other manufacturing setting improvement costs of work centers may not be comparable, then the decision maker should consider the improvement cost as well in the selection of the improvement projects.

As in the study of Köksal and Karşılıklı (2002), another assumption we have, is normal distribution of the characteristics of the products having means at their target values. Additionally, processes are assumed to be stable (which means the variation caused by the characteristic is natural and no special causes affect the output of the processes). In the cases where stability of the process is not achieved, statistical process control tools should be used for monitoring the aim and variability of the process. Besides, special efforts should be spent in order to eliminate variation and maintain consistency in the process instead of decreasing its scrap rate by improvement. Process Capability indices; such as C_p measure is only meaningful at stable and controllable processes. Although there are several methods for estimating process potential for an unstable process, generally they do not represent the actual performance of the processes.

As mentioned before, since characteristics of the products are assumed to be independent from each other and processed at different work centers, a single loss function and process capability index for a single product are defined for each work center. However, most of the time a product has more than one quality related characteristic which may be quantitative or attribute variables. Therefore, composite C_p indices, which are developed for measuring the capabilities of the processes that contain more than one different characteristic at a time, may be used as in the study of Kotz and Lovelace (1998). Besides, DPMO (Defects per million opportunities), which is the main capability measure for six sigma methodology, can easily be applied for the complex and process related production environments and for the attribute type characteristics. Furthermore, multivariate loss functions are developed to describe the quality of the product by measuring the joint effects of its related characteristics. (Kapur and Cho,1996)

On the other hand, building a loss function for attribute type of data may lead to challenges in some cases. Defining the attribute quality characteristic as the number of defects per product may be useful to transform it to a quantitative variable. However, an alternative approach of handling this situation can be using the ‘severity of failure’ measure of FMEA instead of using ‘loss coefficients’ as criteria. One other discussion point of loss coefficients in the very long term analysis is the economic perspective; that the loss function is restricted to the shipment time of a product and ignores the degradation effect of usage over time on quality performance. Therefore, Teran et al (1996) have introduced an integrated approach of determining present worth of expected quality loss.

In our analysis detectability and inspection are assumed to be 100% that means it is not possible to ship a defective product to a customer. Again remembering, due to the Crosby’s philosophy of zero defects, the cost of detectability and inspection is not considered as important as cost of losing a customer. However, in general, since 100 % inspection can not be applied for great production scales, some sampling techniques are developed. On the other hand, 100% detectability is not the general case. However, it is the desired percentage and the companies improve their inspection operations for this purpose. There also exist some example cases such as a military company that produces air defense systems, guns or missiles. Due to the nature of products produced by the company, no customer feedback can be available to identify the detectability ratio unless there is a war. However, in such environments high number of inspections yield to high detectability ratio and generally it is assumed to be approximately 100% within the company. In cases where detectability is low, loss coefficients should take more important role in decision making since the farther the product from its specification limits, the larger the probability of shipping nonconforming product to the customer which will result in serious loss figures. One alternative way of coping with this problem in our proposed method might be adding another criterion as detectability to the analysis.

One other assumption is that the rework or replacement are not performed for the defective parts as in the studies of Atwater and Chackravorty (1995) and Köksal and Karşılıklı(2002). It means that if the parts can not pass screening, then they are scrapped. Actually, it is not common in practice. Therefore, small modifications can be made to the criteria of our proposed algorithm. One of the possible adjustments may be to define yield ratio of each work center as the ratio of the summation of the number of parts that are reworked and between spec products, to the whole amount of parts produced at this work center. Therefore, rework ability of the work centers could be reflected to process capability indexes. If rework costs of work centers differ from each other in distinguishable amounts, then they should also be taken into consideration. In fact, it is not easy to estimate reworking costs in cases where high dependencies exist between operations. A good product may be scrapped at the last operation, although it is between specs at all previous operations. For example in production operations of a coated plate which is generally used in automotive industry, if a scratch is detected on the part's surface, then it is reworked by sanding the surface. However, the rework process may reduce the surface thickness and as a result, the part may be sent to rework again or scrapped, although it has passed thickness control before. Since, rework costs are generally hard to compute, it may be assumed that the rework costs of work centers are comparable.

Therefore, the application of our proposed method under different reworking and detectability conditions would require more modifications to the algorithm which may form basis for future analysis.

One conclusion is that in Throughput-Loss method, lower selling prices makes the model more dependent on the loss coefficients and sometimes result in zero product mixes which means no production will be held in the considered period. In order not to allow this situation, if possible, improvement of more than one work center should be performed. On the other hand, QFD algorithm takes product mix amounts from typical production planning model which ignores the loss concept. Hence, QFD approach could not notice the inadequacy of improving only one work centre due to different product mixes and might lead to negative F values at the end of the period. Some hint that could be given to the decision maker, who utilizes the QFD method, is to compare the selling prices and the loss figures of the products. If selling prices of the products are relatively lower than the total loss associated to the products that are at specification limits, then he/she should get an opinion of improving one work center may not be enough. In our case setting, we met the condition that if selling prices of the products are smaller than twenty-five percent of the total loss associated to the products when their major characteristics are at their specification limits, then more than one work center improvement is required. (If $SP_i \leq 0.25*B_i$, see Section 3.5)

As mentioned earlier , although the same improvement decisions are made, using different product mixes is one of the reasons that cause deviations for integrated QFD methodology from optimal Throughput-Loss method. However, in any production environment working with the make to order strategy in accordance with the demanded firm, product mix decisions would be constant and same for all methods which will yield to better solutions of our proposed methodology.

CHAPTER 4

CONCLUSION

Continuous improvement is key to success in the global marketplace. Companies that are just maintaining the status quo in such key areas as quality, new product development, the adaptation of new technologies and process performance are like a runner who is standing still in a race. An effective strategy that helps a company to survive and compete in the modern market place is to improve continually. Therefore, Quality Improvement efforts have shown an increasing trend in the last twenty years by adapting to Total Quality culture which forms its basis on continuous improvement.

In this study, we have developed an alternative tool for decision making that integrates different methods under a QFD matrix while compensating poor aspects of these methods.

Atwater and Chackravorty (1995) have proposed a method of decision making for process improvement by utilizing TOC. By taking Atwater and Chackravorty's case (1995) as a main starting point, Köksal and Karşılıklı (2002) have generalized the decision making process by utilizing a better approach of LP formulation which is applied in our analysis in detecting optimal decisions at Throughput-Loss Algorithm. Although the algorithm has specially designed to cover a variety of concerns under one roof and yields optimal results, it has some disadvantages, especially in the application. As explained previously, there is no simple rule for solving a model other than the obvious cases. Furthermore, finding model parameters such as those of loss functions is not an easy task to do. On the other hand, it requires LP background to gather the parameters and solve the model.
In order to remove the disadvantages of Throughput-Loss method, we have aimed to develop an easier tool utilizing a QFD matrix that could be used in analyzing the relations

between various different products of the company and the manufacturing operations and helps to focus on the most important operations for customer satisfaction and profitability.

In traditional approach, generally quality managers choose to use SPC and base their improvement decisions on C_p values where some managers choose using different approaches such as TOC, FMEA or Loss functions. We propose an integrated approach where major indicators of these various approaches are evaluated together to determine the work center to improve first.

Furthermore, analysis of the solutions of the numerical example cases in Section 3.8.2 have implied that QFD method's max deviation is 3.53% while traditional C_p method deviates 7.6% from optimal T-L Method. However, C_p method's deviations from optimal are expected to reach to higher values when the loss coefficients of the operations are higher than the cases we have generated. Although integrated QFD Method is not as accurate as the T-L Method, it is easier to understand and apply for quality managers. Besides, method uses typical production planning approach to product mix determination while T-L method includes loss terms and solves a more complex product mix problem. Furthermore, the QFD Method yields better results than simply using the C_p index in choosing the work center to improve.

At the end of our analysis we have concluded that the solutions are case dependent and different responses can be met at different case settings as explained with details in the discussion section.

In practical area, our proposed method of integrated QFD has been utilized in an electronics company which is a leading firm in printed circuit boards (PCB) design and manufacturing. While initiating quality improvement design for the three new lines of PCBs (namely Power, Triac and Logic), integrated QFD method has been applied to determine highest prioritized critical work centers on which improvement studies will be developed. Assembly operations of the PCB's include more attribute type quality characteristics. Therefore, instead of using C_p index, DPMO measure has been used to measure the capability of the processes. Besides, loss function has been modified by assuming the quality characteristics of the processes as the number of defects per product (which is the smaller the better case with target value zero).Since the detectability of the work centers differ from each other, detectability ratio of the work centers have been taken into analysis by forming a probability tree of detectability and the replacement or scrap costs are computed according to these probabilities. On the other hand, the failures of the PCB's are generally related to each other. Therefore, late detection has been penalized by weighting the work centers repair or replacement costs according to their processing sequence.

Moreover, our method has been utilized in selecting the process for FMEA applications in an air defense company the products of which are missiles, guns and air defense systems. As mentioned before, unless there is a war, the failures of the products could not be detected. The management assumes that all failures are detected in the system. However, late detection has been penalized by adding a term of 'cost of late detection'. Because of high variety of failures and their dependency, rework costs are not easy to estimate and have been ignored. 'Severity' term of FMEA has been used instead of loss functions since the quality characteristics are attribute variables.

In both applications, the project teams have easily adapted the QFD methodology and made some modifications according to the conditions of the considered systems. As a result, they have evaluated our proposed method as a reasonable tool that considers the critical criteria in prioritization and helps reach solution decisions more quickly.

To sum up, the analysis is thought to be first basic application of quality management that combines various tools of SPC, Loss, FMEA and TOC measures together. However, more research on the topic may yield even better integrated tools for more general cases than the ones in the study.

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APPENDIX A

VARIANCE CALCULATION STEPS OF SCREENED ITEMS

$$f_{ik}(x) = \frac{1}{\sqrt{2\pi}\sigma_{ik}} e^{(-1/2)((x-\mu_{ik})/\sigma_{ik}{}^2))} \qquad -\infty < x < \infty$$

$$f_{accepted\_ik}(x) = f_{aik}(x) = \frac{f_{ik}(x)}{Y_k} \qquad LSL_{ik} \le x \le USL_{ik}$$

$$Y_k = \int_{LSL_{ik}}^{USL_{ik}} f_{ik}(x)dx$$

$$\sigma_{aik}{}^2 = \int_{LSL_{ik}}^{USL_{ik}} (x-\mu_{ik})^2 f_{aik}(x)dx$$

$$\sigma_{aik}{}^2 = \frac{1}{Y_k}\int_{LSL_{ik}}^{USL_{ik}} (x-\mu_{ik})^2 f_{ik}(x)dx$$

$$\sigma_{aik}{}^2 = \frac{1}{Y_k}\int_{LSL_{ik}}^{USL_{ik}} (x-\mu_{ik})^2 \frac{1}{\sqrt{2\pi}\sigma_{ik}} e^{(-1/2)((x-\mu_{ik})/\sigma_{ik}{}^2))}dx$$

$$u = \frac{x-\mu_{ik}}{\sqrt{2}\sigma_{ik}} \qquad (x-\mu_{ik})^2 = 2\sigma_{ik}{}^2u^2$$

$$du = \frac{1}{\sqrt{2}\sigma_{ik}}dx \qquad dx = \sqrt{2}\sigma_{ik}du$$

$$\sigma^2{}_{aik} = \frac{1}{Y_k\sqrt{2\pi}\sigma_{ik}}\int_{LSL_{ik}}^{USL_{ik}} 2\sigma_{ik}{}^2u^2e^{-u^2}\sqrt{2}\sigma_{ik}du$$

$$\sigma^2{}_{aik} = \frac{2\sigma_{ik}{}^2}{Y_k\sqrt{\pi}}\int_{LSL_{ik}}^{USL_{ik}} u^2 e^{-u^2} du$$

$$\ell = u \qquad\qquad d\nu = ue^{-u^2} du$$

$$d\ell = du \qquad\qquad \nu = -\frac{e^{-u^2}}{2}$$

$$\sigma^2{}_{aik} = \ell\nu - \int \nu d\ell$$

$$\sigma^2{}_{aik} = \frac{2\sigma_{ik}{}^2}{Y_k\sqrt{\pi}}\left[\left.\frac{ue^{-u^2}}{-2}\right| + \int \frac{e^{-u^2}}{2} du\right]$$

$$\sigma^2{}_{aik} = \frac{2\sigma_{ik}{}^2}{Y_k\sqrt{\pi}}\left[\left.\frac{x-\mu_{ik}}{-2\sqrt{2}\sigma_{ik}} e^{-\frac{(x-\mu_{ik})^2}{2\sigma_{ik}{}^2}}\right| + \frac{1}{2}\int_{LSL_{ik}}^{USL_{ik}} \frac{1}{\sqrt{2}\sigma_{ik}} e^{-\frac{(x-\mu_{ik})^2}{2\sigma_{ik}{}^2}} dx\right]$$

$$\sigma^2{}_{aik} = -\frac{\sigma_{ik}}{Y_k\sqrt{2\pi}}(x-\mu_{ik})e^{-\frac{(x-\mu_{ik})^2}{2\sigma_{ik}{}^2}}\Bigg| + \frac{\sigma_{ik}{}^2}{Y_k\sqrt{\pi}}\sqrt{\pi}\underbrace{\int_{LSL_{ik}}^{USL_{ik}} \frac{1}{\sqrt{2\pi}\sigma_{ik}} e^{-\frac{(x-\mu_{ik})^2}{2\sigma_{ik}{}^2}} dx}_{Y_k}$$

$$\sigma^2{}_{aik} = -\frac{\sigma_{ik}}{Y_k\sqrt{2\pi}}\left[(USL_{ik}-\mu_{ik})e^{-\frac{(USL_{ik}-\mu_{ik})^2}{2\sigma_{ik}{}^2}} - (LSL_{ik}-\mu_{ik})e^{-\frac{(LSL_{ik}-\mu_{ik})^2}{2\sigma_{ik}{}^2}}\right] + \sigma_{ik}{}^2$$

$$USL_{ik} - \mu_{ik} = H_{ik}$$
$$LSL_{ik} - \mu_{ik} = -H_{ik}$$

$$\sigma^2{}_{aik} = -\frac{\sigma_{ik}}{Y_k\sqrt{2\pi}}\left[2H_{ik}e^{-\frac{H_{ik}{}^2}{2\sigma_{ik}{}^2}}\right] + \sigma_{ik}{}^2$$

$$\sigma_{aik}{}^2 = \sigma_{ik}{}^2\left(1 - \frac{2H_{ik}e^{(-1/2)(H_{ik}/\sigma_{ik})^2}}{Y_k\sigma_{ik}\sqrt{2\pi}}\right)$$

APPENDIX B

APPLICATION OF THROUGHPUT-LOSS ALGORITHM ON EXAMPLE PROBLEM

By gathering the values of C_{pk} (Table 3.2) and H_{ik} (Table 3.5), following computations are done to obtain model parameters.

$$C_{pk} = \frac{H_{ik}}{3\sigma_{ik}} \quad , \quad \sigma^2{}_{ik} = \left(\frac{H_{ik}}{3 \times C_{pk}} \right)^2$$

Table B.1 Obtained Variances

$\sigma^2{}_{ik}$	Work center 4	Work center 3	Work center2	Work center1
Product X	0,12025	0,27221	1,00902	0,58139
Product Y	0,10421	0,31304	0,90812	0,69767
Product Z	0,08952	0,32665	0,77358	0,63953

Yield rates are computed by the following equation;

$$(1-\frac{1-Y_k}{2}) = (\Phi\left(\frac{H_{ik}}{\sigma_{ik}}\right))$$ where Φ is the standard normal distribution function.

Table B.2 Yield rates before and after improvement

	Work center 4	Work center 3	Work center 2	Work center 1
Yield rates(Y_k)	0.9999932	0.90704	0.822984	0.63188
Scrap rates($1-Y_k$)	0,0000068	0,092957	0,17702	0,368120
Scrap rates after imp. $(1-Y_k)/2$	0,0000034	0,046478	0,08851	0,184060
Yield rate after imp. $Y_k{}' = 1-(1-Y_k)/2$	0.9999966	0,9535214	0.911492	0.81594

Improved variances are calculated by the formulation given below

$$\frac{(H_{ik})}{\sigma'_{ik}} = \Phi^{-1}\left(1 - \frac{1 - Y_k'}{2}\right); \quad \Phi^{-1} \text{ is the inverse of standard normal distribution.}$$

Table B.3 Improved variances

σ'^{2}_{ik}	Work center 4	Work center 3	Work center2	Work center1
Product X	0,11411	0,19381	0,63383	0,26689
Product Y	0,0989	0,22288	0,57045	0,32026
Product Z	0,08495	0,23257	0,48594	0,29357

As detection is assumed to be 100%, then the variance of accepted items is calculated.

$$\sigma_{aik}^{2} = \sigma_{ik}^{2}\left(1 - \frac{2H_{ik}e^{(-1/2)(H_{ik}/\sigma_{ik})^2}}{Y_k\sigma_{ik}\sqrt{2\pi}}\right)$$

Table B.4 Variances of the accepted items

σ_{aik}^{2}	Work center 4	Workcenter 3	Workcenter2	Workcenter1
Product X	0,1202291	0,1741153	0,4781	0,14070793
Product Y	0,1041985	0,2002325	0,43029	0,16884951
Product Z	0,0895038	0,2089385	0,36654	0,15477872

$$\sigma'^{2}_{aik} = \sigma'^{2}_{ik}\left(1 - \frac{2H_{ik}e^{(-1/2)(H_{ik}/\sigma'_{ik})^2}}{Y'_k\sigma'_{ik}\sqrt{2\pi}}\right)$$

Table B.5 Improved Variances of the acceptable items

σ'^{2}_{aik}	Work center 4	Work center 3	Work center2	Work center1
Product X	0,1141027	0,1493193	0,4123	0,12341663
Product Y	0,098889	0,1717177	0,37107	0,14809995
Product Z	0,0849431	0,1791839	0,31609	0,13575829

Remark: If additional improvement is required for already improved work center, similar calculations of improved variances and yield rates are repeated by assuming that the scrap rate (1-Y_k') is halved.

Table B.6 Process Capability indices before and after improvement

	Work center 4	Work center 3	Work center 2	Work center 1
C_{pk}	1.5	0.56	0.45	0.3
C_{pk} after imp.	1.539	0.663	0.567	0.442

APPENDIX C

APPLICATION OF INTEGRATED QFD ALGORITHM ON EXAMPLE PROBLEM

Level Determination

Period 1

Process Capability indices

1. Range=R=max{C_{pk}}-min {C_{pk}}
2. R=max{1.5,0.56,0.45, 0.3}-min{1.5,0.56,0.45, 0.3}

   R=1.5-0.3=1.2

C_{p4} ; C_{p4} =0.3 ≤ min {C_{pk}}+R*0.15= 0.3+1.2*0.15=0.48 ; then Low

C_{p2} ; C_{p2} =0.45 ≤ min {C_{pk}}+R*0.15= 0.3+1.2*0.15=0.48 ; then Low

C_{p3} ; min{C_{pk}}+R*0.15 =0.48<C_{p3} =0.56≤ min {C_{pk}}+R*0.75=1.2 then medium

Cp_1 ; min {C_{pk}}+R*0.75 =1.2<C_{p1} =1.5≤ max{C_{pk}}=1.5 ; then high

Loss coefficients

1. The overall and specific average values associated to each product are calculated.

Product Average=$PA_i = \frac{1}{4}\sum_{k=1}^{4} A_{ik}$

Overall Average=OA=$\frac{1}{12}\sum_{i=1}^{3}\sum_{k=1}^{4} A_{ik}$ =1532,17

Table C.1 Loss coefficients

A_{ik}	Work center 4	Work center 3	Work center 2	Work center 1	PA_i
Product X	96	3500	1800	50	1361,5
Product Y	1650	2200	650	19	1129,75
Product Z	50	5600	2700	71	2105,25

By applying the procedure;

If [($A_{ik} \geq PA_i$) and ($A_{ik} \geq OA$)] then level is 'High', otherwise; 'Low'

Table C.2 Leveled loss coefficients

A_{ik}	Work center 4	Work center 3	Work center 2	Work center 1
Product X	L	H	H	L
Product Y	H	H	L	L
Product Z	L	H	H	L

Closeness to Bottleneck

Applying the formulas below, Table C.3 is formed.

$U_{ik} = U_{i,k+1} / Y_k$, k=1,..,4

$U_{i5}=S_i$

CA_k=76800 min. k=1,..,4

$$C_k = \sum_{i=1}^{m} t_{ik} * U_{ik}$$

If ($CA_k - C_k$=76800-Ck ≤ CA_k*0.01=76800*0.01=768), then the work center k is bottleneck and labeled as 'At' where the following work center k+1 is labeled as 'Next' and the others are 'Far'

Table C.3 'Closeness to bottleneck' levels for Period 1

	Workcenter 4		Workcenter 3		Workcenter 2		Workcenter 1	
S_i	t_{i4}	U_{i4}	t_{i3}	U_{i3}	t_{i2}	U_{i2}	t_{i1}	U_{i1}
S_1=3356	5	3357	4	3700	4	4496	4	7115
S_2=2500	5	2501	6	2757	5	3349	4	5300
S_3=3200	5	3201	7	3528	4	4287	4	6784
C_k	45295		56038		51877		76796	
CA_k-C_k	31505		20762		24923		4	
Levels	Far(F)		Far(F)		Next		At	

Raw material costs

1. Cumulative P_{ik} table (CP_{ik}) is formed.

Table C.4 Raw material costs

P_{ik}	Work center 4	Work center 3	Work center 2	Work center 1
Product X	5	15	45	10
Product Y	10	25	19	2
Product Z	10	35	15	8

Table C.5 Cumulative raw material costs

CP_{ik}	Work center 4	Work center 3	Work center 2	Work center 1
Product X	75	70	55	10
Product Y	56	46	21	2
Product Z	68	58	23	8

The overall and average values associated to each product are calculated.

$$\text{Product Average}=PA_i=\frac{1}{4}\sum_{k=1}^{4}CP_{ik}$$

$$\text{Overall Average}=OA=\frac{1}{12}\sum_{i=1}^{3}\sum_{k=1}^{4}CP_{ik}=41$$

Table C.6 Cumulative raw material costs with product averages

CP_{ik}	Work center 4	Work center 3	Work center 2	Work center 1	PA_i
Product X	75	70	55	10	52,5
Product Y	56	46	21	2	31,25
Product Z	68	58	23	8	39,25

According to the algorithm;

If [($CP_{ik} \geq PA_i$) and ($CP_{ik} \geq OA$)] then level is 'High'; otherwise 'Low'

Table C.7 Leveled raw material costs

CP_{ik}	Work center 4	Work center 3	Work center 2	Work center 1
Product X	H	H	H	L
Product Y	H	H	L	L
Product Z	H	H	L	L

Period 2

Process Capability indices

3. Range=R=max{C_{pk}}-min {C_{pk}}
4. R=max{1.5,0.56,0.567, 0.3}-min{1.5,0.56,0.45, 0.3}
   R=1.5-0.3=1.2

C_{p4}; C_{p4} =0.3 ≤ min {C_{pk}}+R*0.15= 0.3+1.2*0.15=0.48 ; then Low

C_{p3}; min{C_{pk}}+R*0.15 =0.48< Cp_3=0.56 ≤ min {C_{pk}}+R*0.75=1.2 then medium

C_{p2}; min{C_{pk}}+R*0.15 =0.48< Cp_2=0.567 ≤ min {C_{pk}}+R*0.75=1.2 then medium

C_{p1}; min {C_{pk}}+R*0.75 =1.2<Cp_1 =1.5≤ max{C_{pk}}=1.5 ; then high

Loss coefficients and Raw material costs

The levels of loss coefficients and raw material costs are same as previous period (Table C.2 and Table C.7) since these parameters are assumed to be constant during periods.

Closeness to Bottleneck

Table C.8 is constructed in the same manner as in Table C.3

Table C.8 'Closeness to Bottleneck' levels for period 2

	Workcenter 4		Workcenter 3		Workcenter 2		Workcenter 1	
S_i	t_{i4}	U_{i4}	t_{i3}	U_{i3}	t_{i2}	U_{i2}	t_{i1}	U_{i1}
S_1=4200	5	4201	4	4631	4	5081	4	8039
S_2=2500	5	2501	6	2757	5	3024	4	4785
S_3=3200	5	3201	7	3528	4	3871	4	6125
C_k	49515		59762		50928		75796	
CA_k-C_k	27285		17038		25872		1004	
Levels	Far(F)		Far(F)		Far(F)		Far(F)	

APPENDIX D

ORTHOGONAL ARRAY of L_{32}

Columns(Factors)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Cp_4	Cp_3	Cp_2	Cp_1	A_{14}	A_{13}	A_{12}	A_{11}	A_{24}	A_{23}	A_{22}	A_{21}	A_{34}	A_{33}	A_{32}	A_{31}	P_{14}	P_{13}	P_{12}	P_{11}	P_{24}	P_{23}	P_{22}	P_{21}	P_{34}	P_{33}	P_{32}	P_{31}			
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1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1
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1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1
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2	2	1	2	1	1	2	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1	1	2	2	1	2	1	1	2

APPENDIX E

DATA FOR THE SELECTED CASES

Twenty different experiment settings are obtained. Generated data for the experiments 1, 2 and 20 are demonstrated on the following tables to form an example for the parameter generation.

	Data sheet for Experiment 1																											
Cases	**Cp 4**	**Cp 3**	**Cp 2**	**Cp 1**	**A X,4**	**A X,3**	**A X,2**	**A X,1**	**A Y,4**	**A Y,3**	**A Y,2**	**A Y,1**	**A Z,4**	**A Z,3**	**A Z,2**	**A Z,1**	**P X,4**	**P X,3**	**P X,2**	**P X,1**	**P Y,4**	**P Y,3**	**P Y,2**	**P Y,1**	**P Z,4**	**P Z,3**	**P Z,2**	**P Z,1**
1	0.43	0.55	0.53	0.89	43	81	40	43	49	61	41	22	78	75	49	94	41	2	42	6	43	34	21	33	48	11	18	30
2	0.52	0.53	0.92	0.38	72	38	6	41	100	94	9	71	50	85	10	462	58	175	86	212	112	190	85	183	158	151	140	177
3	0.58	0.77	0.45	0.39	71	59	27	860	285	621	557	273	647	482	259	67	29	26	41	13	24	46	30	180	56	69	216	116
4	0.63	0.52	0.46	0.84	83	92	12	953	793	689	821	553	573	632	863	265	99	151	161	72	141	94	163	45	28	4	31	12
5	0.44	0.74	0.43	1.17	211	992	122	35	32	86	72	949	327	303	537	21	24	47	32	245	112	229	126	25	16	46	9	125
6	0.36	0.46	0.89	1.23	508	930	199	54	74	100	9	161	137	129	693	592	98	234	133	30	14	19	43	133	203	103	156	9
7	0.63	0.99	0.52	1.14	860	676	628	336	808	979	504	82	96	87	65	9	13	33	1	225	192	201	160	129	86	193	164	14
8	0.8	0.63	0.76	1.56	144	786	564	833	906	274	827	82	4	28	26	131	63	199	208	36	41	21	0	34	11	32	6	200
9	0.98	1.42	1.19	0.35	25	391	598	20	25	256	857	35	51	882	439	86	20	54	153	5	16	132	220	27	48	60	176	3
10	0.57	1.34	1.54	0.79	58	128	337	70	38	796	637	26	52	414	277	139	170	43	45	147	51	49	0	246	207	21	20	225
11	0.73	1.42	1.26	0.35	75	649	821	968	185	94	84	227	723	17	56	67	12	203	151	38	3	131	233	249	165	18	46	135
12	0.66	1.38	1.55	0.67	3	707	315	990	431	70	55	829	450	82	15	976	105	47	4	210	94	19	5	15	42	241	195	30
13	0.89	1.05	1.05	1.54	867	40	30	14	38	310	221	230	362	50	43	6	33	162	202	193	53	20	21	13	39	65	229	138
14	0.7	1.18	1.29	1.4	987	38	38	3	2	554	978	163	298	64	6	687	89	8	24	35	7	209	63	197	163	8	23	44
15	0.41	1.1	1.38	1.12	709	16	76	909	750	78	76	54	43	179	708	41	38	202	164	102	209	26	44	177	130	33	25	14
16	0.49	1.08	1.28	1.48	940	20	66	859	410	85	12	89	63	775	216	882	132	31	38	42	36	114	176	33	32	249	162	102
17	1.19	0.56	1.11	0.72	284	47	229	65	533	58	150	43	244	81	465	39	231	39	130	25	185	7	103	13	80	7	137	30
18	1.34	0.49	1.27	0.45	144	24	448	87	438	93	591	91	605	49	172	981	20	89	13	161	43	76	29	139	10	73	18	129
19	1.06	0.58	1.33	0.6	630	7	174	594	51	987	19	186	65	473	49	22	222	43	150	14	153	28	201	79	45	205	41	100
20	1.26	0.91	1.36	0.81	605	18	220	357	36	893	35	413	60	303	48	375	31	81	3	71	21	227	13	47	160	34	203	33
21	1.06	0.8	1.3	1.09	83	572	31	31	532	46	309	510	12	220	29	17	163	14	71	61	25	203	31	8	139	37	103	163
22	1.32	0.63	1.16	1.43	5	727	19	76	273	55	121	300	82	391	12	675	41	79	46	50	229	2	120	75	10	64	4	50
23	1.46	0.8	1.1	1.41	77	352	100	559	51	947	74	87	765	39	745	62	87	34	241	228	29	103	25	182	7	104	4	24
24	1.07	0.69	1.28	1.34	50	165	85	694	70	353	40	2	171	63	274	569	1	250	44	22	221	38	236	17	143	3	132	157
25	1.02	1.4	0.99	0.88	194	275	20	77	969	792	87	69	673	897	91	90	223	67	47	25	76	117	33	42	250	51	2	13
26	1.31	1.54	0.41	0.87	944	847	65	35	788	382	14	72	444	527	25	763	20	1	186	163	36	26	149	244	45	18	176	199
27	1.04	1.53	0.98	0.95	405	622	17	813	52	81	458	580	82	77	898	79	62	124	44	14	182	230	6	239	32	32	118	115
28	1.16	1.2	0.4	0.51	244	486	89	727	20	42	734	766	72	59	194	353	25	16	102	209	1	13	131	4	207	208	15	11
29	1.05	1.37	0.92	1.5	77	4	370	68	814	720	15	727	77	47	462	90	106	91	50	230	28	48	130	50	203	168	45	107
30	1.1	1.16	0.85	1.38	53	83	989	69	243	287	83	282	84	70	136	456	22	11	125	3	121	128	43	70	18	19	116	4
31	1.5	1	0.42	1.09	52	97	667	355	19	97	897	79	695	247	10	31	159	218	28	144	47	22	162	95	15	10	219	1
32	1.09	1.43	0.46	1.1	14	57	886	721	72	65	150	86	475	846	10	369	47	34	111	23	247	62	31	22	247	99	5	73

	Data sheet for Experiment 2																											
Cases	**Cp 4**	**Cp 3**	**Cp 2**	**Cp 1**	**A X,4**	**A X,3**	**A X,2**	**A X,1**	**A Y,4**	**A Y,3**	**A Y,2**	**A Y,1**	**A Z,4**	**A Z,3**	**A Z,2**	**A Z,1**	**P X,4**	**P X,3**	**P X,2**	**P X,1**	**P Y,4**	**P Y,3**	**P Y,2**	**P Y,1**	**P Z,4**	**P Z,3**	**P Z,2**	**P Z,1**
1	0.56	0.55	0.71	0.74	77	86	46	44	75	15	26	24	55	15	82	3	14	41	39	13	34	45	27	17	8	32	50	29
2	0.51	0.75	0.65	0.75	80	24	98	25	2	79	46	72	36	22	67	228	58	83	241	144	128	235	213	246	181	188	80	239
3	0.45	0.7	0.36	0.69	81	35	27	874	293	278	382	605	776	244	205	68	4	10	15	31	2	44	33	155	69	181	227	121
4	0.63	0.61	0.49	0.82	30	88	79	796	669	877	542	393	825	504	917	630	127	189	91	80	99	172	244	50	27	21	13	45
5	0.97	0.84	0.64	1.13	466	305	155	33	20	65	56	545	926	500	225	62	4	41	37	115	194	117	176	10	6	13	49	207
6	0.45	0.82	0.74	1.51	936	719	686	25	0	20	57	886	813	938	931	597	194	52	95	49	41	31	3	242	60	135	153	49
7	0.37	0.75	0.91	1.48	173	117	491	604	265	301	338	45	25	99	98	80	45	11	36	189	111	143	67	180	126	118	184	26
8	0.75	0.39	0.58	1.48	152	289	294	280	555	649	910	3	49	54	12	762	115	150	122	39	47	25	34	25	45	50	32	147
9	0.58	1.44	1.1	0.84	57	256	462	82	43	487	215	42	30	823	720	79	4	137	218	22	23	247	218	34	44	126	225	44
10	0.6	1.18	1.05	0.53	75	782	721	59	78	334	892	52	57	131	402	386	132	13	15	56	133	10	45	78	237	33	2	148
11	0.76	1.03	1.22	0.56	82	908	311	570	542	36	45	399	579	8	79	76	19	207	64	14	7	191	99	57	234	2	23	84
12	0.77	1.03	1.32	0.57	1	566	275	710	253	86	60	466	643	22	18	907	120	50	16	160	165	8	40	40	32	185	123	8
13	0.68	1.2	1.3	1.31	733	18	6	59	36	347	430	342	259	80	18	68	4	209	131	157	181	47	29	26	25	178	105	158
14	0.58	1.47	1.2	1.01	380	72	8	17	33	526	303	119	626	31	80	905	78	2	6	41	18	133	226	197	182	39	33	15
15	0.97	1.21	1.48	1.12	768	43	47	872	392	9	95	21	82	781	479	79	13	64	128	216	64	47	39	118	212	39	21	46
16	0.81	1.51	1.12	1.02	163	11	33	816	927	15	60	21	41	524	166	971	158	14	15	42	50	188	132	17	24	61	142	130
17	1.2	0.4	1.55	0.61	360	36	349	57	921	45	650	10	200	15	115	71	246	46	184	36	227	49	161	33	81	21	158	19
18	1.48	0.67	1.5	0.55	418	64	133	61	822	77	241	42	638	47	310	790	47	192	42	124	46	213	5	109	17	51	41	131
19	1.17	0.52	1.52	0.45	349	15	741	683	34	153	38	348	2	531	67	35	156	32	173	42	193	44	132	95	7	189	8	179
20	1.41	0.47	1.3	0.45	789	62	657	750	30	882	8	506	62	487	72	588	25	165	22	98	10	108	42	12	244	39	163	43
21	1.52	0.78	1.05	1.21	15	923	62	6	200	61	831	491	87	949	91	70	156	0	169	110	17	109	42	38	194	50	90	70
22	1.48	0.96	1.31	1.52	65	853	80	0	503	62	533	319	54	491	14	565	42	191	34	16	215	30	117	170	11	53	32	41
23	1.28	0.57	1.23	1.03	85	391	71	195	12	316	90	58	932	83	712	74	136	2	227	85	18	196	36	51	37	79	6	44
24	1.33	0.94	1.12	1.23	5	269	36	363	83	713	8	91	471	38	930	133	15	61	48	24	122	37	203	21	205	3	53	213
25	1.05	1.47	0.86	0.42	626	796	54	24	483	703	65	98	252	942	6	100	104	87	13	49	149	202	50	38	176	213	32	28
26	1.06	1.36	0.66	0.82	195	275	94	84	613	173	28	90	238	466	100	477	21	50	131	238	48	44	69	54	1	12	126	57
27	1.42	1.34	0.59	0.64	400	606	97	670	13	88	167	625	89	38	965	93	54	78	0	32	72	146	34	183	5	50	221	222
28	1.3	1.22	0.52	0.41	228	324	42	697	24	87	712	701	46	70	335	117	39	1	194	152	31	47	132	26	243	143	47	23
29	1.3	1.37	0.43	1.5	39	21	864	96	379	889	32	830	41	100	844	43	198	61	26	151	35	12	141	37	225	99	20	86
30	1.31	1.09	0.44	1.21	58	16	111	71	108	889	17	879	94	76	477	957	22	32	242	14	230	209	24	249	44	20	96	5
31	1.44	1.36	0.45	1.38	91	60	528	145	36	97	611	100	442	564	4	11	188	87	6	216	15	11	140	53	21	5	161	14
32	1.1	1	0.38	1.17	81	18	356	435	90	21	790	48	349	842	84	526	5	48	222	13	84	240	37	9	162	124	15	149

	Data sheet for Experiment 20																											
Cases	**Cp 4**	**Cp 3**	**Cp 2**	**Cp 1**	**A X,4**	**A X,3**	**A X,2**	**A X,1**	**A Y,4**	**A Y,3**	**A Y,2**	**A Y,1**	**A Z,4**	**A Z,3**	**A Z,2**	**A Z,1**	**P X,4**	**P X,3**	**P X,2**	**P X,1**	**P Y,4**	**P Y,3**	**P Y,2**	**P Y,1**	**P Z,4**	**P Z,3**	**P Z,2**	**P Z,1**
1	0.64	0.43	0.96	0.69	44	13	5	61	93	48	43	44	24	57	85	27	44	35	16	45	50	33	18	27	44	29	0	15
2	0.86	0.95	0.96	0.81	25	69	5	38	92	65	94	18	29	53	18	283	189	100	112	244	96	149	144	93	177	111	238	137
3	0.45	0.43	0.7	0.44	53	24	34	521	668	314	308	867	405	812	633	89	46	15	22	26	11	33	8	127	249	133	184	87
4	0.39	0.53	0.87	0.47	54	93	10	762	554	644	796	774	611	595	807	386	210	144	128	85	241	52	76	38	30	6	15	18
5	0.79	0.95	0.57	1.54	454	101	986	3	100	66	100	308	974	781	338	64	45	36	19	78	87	72	199	16	42	15	35	99
6	0.74	0.87	0.36	1.18	144	494	925	78	11	2	97	698	616	563	178	558	206	135	114	15	44	6	11	69	134	88	194	33
7	0.59	0.71	0.95	1.38	140	932	683	913	810	325	546	35	68	73	51	59	42	18	45	63	213	107	170	180	246	239	117	38
8	0.79	0.69	0.75	1.47	154	554	680	346	146	298	322	81	72	25	36	650	243	215	244	26	36	18	22	21	10	9	11	69
9	0.64	1.02	1.22	0.8	96	914	275	21	15	797	701	38	34	440	982	51	32	243	234	7	1	169	99	43	30	124	174	0
10	0.71	1.13	1.56	0.63	36	563	644	53	4	244	381	48	11	665	251	837	116	23	16	139	173	37	12	140	67	15	49	125
11	0.85	1.1	1.14	0.91	11	148	818	540	585	9	61	831	834	90	38	100	36	148	233	19	32	154	103	169	84	25	17	118
12	0.78	1.24	1.21	0.96	17	649	742	107	467	28	82	256	796	79	61	919	212	33	16	144	238	42	32	36	8	193	202	6
13	0.71	1.33	1.14	1.47	481	78	33	10	51	110	213	972	629	41	72	30	13	63	197	211	168	34	4	38	8	89	157	114
14	0.5	1.03	1.33	1.29	429	10	84	10	45	893	984	408	295	77	66	643	81	16	18	8	24	103	239	111	76	31	24	27
15	0.57	1.02	1.4	1.24	355	40	26	782	849	18	62	86	38	591	777	20	34	232	112	122	160	49	20	169	66	28	11	42
16	0.96	1.37	1.39	1.48	161	79	38	728	521	79	59	58	76	999	376	154	70	33	0	46	26	213	53	41	44	221	58	166
17	1.12	0.54	1.24	0.66	642	33	713	80	888	100	386	76	614	68	466	32	201	41	85	8	53	10	177	4	154	40	238	18
18	1.19	0.4	1.4	0.89	954	25	101	57	366	60	205	66	637	34	981	593	8	53	31	190	33	200	3	182	22	180	1	144
19	1.26	0.53	1.13	0.36	881	20	738	535	1	598	90	263	59	926	11	97	67	2	59	40	227	18	200	74	46	134	33	102
20	1.25	0.79	1.4	0.64	912	9	849	525	69	219	68	526	73	546	1	563	47	78	22	145	39	69	14	7	62	24	236	50
21	1	0.54	1.49	1.11	84	201	28	95	903	81	636	541	10	263	55	3	96	20	78	62	22	72	38	42	103	16	178	97
22	1.34	0.57	1.1	1.08	9	251	18	19	309	42	891	210	5	511	71	927	17	144	33	24	111	13	250	229	3	221	1	12
23	1.17	0.9	1.09	1.47	74	884	73	956	59	957	99	58	878	67	419	24	221	0	224	167	24	128	30	118	0	123	37	2
24	1.35	0.68	1.43	1.47	73	944	94	144	61	391	24	22	911	21	606	560	12	146	48	2	93	10	247	31	220	36	92	206
25	1.45	1.52	0.8	0.77	819	696	74	54	737	798	55	79	274	373	11	81	215	111	15	7	58	241	26	3	176	203	37	32
26	1.39	1.4	0.47	0.63	441	835	1	41	483	505	44	97	773	731	41	727	43	39	121	135	15	1	164	196	39	20	164	207
27	1	1.2	0.82	0.64	878	482	61	879	51	15	989	262	6	37	160	86	57	75	22	28	60	156	16	241	27	19	76	246
28	1.35	1.05	0.97	0.42	703	806	3	815	35	18	830	954	92	90	816	853	32	17	85	66	25	45	167	44	223	227	5	36
29	1.43	1.52	0.84	1.44	47	33	901	75	480	911	55	327	29	4	902	100	104	51	4	66	42	2	108	24	154	59	19	101
30	1.3	1.09	0.44	1.1	16	95	536	23	370	190	15	533	14	61	975	975	37	40	77	31	236	245	12	229	30	23	152	29
31	1.05	1.47	0.74	1.08	14	12	914	913	40	90	576	66	417	837	14	96	166	129	44	222	25	21	230	219	28	20	117	3
32	1.28	1.28	0.49	1.09	44	15	114	713	4	11	641	74	301	214	12	823	46	25	135	7	112	242	11	4	147	53	13	250

APPENDIX F

SOLUTIONS OF THE SELECTED CASES

Experiment 1											
	Improvement Decisions						Total 'F' Values				
	T-L method		QFD method		Cp method		T-L	QFD	Cp	Dev QFD	Dev Cp
Cases	P1	P2	P1	P2	P1	P2					
1	4	4	4	3	4	2	9E+07	9E+07	9E+07	0,008700181	1,691831074
2	4	3	1	4	1	1	7E+07	7E+07	7E+07	2,731856235	5,068631928
3	1	1	1	2	1	2	8E+07	8E+07	8E+07	0,440447393	0,440447393
4	3	3	2	3	2	3	7E+07	7E+07	7E+07	1,912223635	1,912223635
5	4	4	4	2	2	4	8E+07	8E+07	8E+07	0,964304646	3,868075432
6	4	3	4	3	4	3	7E+07	7E+07	7E+07	0,289894599	0,289894599
7	4	2	2	4	2	2	9E+07	9E+07	8E+07	0,493798431	1,213393713
8	3	3	3	3	3	3	9E+07	9E+07	9E+07	0,80533799	0,80533799
9	1	2	1	1	1	1	1E+08	1E+08	1E+08	0,053379698	0,053379698
10	4	4	4	4	4	4	1E+08	1E+08	1E+08	0	0
11	1	1	1	1	1	1	8E+07	8E+07	8E+07	0,090348103	0,090348103
12	4	1	4	4	4	1	9E+07	9E+07	9E+07	0,435724246	0
13	4	4	4	4	4	4	1E+08	1E+08	1E+08	0	0
14	4	4	4	4	4	4	1E+08	1E+08	1E+08	0	0
15	4	4	4	4	4	4	8E+07	8E+07	8E+07	0	0
16	4	4	4	4	4	4	9E+07	9E+07	9E+07	0	0
17	3	3	3	3	3	3	1E+08	1E+08	1E+08	0	0
18	3	3	3	1	1	3	9E+07	9E+07	9E+07	1,442591619	3,65628438
19	3	3	3	3	3	1	9E+07	9E+07	9E+07	0	0,502441067
20	1	1	1	3	1	1	1E+08	1E+08	1E+08	0,0229306	0,011517827
21	3	3	3	3	3	3	1E+08	1E+08	1E+08	0,009514767	0,009514767
22	3	3	3	3	3	3	1E+08	1E+08	1E+08	0	0
23	3	3	3	3	3	3	1E+08	1E+08	1E+08	0	0
24	3	3	3	3	3	3	1E+08	1E+08	1E+08	0	0
25	4	4	4	4	1	1	1E+08	1E+08	1E+08	0,00249058	0,120306727
26	2	2	2	2	2	2	1E+08	1E+08	1E+08	0,004244175	0,004244175
27	1	1	1	1	1	2	1E+08	1E+08	1E+08	0	0,117229266
28	2	1	1	2	2	1	9E+07	8E+07	9E+07	1,411500059	0,003710394
29	2	2	2	4	2	2	1E+08	1E+08	1E+08	0,027798262	0
30	2	2	2	2	2	2	1E+08	1E+08	1E+08	0	0
31	2	2	2	2	2	2	9E+07	9E+07	9E+07	0	0
32	2	2	2	2	2	2	1E+08	1E+08	1E+08	0	0

Experiment 2												
	Improvement Decisions						Total 'F' Values					
	T-L method		QFD method		Cp method		T-L	QFD	Cp	Dev QFD	Dev Cp
Cases	P1	P2	P1	P2	P1	P2					
1	3	4	4	3	3	4	1E+08	1E+08	1E+08	0,100650462	0
2	4	4	4	4	4	4	8E+07	8E+07	8E+07	0	0
3	2	4	2	4	2	4	8E+07	8E+07	8E+07	0,00016119	0,00016119
4	3	4	2	4	2	2	8E+07	7E+07	7E+07	1,414507245	2,148030469
5	3	2	3	3	2	2	1E+08	1E+08	1E+08	0,022745054	0,216435723
6	4	4	4	4	4	4	8E+07	8E+07	8E+07	0	0
7	4	4	4	4	4	4	8E+07	8E+07	8E+07	0	0
8	3	3	3	3	3	3	8E+07	8E+07	8E+07	2,344967391	2,344967391
9	4	4	4	4	4	4	1E+08	1E+08	1E+08	0	0
10	4	4	4	1	1	4	1E+08	1E+08	1E+08	0,457814383	1,56701914
11	4	1	1	1	1	1	1E+08	1E+08	1E+08	0,089836478	0,089836478
12	1	1	1	1	1	1	9E+07	9E+07	9E+07	0	0
13	4	4	4	4	4	4	1E+08	1E+08	1E+08	0	0
14	4	4	4	4	4	4	1E+08	1E+08	1E+08	0	0
15	1	4	4	4	4	4	1E+08	1E+08	1E+08	0,058531152	0,058531152
16	4	1	4	4	4	4	1E+08	1E+08	1E+08	0,036903193	0,036903193
17	3	3	3	3	3	3	9E+07	9E+07	9E+07	0	0
18	3	3	3	1	1	1	1E+08	1E+08	1E+08	0,212201617	1,401881321
19	3	3	3	1	1	3	8E+07	8E+07	8E+07	0,49676223	2,212441005
20	3	3	3	3	1	3	8E+07	8E+07	8E+07	0	3,265557442
21	3	3	3	3	3	3	1E+08	1E+08	1E+08	0	0
22	3	3	3	3	3	3	1E+08	1E+08	1E+08	0	0
23	3	3	3	3	3	3	1E+08	1E+08	1E+08	0	0
24	3	3	3	3	3	3	1E+08	1E+08	1E+08	0	0
25	1	1	4	4	1	1	1E+08	1E+08	1E+08	0,220014758	0
26	2	1	2	1	2	2	1E+08	1E+08	1E+08	0,003248053	0,029485309
27	1	1	1	2	2	1	1E+08	1E+08	1E+08	0,116853867	0,352142684
28	1	1	1	1	1	2	9E+07	9E+07	9E+07	0,001898147	0,242981989
29	2	2	2	2	2	2	1E+08	1E+08	1E+08	0	0
30	2	2	2	2	2	2	1E+08	1E+08	1E+08	0	0
31	2	2	2	2	2	2	1E+08	1E+08	1E+08	0	0
32	2	2	2	2	2	2	9E+07	9E+07	9E+07	0,015163641	0,015163641

Experiment 20												
	Improvement Decisions						Total 'F' Values					
	T-L method		QFD method		Cp method		T-L	QFD	Cp	Dev QFD	Dev Cp
Cases	**P1**	**P2**	**P1**	**P2**	**P1**	**P2**					
1	3	3	3	3	3	3	1E+08	1E+08	1E+08	0	0
2	4	4	1	4	1	4	1E+08	1E+08	1E+08	0,171506052	0,171506052
3	4	2	2	4	2	4	8E+07	7E+07	7E+07	3,532884497	3,532884497
4	4	4	4	4	4	1	6E+07	6E+07	6E+07	0	1,537500722
5	2	2	2	4	2	2	1E+08	1E+08	1E+08	0,037340675	0
6	2	2	2	2	2	2	9E+07	9E+07	9E+07	0,061495777	0,061495777
7	4	4	4	3	4	4	9E+07	9E+07	9E+07	0,038228054	0
8	3	3	3	3	3	2	1E+08	1E+08	1E+08	0	0,125510153
9	4	4	4	4	4	4	1E+08	1E+08	1E+08	0	0
10	4	4	4	1	1	4	1E+08	1E+08	1E+08	0,152862378	0,525020966
11	1	4	4	4	4	1	1E+08	1E+08	1E+08	0,175438417	0,033621859
12	4	4	4	4	4	4	1E+08	1E+08	1E+08	0	0
13	4	4	4	4	4	4	1E+08	1E+08	1E+08	0,009748814	0,009748814
14	4	4	4	4	4	4	1E+08	1E+08	1E+08	0	0
15	4	4	4	4	4	4	1E+08	1E+08	1E+08	0	0
16	4	4	4	4	4	4	1E+08	1E+08	1E+08	0	0
17	3	3	3	3	3	3	1E+08	1E+08	1E+08	0	0
18	3	3	3	3	3	3	9E+07	9E+07	9E+07	0,0458247	0,0458247
19	3	1	1	3	1	1	9E+07	9E+07	8E+07	0,446938784	2,132762372
20	1	1	1	3	1	1	1E+08	1E+08	1E+08	0,053143714	0
21	3	3	3	3	3	3	1E+08	1E+08	1E+08	0,011617486	0,011617486
22	3	3	3	3	3	3	1E+08	1E+08	1E+08	0	0
23	3	3	3	3	3	3	1E+08	1E+08	1E+08	0,013745238	0,013745238
24	3	3	3	3	3	3	1E+08	1E+08	1E+08	0	0
25	1	1	1	2	1	2	1E+08	1E+08	1E+08	0,006576943	0,006576943
26	2	1	2	1	2	2	1E+08	1E+08	1E+08	0,000625588	0,027810012
27	1	1	1	1	1	1	1E+08	1E+08	1E+08	0	0
28	1	1	1	1	1	1	9E+07	9E+07	9E+07	0,005812599	0,005812599
29	2	2	2	2	2	2	1E+08	1E+08	1E+08	0	0
30	2	2	2	2	2	2	1E+08	1E+08	1E+08	0	0
31	2	2	2	2	2	2	9E+07	9E+07	9E+07	0,013687717	0,013687717
32	2	2	2	2	2	2	1E+08	1E+08	1E+08	0,002974513	0,002974513

	Product Mixes of Experiment 1								
	T-L Method			**QFD Method**			**Cp Method**		
Cases	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	P3
1	(6400;1260;3200)	(6400;2397;3200)	(6400;2965;3200)	(6400;1260;3200)	(6400;2397;3200)	(6400;2968;3200)	(6400;1260;3200)	(6400;2397;3200)	(6400;2397;3200)
2	(4969;2973;3199)	(5196;3497;3199)	(5422;4020;3198)	(4969;2972;3200)	(6400;2018;3200)	(6400;2649;3200)	(4969;2972;3200)	(6400;2018;3200)	(6400;2018;3200)
3	(2767;4800;3200)	(4538;4747;3200)	(6400;3506;3200)	(2767;4800;3200)	(4538;4747;3200)	(6400;4800;2091)	(2767;4800;3200)	(4538;4747;3200)	(6400;4800;2091)
4	(6400;2617;3200)	(6400;3332;3200)	(6400;3690;3200)	(6400;2617;3200)	(6400;2617;3200)	(6400;3332;3200)	(6400;2617;3200)	(6400;2617;3200)	(6400;3332;3200)
5	(6400;2084;3200)	(6400;3205;3200)	(6400;3766;3200)	(6400;2084;3200)	(6400;3205;3200)	(6400;3297;3200)	(6400;2084;3200)	(6400;2133;3200)	(6400;3297;3200)
6	(0;4800;2460)	(6400;4800;82)	(6400;4800;872)	(4305;4800;0)	(5463;4800;0)	(6400;4800;872)	(4305;4800;0)	(6400;4800;82)	(6400;4800;872)
7	(6400;4012;3200)	(6400;4386;3200)	(6400;4386;3200)	(6400;4012;3200)	(6400;4012;3200)	(6400;4386;3200)	(6400;4012;3200)	(6400;4012;3200)	(6400;4012;3200)
8	(4975;4800;3200)	(5530;4800;3200)	(5807;4800;3200)	(6400;4800;2386)	(6400;4800;2703)	(6400;4800;2861)	(6400;4800;2386)	(6400;4800;2703)	(6400;4800;2861)
9	(5510;4800;3200)	(6400;4757;3200)	(6400;4757;3200)	(5510;4800;3200)	(6400;4757;3200)	(6400;4757;3200)	(5510;4800;3200)	(6400;4757;3200)	(6400;4757;3200)
10	(6400;4800;2241)	(6400;4800;2720)	(6400;4800;2960)	(6400;4800;2241)	(6400;4800;2720)	(6400;4800;2960)	(6400;4800;2241)	(6400;4800;2720)	(6400;4800;2960)
11	(5171;4800;3200)	(5851;4800;3200)	(5851;4800;3200)	(5171;4800;3200)	(6400;4434;3200)	(6400;4434;3200)	(5171;4800;3200)	(6400;4434;3200)	(6400;4434;3200)
12	(6400;4800;2676)	(6400;4800;2937)	(6400;4800;2937)	(6400;4800;2676)	(6400;4800;2937)	(6400;4800;3068)	(6400;4800;2676)	(6400;4800;2937)	(6400;4800;2937)
13	(6400;4800;3099)	(6400;4800;3140)	(6400;4800;3161)	(6400;4800;3099)	(6400;4800;3140)	(6400;4800;3161)	(6400;4800;3099)	(6400;4800;3140)	(6400;4800;3161)
14	(6400;4337;3200)	(6400;4566;3200)	(6400;4680;3200)	(6400;4337;3200)	(6400;4566;3200)	(6400;4680;3200)	(6400;4337;3200)	(6400;4566;3200)	(6400;4680;3200)
15	(6400;1991;3200)	(6400;3389;3200)	(6400;4088;3200)	(6400;1991;3200)	(6400;3389;3200)	(6400;4088;3200)	(6400;1991;3200)	(6400;3389;3200)	(6400;4088;3200)
16	(6400;4800;1635)	(6400;4800;2411)	(6400;4800;2799)	(6400;4800;1635)	(6400;4800;2411)	(6400;4800;2799)	(6400;4800;1635)	(6400;4800;2411)	(6400;4800;2799)
17	(6400;3606;3200)	(6400;4200;3200)	(6400;4498;3200)	(6400;3606;3200)	(6400;4200;3200)	(6400;4498;3200)	(6400;3606;3200)	(6400;4200;3200)	(6400;4498;3200)
18	(6400;4800;1646)	(6400;4800;2422)	(6400;4800;2811)	(6400;2987;3200)	(6400;3893;3200)	(6400;3893;3200)	(6400;2987;3200)	(6400;2987;3200)	(6400;3893;3200)
19	(6400;3734;3200)	(6400;4258;3200)	(6400;4519;3200)	(6400;3734;3200)	(6400;4258;3200)	(6400;4519;3200)	(6400;3734;3200)	(6400;4258;3200)	(6400;4258;3200)
20	(6400;4716;3200)	(6400;4716;3200)	(6400;4716;3200)	(6400;4800;3128)	(6400;4800;3128)	(6400;4800;3163)	(6400;4800;3128)	(6400;4800;3128)	(6400;4800;3128)
21	(6400;4571;3200)	(6400;4676;3200)	(6400;4728;3200)	(6400;4800;3004)	(6400;4800;3094)	(6400;4800;3138)	(6400;4800;3004)	(6400;4800;3094)	(6400;4800;3138)
22	(6400;4046;3200)	(6400;4423;3200)	(6400;4611;3200)	(6400;4046;3200)	(6400;4423;3200)	(6400;4611;3200)	(6400;4046;3200)	(6400;4423;3200)	(6400;4611;3200)
23	(6400;4589;3200)	(6400;4694;3200)	(6400;4747;3200)	(6400;4589;3200)	(6400;4694;3200)	(6400;4747;3200)	(6400;4589;3200)	(6400;4694;3200)	(6400;4747;3200)
24	(6400;4291;3200)	(6400;4537;3200)	(6400;4660;3200)	(6400;4291;3200)	(6400;4537;3200)	(6400;4660;3200)	(6400;4291;3200)	(6400;4537;3200)	(6400;4660;3200)
25	(6400;4771;3200)	(6400;4785;3200)	(6400;4792;3200)	(6400;4800;3175)	(6400;4800;3187)	(6400;4800;3193)	(6400;4800;3175)	(6400;4800;3175)	(6400;4800;3175)
26	(6400;4319;3200)	(6400;4800;3199)	(6400;4800;3199)	(6400;4319;3200)	(6400;4798;3200)	(6400;4798;3200)	(6400;4319;3200)	(6400;4798;3200)	(6400;4798;3200)
27	(6400;4776;3200)	(6400;4776;3200)	(6400;4776;3200)	(6400;4776;3200)	(6400;4776;3200)	(6400;4776;3200)	(6400;4776;3200)	(6400;4776;3200)	(6400;4776;3200)
28	(4908;4800;3200)	(6400;4789;3200)	(6400;4789;3200)	(4908;4800;3200)	(5569;4800;3200)	(6400;4800;3191)	(4908;4800;3200)	(6400;4800;3191)	(6400;4800;3191)
29	(6400;4800;3181)	(6400;4800;3181)	(6400;4800;3181)	(6400;4800;3181)	(6400;4800;3181)	(6400;4800;3190)	(6400;4800;3181)	(6400;4800;3181)	(6400;4800;3181)
30	(6400;4781;3200)	(6400;4781;3200)	(6400;4781;3200)	(6400;4781;3200)	(6400;4781;3200)	(6400;4781;3200)	(6400;4781;3200)	(6400;4781;3200)	(6400;4781;3200)
31	(5971;4800;3200)	(6400;4765;3200)	(6400;4765;3200)	(5971;4800;3200)	(6400;4765;3200)	(6400;4765;3200)	(5971;4800;3200)	(6400;4765;3200)	(6400;4765;3200)
32	(6400;4800;3188)	(6400;4800;3188)	(6400;4800;3188)	(6400;4800;3188)	(6400;4800;3188)	(6400;4800;3188)	(6400;4800;3188)	(6400;4800;3188)	(6400;4800;3188)

	Product Mixes of Experiment 2								
	T-L Method			**QFD Method**			**Cp Method**		
Cases	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	P3
1	(6400;2461;3200)	(6400;3035;3200)	(6400;3601;3200)	(6400;2461;3200)	(6400;2997;3200)	(6400;3601;3200)	(6400;2461;3200)	(6400;3035;3200)	(6400;3601;3200)
2	(6400;2913;3200)	(6400;3700;3200)	(6400;4093;3200)	(6400;2913;3200)	(6400;3700;3200)	(6400;4093;3200)	(6400;2913;3200)	(6400;3700;3200)	(6400;4093;3200)
3	(5660;1686;3200)	(6400;4207;1443)	(6400;4800;1871)	(5659;1687;3200)	(6400;4207;1443)	(6400;4800;1871)	(5659;1687;3200)	(6400;4207;1443)	(6400;4800;1871)
4	(6400;3237;3200)	(6400;3642;3200)	(6400;4006;3200)	(6400;3237;3200)	(6400;3237;3200)	(6400;3588;3200)	(6400;3237;3200)	(6400;3237;3200)	(6400;3237;3200)
5	(6400;4604;3200)	(6400;4678;3200)	(6400;4678;3200)	(6400;4604;3200)	(6400;4678;3200)	(6400;4678;3200)	(6400;4604;3200)	(6400;4604;3200)	(6400;4604;3200)
6	(6400;4800;1132)	(6400;4800;2089)	(6400;4800;2568)	(6400;4800;1132)	(6400;4800;2089)	(6400;4800;2568)	(6400;4800;1132)	(6400;4800;2089)	(6400;4800;2568)
7	(6400;1153;3200)	(6400;2820;3200)	(6400;3653;3200)	(6400;1153;3200)	(6400;2820;3200)	(6400;3653;3200)	(6400;1153;3200)	(6400;2820;3200)	(6400;3653;3200)
8	(6400;1465;3200)	(6400;2976;3200)	(6400;3731;3200)	(6400;4800;341)	(6400;4800;1636)	(6400;4800;2284)	(6400;4800;341)	(6400;4800;1636)	(6400;4800;2284)
9	(6400;3752;3200)	(6400;4275;3200)	(6400;4537;3200)	(6400;3752;3200)	(6400;4275;3200)	(6400;4537;3200)	(6400;3752;3200)	(6400;4275;3200)	(6400;4537;3200)
10	(6400;4800;2407)	(6400;4800;2801)	(6400;4800;2998)	(6400;4800;2407)	(6400;4800;2801)	(6400;4800;2801)	(6400;4800;2407)	(6400;4800;2407)	(6400;4800;2801)
11	(6400;4485;3200)	(6400;4629;3200)	(6400;4629;3200)	(6400;4485;3200)	(6400;4485;3200)	(6400;4485;3200)	(6400;4485;3200)	(6400;4485;3200)	(6400;4485;3200)
12	(6400;4800;2949)	(6400;4800;2949)	(6400;4800;2949)	(6400;4800;2949)	(6400;4800;2949)	(6400;4800;2949)	(6400;4800;2949)	(6400;4800;2949)	(6400;4800;2949)
13	(6400;4800;2742)	(6400;4800;2969)	(6400;4800;3083)	(6400;4800;2742)	(6400;4800;2969)	(6400;4800;3083)	(6400;4800;2742)	(6400;4800;2969)	(6400;4800;3083)
14	(6400;3752;3200)	(6400;4275;3200)	(6400;4537;3200)	(6400;3752;3200)	(6400;4275;3200)	(6400;4537;3200)	(6400;3752;3200)	(6400;4275;3200)	(6400;4537;3200)
15	(6400;4800;3157)	(6400;4800;3157)	(6400;4800;3177)	(6400;4800;3157)	(6400;4800;3177)	(6400;4800;3186)	(6400;4800;3157)	(6400;4800;3177)	(6400;4800;3186)
16	(6400;4800;3034)	(6400;4800;3117)	(6400;4800;3117)	(6400;4606;3200)	(6400;4703;3200)	(6400;4751;3200)	(6400;4606;3200)	(6400;4703;3200)	(6400;4751;3200)
17	(6400;1851;3200)	(6400;3323;3200)	(6400;4059;3200)	(6400;1851;3200)	(6400;3323;3200)	(6400;4059;3200)	(6400;1851;3200)	(6400;3323;3200)	(6400;4059;3200)
18	(6400;4800;2712)	(6400;4800;2956)	(6400;4800;3078)	(6400;4231;3200)	(6400;4515;3200)	(6400;4515;3200)	(6400;4231;3200)	(6400;4231;3200)	(6400;4231;3200)
19	(6400;3274;3200)	(6400;4034;3200)	(6400;4414;3200)	(6400;3274;3200)	(6400;4034;3200)	(6400;4034;3200)	(6400;3274;3200)	(6400;3274;3200)	(6400;4034;3200)
20	(6400;4800;1460)	(6400;4800;2330)	(6400;4800;2764)	(6400;4800;1460)	(6400;4800;2330)	(6400;4800;2764)	(6400;4800;1460)	(6400;4800;1460)	(6400;4800;2330)
21	(6400;4800;2988)	(6400;4800;3094)	(6400;4800;3147)	(6400;4800;2988)	(6400;4800;3094)	(6400;4800;3147)	(6400;4800;2988)	(6400;4800;3094)	(6400;4800;3147)
22	(6400;4748;3200)	(6400;4774;3200)	(6400;4787;3200)	(6400;4748;3200)	(6400;4774;3200)	(6400;4787;3200)	(6400;4748;3200)	(6400;4774;3200)	(6400;4787;3200)
23	(6400;3681;3200)	(6400;4239;3200)	(6400;4519;3200)	(6400;3681;3200)	(6400;4239;3200)	(6400;4519;3200)	(6400;3681;3200)	(6400;4239;3200)	(6400;4519;3200)
24	(6400;4800;3146)	(6400;4800;3172)	(6400;4800;3186)	(6400;4800;3146)	(6400;4800;3172)	(6400;4800;3186)	(6400;4800;3146)	(6400;4800;3172)	(6400;4800;3186)
25	(6400;4778;3200)	(6400;4778;3200)	(6400;4778;3200)	(6400;4778;3200)	(6400;4778;3200)	(6400;4789;3200)	(6400;4778;3200)	(6400;4778;3200)	(6400;4778;3200)
26	(6400;4800;3183)	(6400;4800;3183)	(6400;4800;3183)	(6400;4780;3200)	(6400;4780;3200)	(6400;4780;3200)	(6400;4780;3200)	(6400;4780;3200)	(6400;4780;3200)
27	(6400;4798;3200)	(6400;4798;3200)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)
28	(5214;4800;3200)	(6400;4795;3200)	(6400;4795;3200)	(5214;4800;3200)	(6400;4800;3196)	(6400;4800;3196)	(5214;4800;3200)	(6400;4800;3196)	(6400;4800;3196)
29	(6214;4800;3200)	(6400;4800;3198)	(6400;4800;3198)	(6214;4800;3200)	(6400;4800;3198)	(6400;4800;3198)	(6214;4800;3200)	(6400;4800;3198)	(6400;4800;3198)
30	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)
31	(6400;4799;3200)	(6400;4799;3200)	(6400;4799;3200)	(6400;4799;3200)	(6400;4799;3200)	(6400;4799;3200)	(6400;4799;3200)	(6400;4799;3200)	(6400;4799;3200)
32	(6400;3732;3200)	(6400;4753;3200)	(6400;4753;3200)	(6400;3732;3200)	(6400;4800;3159)	(6400;4800;3159)	(6400;3732;3200)	(6400;4800;3159)	(6400;4800;3159)

	Product Mixes of Experiment 20								
	T-L Method			QFD Method			Cp Method		
Cases	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
1	(6400;1713;3200)	(6400;2905;3200)	(6400;3501;3200)	(6400;1713;3200)	(6400;2905;3200)	(6400;3501;3200)	(6400;1713;3200)	(6400;2905;3200)	(6400;3501;3200)
2	(6400;4800;3044)	(6400;4800;3098)	(6400;4800;3125)	(6400;4800;3044)	(6400;4800;3044)	(6400;4800;3098)	(6400;4800;3044)	(6400;4800;3044)	(6400;4800;3098)
3	(6400;348;3200)	(6400;2007;2762)	(6400;4287;1683)	(4697;4800;451)	(6400;4191;0)	(6400;4800;258)	(4697;4800;451)	(5469;4800;900)	(6400;4800;368)
4	(6400;617;3200)	(6400;1992;3200)	(6400;2680;3200)	(6400;617;3200)	(6400;1992;3200)	(6400;2680;3200)	(6400;617;3200)	(6400;1992;3200)	(6400;1992;3200)
5	(6400;4517;3200)	(6400;4517;3200)	(6400;4517;3200)	(6400;4517;3200)	(6400;4517;3200)	(6400;4630;3200)	(6400;4517;3200)	(6400;4517;3200)	(6400;4517;3200)
6	(4134;4800;3200)	(5723;4800;3200)	(5723;4800;3200)	(4134;4800;3200)	(6400;4800;2813)	(6400;4800;2813)	(4134;4800;3200)	(6400;4800;2813)	(6400;4800;2813)
7	(6400;3425;3200)	(6400;3900;3200)	(6400;4138;3200)	(6400;3425;3200)	(6400;3900;3200)	(6400;4104;3200)	(6400;3425;3200)	(6400;3900;3200)	(6400;4138;3200)
8	(5333;4800;3200)	(5695;4800;3200)	(5877;4800;3200)	(5333;4800;3200)	(5695;4800;3200)	(5877;4800;3200)	(5333;4800;3200)	(5695;4800;3200)	(5695;4800;3200)
9	(6400;4071;3200)	(6400;4421;3200)	(6400;4596;3200)	(6400;4071;3200)	(6400;4421;3200)	(6400;4596;3200)	(6400;4071;3200)	(6400;4421;3200)	(6400;4596;3200)
10	(6400;4800;2828)	(6400;4800;3010)	(6400;4800;3101)	(6400;4366;3200)	(6400;4578;3200)	(6400;4578;3200)	(6400;4366;3200)	(6400;4366;3200)	(6400;4578;3200)
11	(6400;4649;3200)	(6400;4649;3200)	(6400;4718;3200)	(6400;4649;3200)	(6400;4718;3200)	(6400;4753;3200)	(6400;4649;3200)	(6400;4718;3200)	(6400;4718;3200)
12	(6400;4800;2986)	(6400;4800;3092)	(6400;4800;3144)	(6400;4800;2986)	(6400;4800;3092)	(6400;4800;3144)	(6400;4800;2986)	(6400;4800;3092)	(6400;4800;3144)
13	(6400;4374;3200)	(6400;4586;3200)	(6400;4693;3200)	(6400;4800;2835)	(6400;4800;3017)	(6400;4800;3108)	(6400;4800;2835)	(6400;4800;3017)	(6400;4800;3108)
14	(6400;3067;3200)	(6400;3920;3200)	(6400;4347;3200)	(6400;3067;3200)	(6400;3920;3200)	(6400;4347;3200)	(6400;3067;3200)	(6400;3920;3200)	(6400;4347;3200)
15	(6400;3657;3200)	(6400;4214;3200)	(6400;4493;3200)	(6400;3657;3200)	(6400;4214;3200)	(6400;4493;3200)	(6400;3657;3200)	(6400;4214;3200)	(6400;4493;3200)
16	(6400;4800;3155)	(6400;4800;3177)	(6400;4800;3188)	(6400;4800;3155)	(6400;4800;3177)	(6400;4800;3188)	(6400;4800;3155)	(6400;4800;3177)	(6400;4800;3188)
17	(6400;4800;2037)	(6400;4800;2614)	(6400;4800;2903)	(6400;4800;2037)	(6400;4800;2614)	(6400;4800;2903)	(6400;4800;2037)	(6400;4800;2614)	(6400;4800;2903)
18	(6400;1850;3200)	(6400;4800;1934)	(6400;4800;2565)	(6400;1850;3200)	(6400;3323;3200)	(6400;4059;3200)	(6400;1850;3200)	(6400;3323;3200)	(6400;4059;3200)
19	(4295;4770;3200)	(5037;4800;3200)	(6400;4082;3200)	(4295;4770;3200)	(5037;4800;3200)	(5423;4800;3200)	(4295;4770;3200)	(6400;3366;3200)	(6400;3366;3200)
20	(6400;4800;3002)	(6400;4800;3002)	(6400;4800;3002)	(6400;4800;3002)	(6400;4800;3002)	(6400;4800;3100)	(6400;4800;3002)	(6400;4800;3002)	(6400;4800;3002)
21	(6400;4800;2018)	(6400;4093;3200)	(6400;4429;3200)	(6400;4800;2018)	(6400;4800;2594)	(6400;4800;2882)	(6400;4800;2018)	(6400;4800;2594)	(6400;4800;2882)
22	(6400;3682;3200)	(6400;4240;3200)	(6400;4520;3200)	(6400;3682;3200)	(6400;4240;3200)	(6400;4520;3200)	(6400;3682;3200)	(6400;4240;3200)	(6400;4520;3200)
23	(6258;4800;3200)	(6324;4800;3200)	(6358;4800;3200)	(6400;4705;3200)	(6400;4749;3200)	(6400;4772;3200)	(6400;4705;3200)	(6400;4749;3200)	(6400;4772;3200)
24	(6400;4800;2745)	(6400;4800;2972)	(6400;4800;3086)	(6400;4800;2745)	(6400;4800;2972)	(6400;4800;3086)	(6400;4800;2745)	(6400;4800;2972)	(6400;4800;3086)
25	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)
26	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4799;3200)	(6400;4799;3200)	(6400;4799;3200)	(6400;4799;3200)	(6400;4799;3200)	(6400;4799;3200)
27	(6400;4761;3200)	(6400;4761;3200)	(6400;4761;3200)	(6400;4761;3200)	(6400;4761;3200)	(6400;4761;3200)	(6400;4761;3200)	(6400;4761;3200)	(6400;4761;3200)
28	(6400;4778;3200)	(6400;4778;3200)	(6400;4778;3200)	(6400;4800;3181)	(6400;4800;3181)	(6400;4800;3181)	(6400;4800;3181)	(6400;4800;3181)	(6400;4800;3181)
29	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)	(6400;4800;3199)
30	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)	(6400;4785;3200)
31	(6368;4800;3200)	(6368;4800;3200)	(6368;4800;3200)	(6400;4778;3200)	(6400;4778;3200)	(6400;4778;3200)	(6400;4778;3200)	(6400;4778;3200)	(6400;4778;3200)
32	(6400;4796;3200)	(6400;4796;3200)	(6400;4796;3200)	(6400;4800;3197)	(6400;4800;3197)	(6400;4800;3197)	(6400;4800;3197)	(6400;4800;3197)	(6400;4800;3197)

APPENDIX G

FINAL DEVIATION TABLES

The deviations of both methods of integrated QFD and Process Capability from optimal Throughput-Loss method at each case setting are demonstrated in Tables G.1 and G.2 as the following.

Table G.1 QFD deviations

Cases	Experiments																				Av_QFD	St_QFD	Max
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20			
1	0	0,1	0	0	0,3	0	0	0	0,1	0	0,1	0,5	0,9	0,5	0	0	0	0	0,1	0	0,129	0,236	0,85
2	2,7	0	1,8	1,3	2,4	0	0	0	0	0	0,9	0	0	0,4	0	0,6	0	1	0,1	0,2	0,576	0,863	2,73
3	0,4	0	0,4	3,5	0	0,5	0,1	0	2,2	1,1	2,1	0,1	2,7	0,4	0,7	1	0,6	0,6	0	3,5	1,007	1,167	3,53
4	1,9	1,4	1,6	0,5	0,2	0	2,1	0,9	0	2,7	1	1	0,1	2,6	0,7	0	0	0,1	0,2	0	0,854	0,919	2,73
5	1	0	0	0	0	0	0,7	0	0,8	0	2,3	0,1	0	0,2	0,1	0	1	0	0,3	0	0,333	0,59	2,35
6	0,3	0	0	1,2	0	0	0	0,3	0	0,2	0	0	0	0	0	0,1	0	0	0	0,1	0,106	0,276	1,21
7	0,5	0	0	0	0	0	0	0	0	0,3	0	0,9	0,7	0	0	0,3	0	0	0	0	0,137	0,261	0,87
8	0,8	2,3	1,4	1,2	3,1	0,3	1	0,5	0,8	0	3,3	0,6	0	2,5	0	2,3	1	0,3	0,8	0	1,11	1,047	3,28
9	0,1	0	0,6	0	0,1	1,1	0	0,3	0	0	0,2	0,2	0,1	0	0	0	0	0	0,5	0	0,157	0,268	1,05
10	0	0,5	0	0	0,1	0,3	0,3	0	0	2	0,1	0	0	0	0	0,1	0	0	0,1	0,2	0,176	0,436	1,95
11	0,1	0,1	0	0,1	0,6	0,1	0,2	0,2	0	0,5	0	0	0	0,6	0	0	0,4	0	0	0,2	0,158	0,211	0,64
12	0,4	0	0,1	0,3	0	0,2	0,1	0,3	0,2	0,4	0	0,3	0	1,6	0	0	0	0,1	0,2	0	0,209	0,35	1,56
13	0	0	0	0	0,6	0,2	0	0	0	0	0	0	0	0	0,1	0	0	0	0	0	0,044	0,13	0,56
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9E-04	0,004	0,02
15	0	0,1	0	0	0	0,2	0	0	0	0	0	0,1	0	0	0	0	0	0	0	0	0,02	0,059	0,25
16	0	0	0	0	0	0	0	0	0,1	0	0,1	0	0	0	0	0	0	0	0	0	0,014	0,035	0,14
17	0	0	0	0,4	0,1	0,1	0,9	0,2	0	0	0,5	0,1	0	0	0	3,3	0	0	1	0	0,322	0,753	3,25
18	1,4	0,2	0,8	0	2	0	0	0,2	0,6	0	1,8	1	0	0,6	0	0	0	0	0	0	0,438	0,636	1,96
19	0	0,5	0	0,2	0,2	0,2	0	0	0	0,1	0	0	0	0,5	0,3	0	0	0	0	0,4	0,127	0,185	0,52
20	0	0	0	0,3	0,1	0,2	0	0	0,1	0,7	3,3	0	0,6	0,5	0,2	0	0	0	0	0,1	0,308	0,745	3,34
21	0	0	0	0	0	0	0,2	0	0	0	0	0	0,1	0	0	0,2	0	0,3	0	0	0,042	0,092	0,33
22	0	0	0	0	0	0	0	0	0	0	0	0,1	0	0	0	0	0	0	0	0	0,006	0,021	0,09
23	0	0	0,1	0	0	0	0	0	0	0,1	0	0	0	0,6	0	0	0	0,8	0	0	0,082	0,214	0,81
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2E-07	9E-07	0
25	0	0,2	0	0	0	0	0	0	0	0	0	0	0,1	0	0	0	0	0	0	0	0,023	0,051	0,22
26	0	0	0	0	0	0	0,1	0	0	0	0	0	0	0	0,6	0	0,3	0,6	0,2	0	0,093	0,193	0,61
27	0	0,1	0	0	0	0	0	0	0,2	0	0	0	0	0	0	0	0	0,2	0	0	0,031	0,073	0,24
28	1,4	0	0	0	0	0	0	0	0,2	0	0,1	0	0	0	0	0,5	0,1	0	0	0	0,118	0,329	1,41
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,005	0,012	0,05
30	0	0	0	0	0,1	0	0	0	0	0	0	0	0	0	0,2	0	0	0	0	0	0,015	0,051	0,22
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,004	0,009	0,04
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,002	0,004	0,02

Table G.2 Cp deviations

Cases	Experiments																				Av_Cp	St_Cp	Max
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20			
1	1.7	0	0.9	0	0.5	2.2	2.9	0.7	0.6	2.4	0.1	0.5	0.9	0.5	0	0	2	0.9	0.1	0	0.839	0.903	2.9
2	5.1	0	1.8	1.3	2.4	0	1.3	0	3	0	5.3	0	0.7	0.4	0.4	2.1	0	1.8	5.9	0.2	1.583	1.888	5.9
3	0.4	0	0.4	3.5	0.5	0.8	0.1	0	2.2	1.1	2.1	0	2.7	0.4	0.7	3.6	0.6	0.6	0	3.5	1.173	1.281	3.6
4	1.9	2.1	1.6	0.5	0	0	2.1	3.7	0	5.4	1	2.9	0.2	2.6	0	0.4	1.9	0.1	0.2	1.5	1.406	1.466	5.4
5	3.9	0.2	0	0	0	0	0	0	1.4	0	0	0	0	0.2	0	0	2.1	2.5	0.3	0	0.526	1.074	3.9
6	0.3	0	0	1.2	0	0	1	1.3	0	0.2	0	0.1	0	0.1	0.8	0.2	0	0	0.3	0.1	0.276	0.436	1.3
7	1.2	0	2.4	0	0	0	1.5	0	0	0.3	0	3.1	2	0.4	0.1	1	1	0	0	0	0.656	0.945	3.1
8	0.8	2.3	1.4	1.2	2.2	1.2	1	0.3	0.8	0	5.5	0.7	1.3	2.5	0	1.6	0	0.3	3.7	0.1	1.351	1.38	5.5
9	0.1	0	0.6	0	0.2	1.1	0	0.3	0	0	0.1	0.2	0.1	0.1	0.1	0	0	0	0.5	0	0.168	0.267	1.1
10	0	1.6	0	0	0.1	0.3	1.1	0.5	0	2	0.2	0	0	0	0	0.1	0	0	0.3	0.5	0.329	0.559	2
11	0.1	0.1	0.2	0	2.3	0	0.2	0	0.1	1.8	2.4	0	3.4	2.4	0	0	1.8	0.4	0.3	0	0.773	1.105	3.4
12	0	0	0.1	0.3	0.5	0.2	0.1	0	0	0.5	0	0.1	0	2.8	0	0.1	0	0.3	0.1	0	0.255	0.624	2.8
13	0	0	0	0	0.6	0.2	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0.044	0.13	0.6
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9E-04	0.004	0
15	0	0.1	0	0	0	0.2	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0.02	0.059	0.2
16	0	0	0	0	0	0	0	0	0.1	0	0.1	0	0	0	0	0	0	0	0	0	0.015	0.036	0.1
17	0	0	0.1	0.4	0.1	0.1	0.9	0.4	0.3	0	0.5	0.1	0.9	0.1	0	0	0	0	1	0	0.234	0.336	1
18	3.7	1.4	0.8	2.7	4.4	0	0	1.1	0.4	0	4.5	1	0	2	0.2	0	0	0	0	0	1.111	1.533	4.5
19	0.5	2.2	0.1	0.2	0.9	0.1	0	0	0	0	0	0	0	0.5	0.3	0	0	0	0	2.1	0.344	0.669	2.2
20	0	3.3	0	2.8	0.1	0.3	0	0	0.1	4.7	5.1	0	0.6	0.5	0.2	0	0	2.1	0	0	0.991	1.66	5.1
21	0	0	0	0	0	0	0.2	0	0	0	0	0	0.1	0	0	0.2	0	0.3	0	0	0.042	0.092	0.3
22	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0.006	0.021	0.1
23	0	0	0.1	0	0	0	0	0	0	0.1	0	0	0	0.6	0	0	0	0.8	0	0	0.082	0.214	0.8
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2E-07	8E-07	0
25	0.1	0	0.1	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0.2	0.2	0	0	0.044	0.07	0.2
26	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.013	0.02	0.1
27	0.1	0.4	0	0	0	0	0	0	0.2	0.3	0	0	0	0	0	0	0	0.5	0	0	0.079	0.154	0.5
28	0	0.2	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0.1	0.3	0	0	0	0.035	0.082	0.3
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.002	0.005	0
30	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0.015	0.051	0.2
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.004	0.009	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.003	0.007	0

APPENDIX H

ALIAS TABLE

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Alias Structure (up to order 2)

CP4
- CP3*CP2 - CP1*AX4 - AX3*AX2 - AX1*AY4 - AY3*AY2 - AY1*AZ4
- AZ3*AZ2 - AZ1*PX4 - PX3*PX2 - PX1*PY4 - PY3*PY2 - PY1*PZ4 -
PZ3*PZ2

CP3
- CP4*CP2 - CP1*AX3 - AX4*AX2 - AX1*AY3 - AY4*AY2 - AY1*AZ3
- AZ4*AZ2 - AZ1*PX3 - PX4*PX2 - PX1*PY3 - PY4*PY2 - PY1*PZ3 -
PZ4*PZ2

CP2
- CP4*CP3 - CP1*AX2 - AX4*AX3 - AX1*AY2 - AY4*AY3 - AY1*AZ2
– AZ4*AZ3 - AZ1*PX2 - PX4*PX3 - PX1*PY2 - PY4*PY3 - PY1*PZ2 -
PZ4*PZ3

CP1
- CP4*AX4 - CP3*AX3 - CP2*AX2 - AX1*AY1 - AY4*AZ4 - AY3*AZ3
- AY2*AZ2 - AZ1*PX1 - PX4*PY4 - PX3*PY3 - PX2*PY2 - PY1*PZ1

AX4
- CP4*CP1 - CP3*AX2 - CP2*AX3 - AX1*AZ4 - AY4*AY1 - AY3*AZ2
- AY2*AZ3 - AZ1*PY4 - PX4*PX1 - PX3*PY2 - PX2*PY3 - PZ4*PZ1

AX3
- CP4*AX2 - CP3*CP1 - CP2*AX4 - AX1*AZ3 - AY4*AZ2 - AY3*AY1
- AY2*AZ4 - AZ1*PY3 - PX4*PY2 - PX3*PX1 - PX2*PY4 - PZ3*PZ1

AX2
- CP4*AX3 - CP3*AX4 - CP2*CP1 - AX1*AZ2 - AY4*AZ3 - AY3*AZ4
- AY2*AY1 - AZ1*PY2 - PX4*PY3 - PX3*PY4 - PX2*PX1 - PZ2*PZ1

AX1
- CP4*AY4 - CP3*AY3 - CP2*AY2 - CP1*AY1 - AX4*AZ4 - AX3*AZ3
- AX2*AZ2 - AZ1*PY1 - PX4*PZ4 - PX3*PZ3 - PX2*PZ2 - PX1*PZ1

AY4
- CP4*AX1 - CP3*AY2 - CP2*AY3 - CP1*AZ4 - AX4*AY1 - AX3*AZ2
- AX2*AZ3 - AZ1*PZ4 - PX4*PY1 - PX3*PZ2 - PX2*PZ3 - PY4*PZ1

AY3
- CP4*AY2 - CP3*AX1 - CP2*AY4 - CP1*AZ3 - AX4*AZ2 - AX3*AY1
- AX2*AZ4 - AZ1*PZ3 - PX4*PZ2 - PX3*PY1 - PX2*PZ4 - PY3*PZ1
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AY2
- CP4*AY3 - CP3*AY4 - CP2*AX1 - CP1*AZ2 - AX4*AZ3 - AX3*AZ4
- AX2*AY1 - AZ1*PZ2 - PX4*PZ3 - PX3*PZ4 - PX2*PY1 - PY2*PZ1

AY1
- CP4*AZ4 - CP3*AZ3 - CP2*AZ2 - CP1*AX1 - AX4*AY4 - AX3*AY3
- AX2*AY2 - AZ1*PZ1 - PX1*PY1 - PY4*PZ4 - PY3*PZ3 - PY2*PZ2

AZ4
- CP4*AY1 - CP3*AZ2 - CP2*AZ3 - CP1*AY4 - AX4*AX1 - AX3*AY2
- AX2*AY3 - PX4*PZ1 - PX1*PZ4 - PY4*PY1 - PY3*PZ2 - PY2*PZ3

AZ3
- CP4*AZ2 - CP3*AY1 - CP2*AZ4 - CP1*AY3 - AX4*AY2 - AX3*AX1
- AX2*AY4 - PX3*PZ1 - PX1*PZ3 - PY4*PZ2 - PY3*PY1 - PY2*PZ4
AZ2
- CP4*AZ3 - CP3*AZ4 - CP2*AY1 - CP1*AY2 - AX4*AY3 - AX3*AY4
- AX2*AX1 - PX2*PZ1 - PX1*PZ2 - PY4*PZ3 - PY3*PZ4 - PY2*PY1
AZ1
- CP4*PX4 - CP3*PX3 - CP2*PX2 - CP1*PX1 - AX4*PY4 - AX3*PY3
- AX2*PY2 - AX1*PY1 - AY4*PZ4 - AY3*PZ3 - AY2*PZ2 - AY1*PZ1

PX4
- CP4*AZ1 - CP3*PX2 - CP2*PX3 - CP1*PY4 - AX4*PX1 - AX3*PY2
- AX2*PY3 - AX1*PZ4 - AY4*PY1 - AY3*PZ2 - AY2*PZ3 - AZ4*PZ1

PX3
- CP4*PX2 - CP3*AZ1 - CP2*PX4 - CP1*PY3 - AX4*PY2 - AX3*PX1
- AX2*PY4 - AX1*PZ3 - AY4*PZ2 - AY3*PY1 - AY2*PZ4 - AZ3*PZ1
PX2
- CP4*PX3 - CP3*PX4 - CP2*AZ1 - CP1*PY2 - AX4*PY3 - AX3*PY4
- AX2*PX1 - AX1*PZ2 - AY4*PZ3 - AY3*PZ4 - AY2*PY1 - AZ2*PZ1

PX1
- CP4*PY4 - CP3*PY3 - CP2*PY2 - CP1*AZ1 - AX4*PX4 - AX3*PX3
- AX2*PX2 - AX1*PZ1 - AY1*PY1 - AZ4*PZ4 - AZ3*PZ3 - AZ2*PZ2

PY4
- CP4*PX1 - CP3*PY2 - CP2*PY3 - CP1*PX4 - AX4*AZ1 - AX3*PX2
- AX2*PX3 - AY4*PZ1 - AY1*PZ4 - AZ4*PY1 - AZ3*PZ2 - AZ2*PZ3

PY3
- CP4*PY2 - CP3*PX1 - CP2*PY4 - CP1*PX3 - AX4*PX2 - AX3*AZ1
- AX2*PX4 - AY3*PZ1 - AY1*PZ3 - AZ4*PZ2 - AZ3*PY1 - AZ2*PZ4

PY2
- CP4*PY3 - CP3*PY4 - CP2*PX1 - CP1*PX2 - AX4*PX3 - AX3*PX4
- AX2*AZ1 - AY2*PZ1 - AY1*PZ2 - AZ4*PZ3 - AZ3*PZ4 - AZ2*PY1

PY1
- CP4*PZ4 - CP3*PZ3 - CP2*PZ2 - CP1*PZ1 - AX1*AZ1 - AY4*PX4
- AY3*PX3 - AY2*PX2 - AY1*PX1 - AZ4*PY4 - AZ3*PY3 - AZ2*PY2

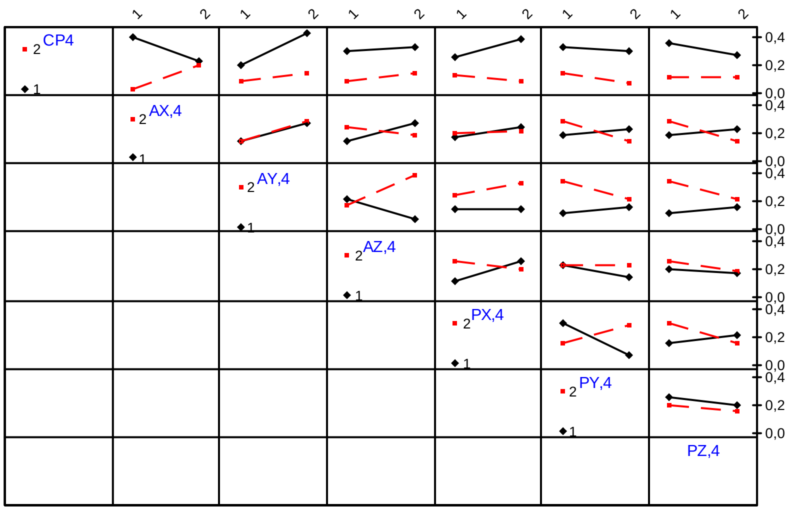
PZ4
- CP4*PY1 - CP3*PZ2 - CP2*PZ3 - AX4*PZ1 - AX1*PX4 - AY4*AZ1
- AY3*PX2 - AY2*PX3 - AY1*PY4 - AZ4*PX1 - AZ3*PY2 - AZ2*PY3
PZ3
- CP4*PZ2 - CP3*PY1 - CP2*PZ4 - AX3*PZ1 - AX1*PX3 - AY4*PX2
- AY3*AZ1 - AY2*PX4 - AY1*PY3 - AZ4*PY2 - AZ3*PX1 - AZ2*PY4

PZ2
- CP4*PZ3 - CP3*PZ4 - CP2*PY1 - AX2*PZ1 - AX1*PX2 - AY4*PX3
- AY3*PX4 - AY2*AZ1 - AY1*PY2 - AZ4*PY3 - AZ3*PY4 - AZ2*PX1
PZ1
- CP1*PY1 - AX4*PZ4 - AX3*PZ3 - AX2*PZ2 - AX1*PX1 - AY4*PY4 -
AY3*PY3 - AY2*PY2 - AY1*AZ1 - AZ4*PX4 - AZ3*PX3 - AZ2*PX2
```

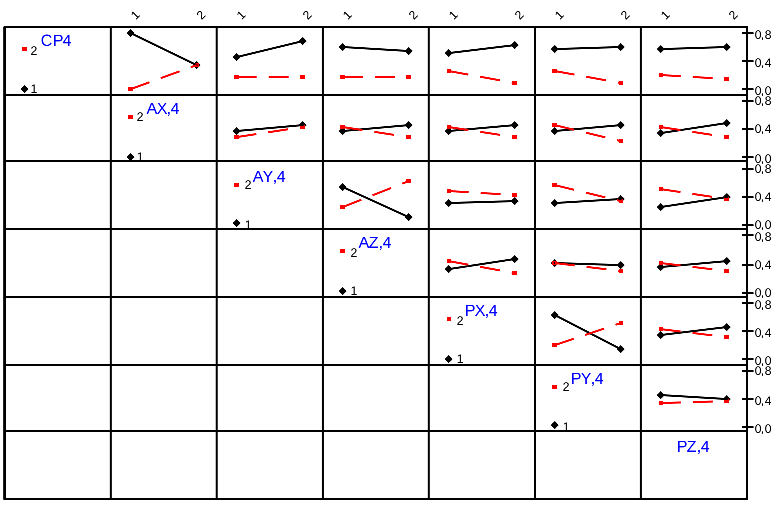
APPENDIX I

INTERACTION PLOTS OF FACTORS

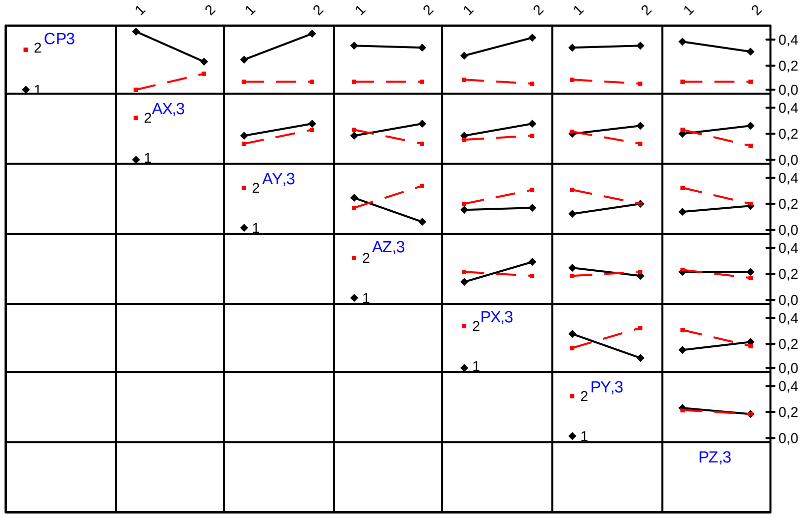
Interaction Plot - Data Means for Av_QFD at w orkcenter 4



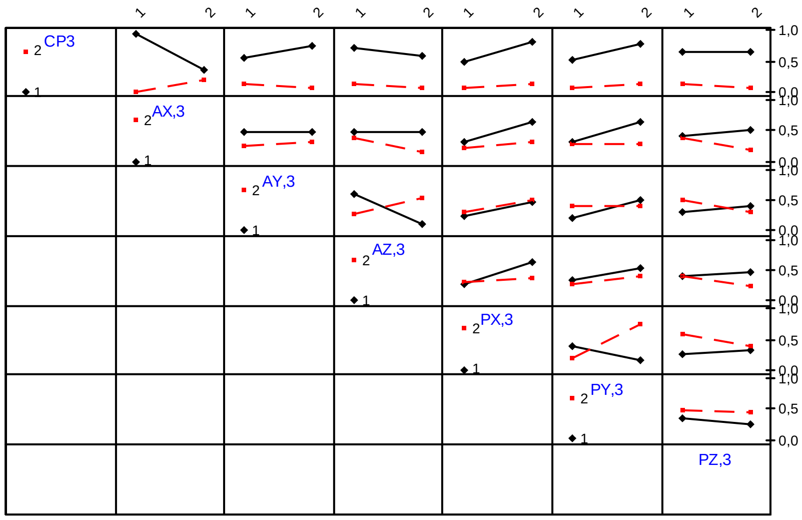
Interaction Plot - Data Means for Av_Cp at w orkcenter 4



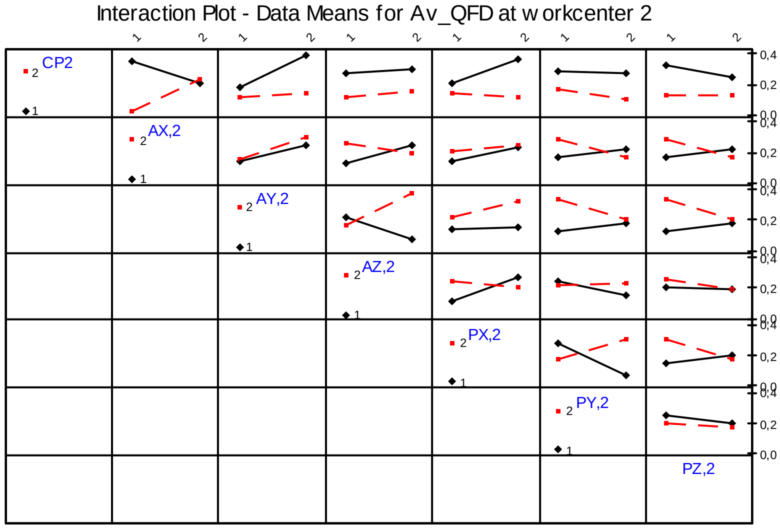
Interaction Plot - Data Means for Av_QFD at w orkcenter 3



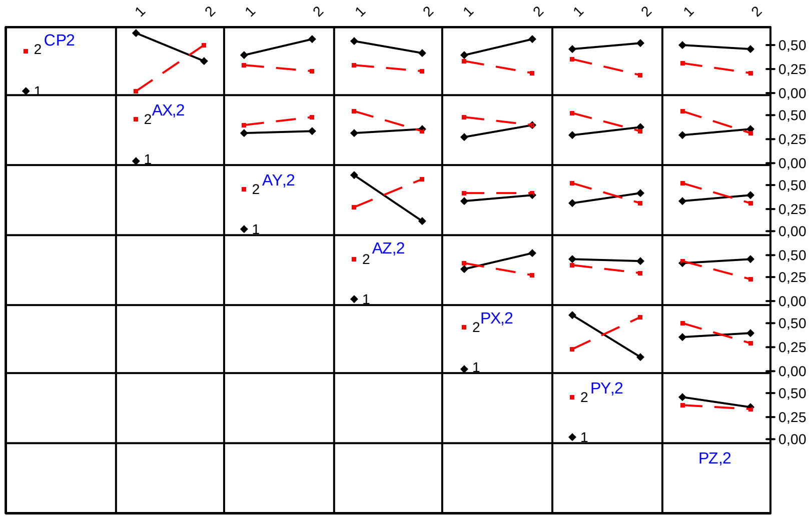
Interaction Plot - Data Means for Av_Cp at w orkcenter 3



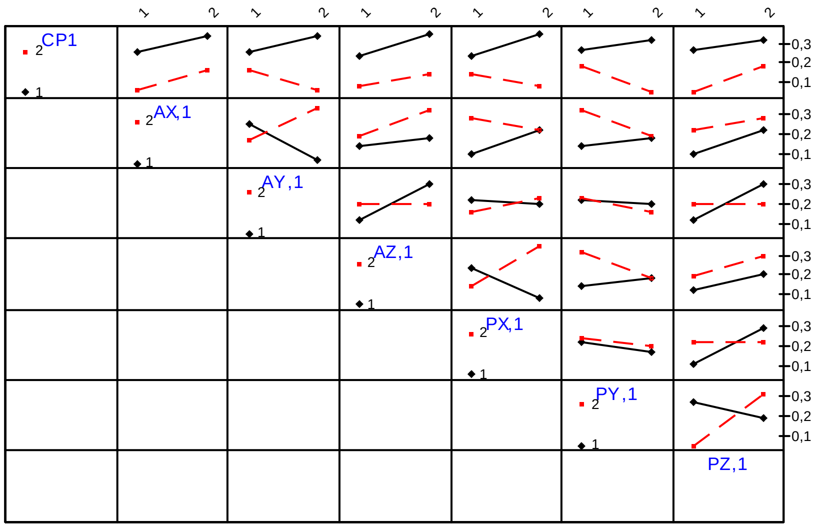
Interaction Plot - Data Means for Av_QFD at w orkcenter 2



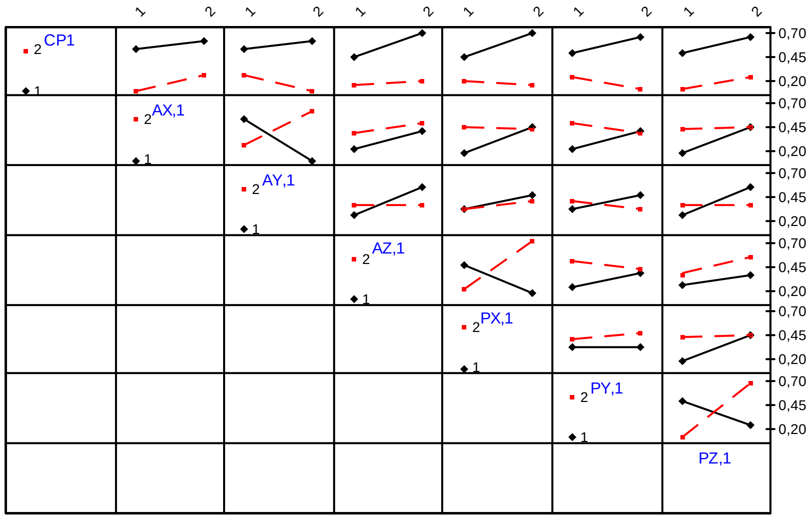
Interaction Plot - Data Means for Av_Cp at w orkcenter 2



Interaction Plot - Data Means for Av_QFD at workcenter 1



Interaction Plot - Data Means for Av_Cp at w orkcenter 1



APPENDIX J

ANOVA ASSUMPTIONS

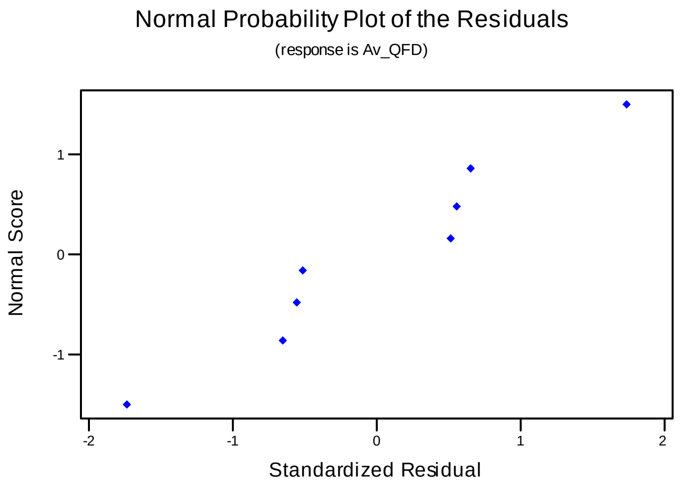


Figure J. 1 Normal Probability plot of the residuals for the response Av_ QFD

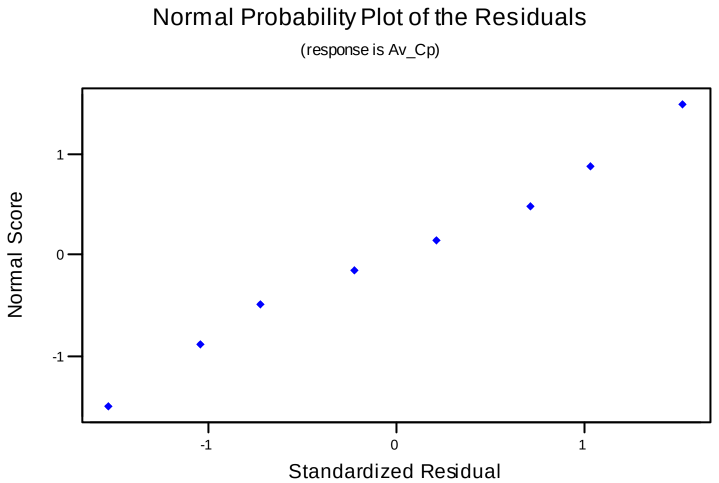


Figure J.2 Normal Probability Plot of the residuals for the response Av_Cp

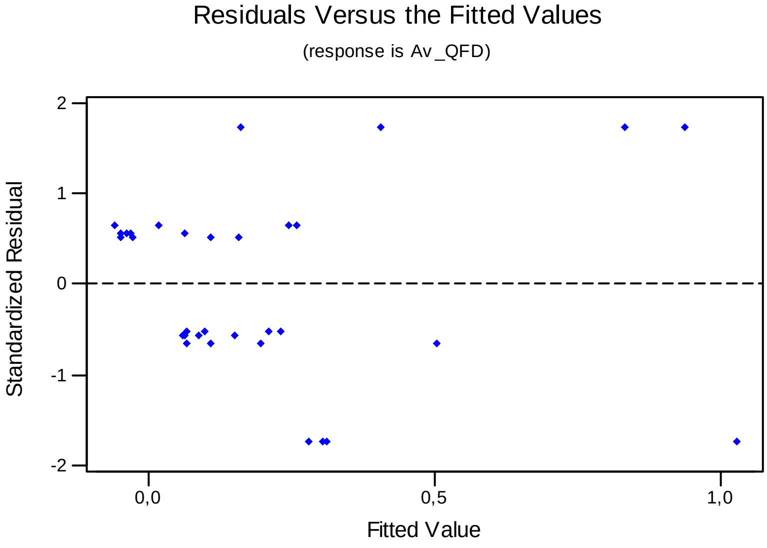


Figure J.3 Residuals-Fits graph of the response Av_QFD

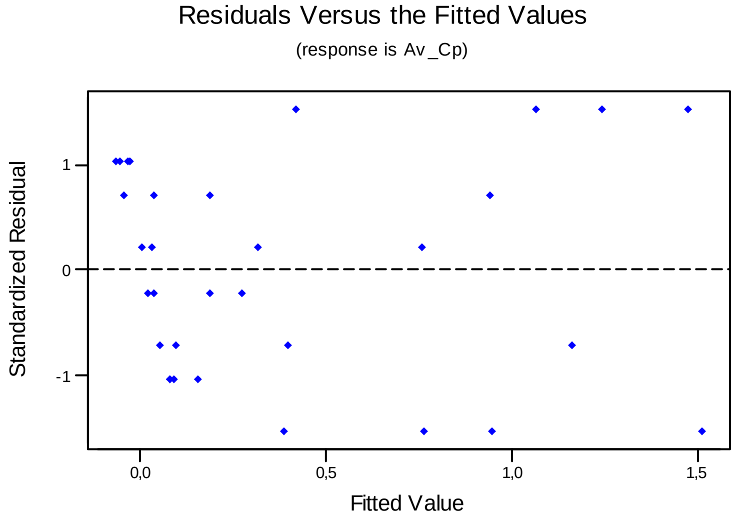


Figure J.4 Residuals-Fits graph of the response Av_Cp

Table J.1 Durbin-Watson test statistics

```
                 For the responses

Av_QFD;   Durbin-Watson statistic (d) = 2.64
Av_Cp;    Durbin-Watson statistic (d) = 2.70
```

APPENDIX K

ANOVA TABLES

General Linear Model: Av_QFD; Av_Cp versus CP 4; CP 3; ...

Factor	Type	Levels	Values
CP4	fixed	2	1 2
CP3	fixed	2	1 2
CP2	fixed	2	1 2
CP1	fixed	2	1 2
AX4	fixed	2	1 2
AX3	fixed	2	1 2
AX2	fixed	2	1 2
AX1	fixed	2	1 2
AY4	fixed	2	1 2
AY3	fixed	2	1 2
AY2	fixed	2	1 2
AY1	fixed	2	1 2
AZ4	fixed	2	1 2
AZ3	fixed	2	1 2
AZ2	fixed	2	1 2
AZ1	fixed	2	1 2
PX4	fixed	2	1 2
PX3	fixed	2	1 2
PX2	fixed	2	1 2
PX1	fixed	2	1 2
PY4	fixed	2	1 2
PY3	fixed	2	1 2
PY2	fixed	2	1 2
PY1	fixed	2	1 2
PZ4	fixed	2	1 2
PZ3	fixed	2	1 2
PZ2	fixed	2	1 2
PZ1	fixed	2	1 2

Analysis of Variance for Av_QFD

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	28	2,3311	2,3311	0,08325	0,78	0,700
Residual Error	3	0,3199	0,3199	0,10662		
Total	31	2,6510				

Analysis of Variance for Av_QFD, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
CP4	1	0,3648	0,3648	0,3648	3,42	0,161
CP3	1	0,6350	0,6350	0,6350	5,96	0,092
CP2	1	0,1856	0,1856	0,1856	1,74	0,279
CP1	1	0,2461	0,2461	0,2461	2,31	0,226
AX4	1	0,0012	0,0012	0,0012	0,01	0,922
AX3	1	0,0368	0,0368	0,0368	0,34	0,598
AX2	1	0,0100	0,0100	0,0100	0,09	0,779
AX1	1	0,0918	0,0918	0,0918	0,86	0,422

AY4	1	0,1598	0,1598	0,1598	1,50	0,308
AY3	1	0,0831	0,0831	0,0831	0,78	0,442
AY2	1	0,1581	0,1581	0,1581	1,48	0,310
AY1	1	0,0002	0,0002	0,0002	0,00	0,969
AZ4	1	0,0154	0,0154	0,0154	0,14	0,729
AZ3	1	0,0003	0,0003	0,0003	0,00	0,959
AZ2	1	0,0158	0,0158	0,0158	0,15	0,726
AZ1	1	0,0618	0,0618	0,0618	0,58	0,502
PX4	1	0,0161	0,0161	0,0161	0,15	0,723
PX3	1	0,0333	0,0333	0,0333	0,31	0,615
PX2	1	0,0316	0,0316	0,0316	0,30	0,624
PX1	1	0,0017	0,0017	0,0017	0,02	0,907
PY4	1	0,0252	0,0252	0,0252	0,24	0,660
PY3	1	0,0029	0,0029	0,0029	0,03	0,879
PY2	1	0,0219	0,0219	0,0219	0,21	0,681
PY1	1	0,0151	0,0151	0,0151	0,14	0,732
PZ4	1	0,0130	0,0130	0,0130	0,12	0,750
PZ3	1	0,0094	0,0094	0,0094	0,09	0,786
PZ2	1	0,0084	0,0084	0,0084	0,08	0,797
PZ1	1	0,0868	0,0868	0,0868	0,81	0,433
Error	3	0,3199	0,3199	0,1066		
Total	31	2,6510				

Analysis of Variance for Av_Cp

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	28	7,3999	7,3999	0,26428	4,95	0,106
Residual Error	3	0,1602	0,1602	0,05339		
Total	31	7,5601				

Analysis of Variance for Av_Cp, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
CP4	1	1,28384	1,28384	1,28384	24,05	0,016
CP3	1	2,43091	2,43091	2,43091	45,53	0,007
CP2	1	0,40233	0,40233	0,40233	7,54	0,071
CP1	1	1,25537	1,25537	1,25537	23,51	0,017
AX4	1	0,02750	0,02750	0,02750	0,51	0,525
AX3	1	0,30936	0,30936	0,30936	5,79	0,095
AX2	1	0,08577	0,08577	0,08577	1,61	0,294
AX1	1	0,11936	0,11936	0,11936	2,24	0,232
AY4	1	0,10251	0,10251	0,10251	1,92	0,260
AY3	1	0,02087	0,02087	0,02087	0,39	0,576
AY2	1	0,02329	0,02329	0,02329	0,44	0,556
AY1	1	0,00732	0,00732	0,00732	0,14	0,736
AZ4	1	0,00880	0,00880	0,00880	0,16	0,712
AZ3	1	0,09005	0,09005	0,09005	1,69	0,285
AZ2	1	0,06812	0,06812	0,06812	1,28	0,341
AZ1	1	0,17410	0,17410	0,17410	3,26	0,169
PX4	1	0,00331	0,00331	0,00331	0,06	0,819
PX3	1	0,33928	0,33928	0,33928	6,35	0,086
PX2	1	0,00407	0,00407	0,00407	0,08	0,800
PX1	1	0,09900	0,09900	0,09900	1,85	0,267
PY4	1	0,05541	0,05541	0,05541	1,04	0,383
PY3	1	0,20643	0,20643	0,20643	3,87	0,144
PY2	1	0,02467	0,02467	0,02467	0,46	0,545
PY1	1	0,00810	0,00810	0,00810	0,15	0,723
PZ4	1	0,00028	0,00028	0,00028	0,01	0,947
PZ3	1	0,02147	0,02147	0,02147	0,40	0,571
PZ2	1	0,05476	0,05476	0,05476	1,03	0,386
PZ1	1	0,17360	0,17360	0,17360	3,25	0,169
Error	3	0,16018	0,16018	0,05339		
Total	31	7,56008				

APPENDIX L

RESPONSE TABLES

Response Table for Means (Av_QFD)

Level	CP4	CP3	CP2	CP1	AX4	AX3
1	0,314459	0,348566	0,283853	0,295395	0,213850	0,241588
2	0,100927	0,066821	0,131533	0,119992	0,201536	0,173798
Delta	0,213532	0,281745	0,152321	0,175403	0,012314	0,067790
Rank	2	1	4	3	26	11

Level	AX2	AX1	AY4	AY3	AY2	AY1
1	0,189985	0,154145	0,137033	0,156730	0,137398	0,205229
2	0,225401	0,261241	0,278353	0,258656	0,277988	0,210157
Delta	0,035416	0,107096	0,141320	0,101927	0,140590	0,004928
Rank	21	7	5	9	6	28

Level	AZ4	AZ3	AZ2	AZ1	PX4	PX3
1	0,185742	0,210894	0,185468	0,163756	0,185249	0,175453
2	0,229644	0,204492	0,229918	0,251630	0,230137	0,239933
Delta	0,043901	0,006402	0,044450	0,087874	0,044888	0,064480
Rank	18	27	17	10	16	12

Level	PX2	PX1	PY4	PY3	PY2	PY1
1	0,176284	0,200346	0,235762	0,217237	0,233832	0,229389
2	0,239102	0,215040	0,179625	0,198149	0,181554	0,185998
Delta	0,062819	0,014694	0,056137	0,019088	0,052277	0,043391
Rank	13	25	14	24	15	19

Level	PZ4	PZ3	PZ2	PZ1
1	0,227847	0,224800	0,223885	0,155621
2	0,187540	0,190587	0,191502	0,259765
Delta	0,040307	0,034213	0,032383	0,104144
Rank	20	22	23	8

Response Table for Means(Av-Cp)

Level	CP4	CP3	CP2	CP1	AX4	AX3
1	0,588441	0,663760	0,500270	0,586207	0,417454	0,486465
2	0,187841	0,112522	0,276012	0,190075	0,358827	0,289817
Delta	0,400600	0,551238	0,224258	0,396132	0,058627	0,196647
Rank	2	1	4	3	18	6

Level	AX2	AX1	AY4	AY3	AY2	AY1
1	0,336369	0,327067	0,331543	0,362601	0,361162	0,403261
2	0,439913	0,449214	0,444739	0,413681	0,415120	0,373021
Delta	0,103544	0,122147	0,113197	0,051081	0,053957	0,030240
Rank	14	10	11	22	20	25

Level	AZ4	AZ3	AZ2	AZ1	PX4	PX3
1	0,404727	0,441188	0,434280	0,314380	0,398317	0,285172
2	0,371555	0,335094	0,342002	0,461902	0,377965	0,491109
Delta	0,033173	0,106094	0,092279	0,147522	0,020353	0,205937
Rank	23	13	15	8	27	5

Level	PX2	PX1	PY4	PY3	PY2	PY1
1	0,376861	0,332518	0,429754	0,307823	0,415909	0,372232
2	0,399421	0,443763	0,346528	0,468459	0,360373	0,404050
Delta	0,022560	0,111245	0,083225	0,160637	0,055537	0,031818
Rank	26	12	16	7	19	24

Level	PZ4	PZ3	PZ2	PZ1
1	0,391109	0,414045	0,429507	0,314486
2	0,385172	0,362237	0,346775	0,461796
Delta	0,005937	0,051807	0,082732	0,147310
Rank	28	21	17	9

APPENDIX M

MAIN EFFECTS PLOTS

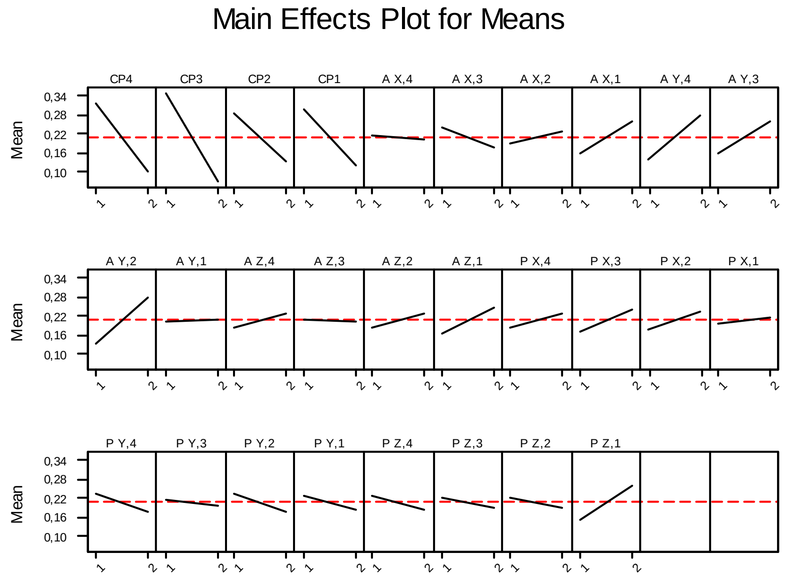


Figure M. 1 Main effects plot for average deviations of method QFD

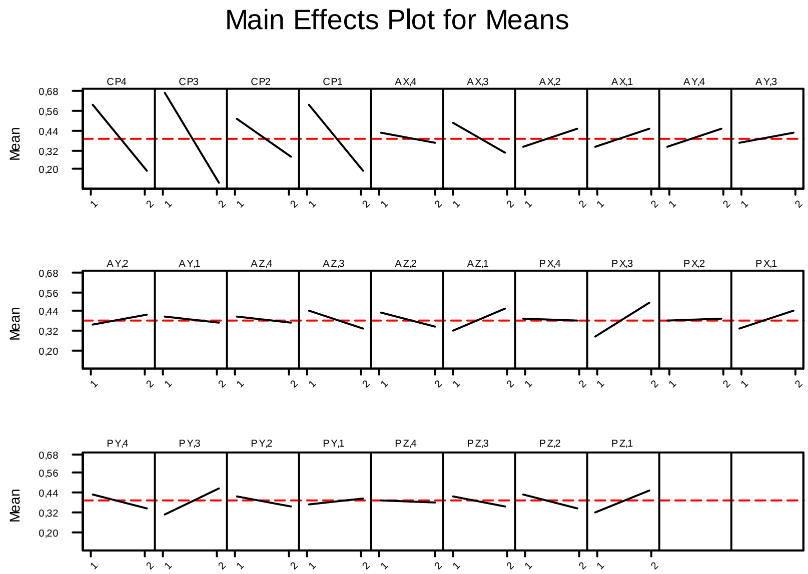


Figure M.2 Main effects plot for average deviations of method Cp

APPENDIX N

ANCOVA ASSUMPTIONS

Table N.1 Correlation matrix of the factors

	CP4	CP3	CP2	CP1	AX4	AX3	AX2	AX1
CP3	0,000							
	1,000							
CP2	0,000	0,000						
	1,000	1,000						
CP1	0,000	0,000	0,000					
	1,000	1,000	1,000					
AX4	0,000	0,000	0,000	0,000				
	1,000	1,000	1,000	1,000				
AX3	0,000	0,000	0,000	0,000	0,000			
	1,000	1,000	1,000	1,000	1,000			
AX2	0,000	0,000	0,000	0,000	0,000	0,000		
	1,000	1,000	1,000	1,000	1,000	1,000		
AX1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	
AY4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AY3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AY2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AY1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AZ4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AZ3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AZ2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AZ1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PX4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PX3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1.000	1,000	1,000	1,000	1,000
PY3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PY2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000

PY1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
X_{pr}^2	-0,160	-0,223	0,036	***-0,417***	0,083	0,063	0,288	0,111
	0,381	0,219	0,845	0,018	0,652	0,730	0,110	0,544

	AY4	AY3	AY2	AY1	AZ4	AZ3	AZ2	AZ1
AY3	0,000							
	1,000							
AY2	0,000	0,000						
	1,000	1,000						
AY1	0,000	0,000	0,000					
	1,000	1,000	1,000					
AZ4	0,000	0,000	0,000	0,000				
	1,000	1,000	1,000	1,000				
AZ3	0,000	0,000	0,000	0,000	0,000			
	1,000	1,000	1,000	1,000	1,000			
AZ2	0,000	0,000	0,000	0,000	0,000	0,000		
	1,000	1,000	1,000	1,000	1,000	1,000		
AZ1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	
PX4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PX3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PX2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PX1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PY4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PY3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PY2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PY1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
X_{pr}^2	0,225	0,154	0,153	-0,073	0,057	0,020	-0,128	0,284
	0,215	0,399	0,402	0,693	0,756	0,914	0,487	0,115

	PX4	PX3	PX2	PX1	PY4	PY3	PY2	PY1
PX3	0,000							
	1,000							

PX2	0,000	0,000						
	1,000	1,000						
PX1	0,000	0,000	0,000					
	1,000	1,000	1,000					
PY4	0,000	0,000	0,000	0,000				
	1,000	1,000	1,000	1,000				
PY3	0,000	0,000	0,000	0,000	0,000			
	1,000	1,000	1,000	1,000	1,000			
PY2	0,000	0,000	0,000	0,000	0,000	0,000		
	1,000	1,000	1,000	1,000	1,000	1,000		
PY1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	
PZ4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
X_{pr}^2	-0,042	0,108	-0,027	0,194	***-0,321***	-0,059	***-0,331***	-0,130
	0,821	0,555	0,883	0,286	0,074	0,749	0,064	0,477

	PZ4	PZ3	PZ2	PZ1
PZ3	0,000			
	1,000			
PZ2	0,000	0,000		
	1,000	1,000		
PZ1	0,000	0,000	0,000	
	1,000	1,000	1,000	
X_{pr}^2	-0,122	-0,090	-0,041	0,237
	0,505	0,623	0,824	0,191

Cell Contents: Pearson correlation
P-Value

Table N.2 Correlation matrix of the factors and PC1

	CP4	CP3	CP2	AX4	AX3	AX2	AX1	AY4
CP3	0,000							
	1,000							
CP2	0,000	0,000						
	1,000	1,000						
AX4	0,000	0,000	0,000					
	1,000	1,000	1,000					
AX3	0,000	0,000	0,000	0,000				
	1,000	1,000	1,000	1,000				
AX2	0,000	0,000	0,000	0,000	0,000			
	1,000	1,000	1,000	1,000	1,000			
AX1	0,000	0,000	0,000	0,000	0,000	0,000		
	1,000	1,000	1,000	1,000	1,000	1,000		
AY4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	
AY3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AY2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000

AY1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AZ4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AZ3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AZ2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
AZ1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PX4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PX3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PX2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PX1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PY3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PY1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PC1	-0,160	-0,223	0,036	0,083	0,063	0,218	0,111	0,225
	0,382	0,220	0,845	0,652	0,731	0,130	0,544	0,215

	AY3	AY2	AY1	AZ4	AZ3	AZ2	AZ1	PX4
AY2	0,000							
	1,000							
AY1	0,000	0,000						
	1,000	1,000						
AZ4	0,000	0,000	0,000					
	1,000	1,000	1,000					
AZ3	0,000	0,000	0,000	0,000				
	1,000	1,000	1,000	1,000				
AZ2	0,000	0,000	0,000	0,000	0,000			
	1,000	1,000	1,000	1,000	1,000			
AZ1	0,000	0,000	0,000	0,000	0,000	0,000		
	1,000	1,000	1,000	1,000	1,000	1,000		
PX4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	
PX3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PX2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PX1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PY3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000

PY1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PZ1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PC1	0,154	0,153	-0,072	0,057	0,020	-0,127	0,214	-0,042
	0,399	0,403	0,693	0,756	0,914	0,487	0,136	0,821

	PX3	PX2	PX1	PY3	PY1	PZ4	PZ3	PZ2
PX2	0,000							
	1,000							
PX1	0,000	0,000						
	1,000	1,000						
PY3	0,000	0,000	0,000					
	1,000	1,000	1,000					
PY1	0,000	0,000	0,000	0,000				
	1,000	1,000	1,000	1,000				
PZ4	0,000	0,000	0,000	0,000	0,000			
	1,000	1,000	1,000	1,000	1,000			
PZ3	0,000	0,000	0,000	0,000	0,000	0,000		
	1,000	1,000	1,000	1,000	1,000	1,000		
PZ2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	
PZ1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
PC1	0,108	-0,027	0,194	-0,059	-0,130	-0,122	-0,090	-0,041
	0,555	0,883	0,287	0,749	0,477	0,505	0,623	0,824

	PZ1
PC1	0,237
	0,191

Cell Contents: Pearson correlation
P-Value

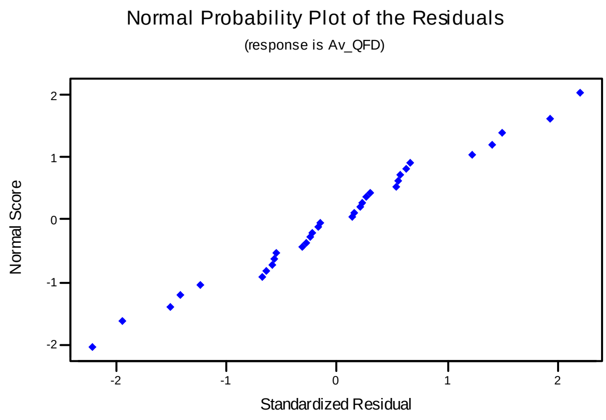


Figure N.1 Normal Probability Plot of the residuals of ANCOVA model

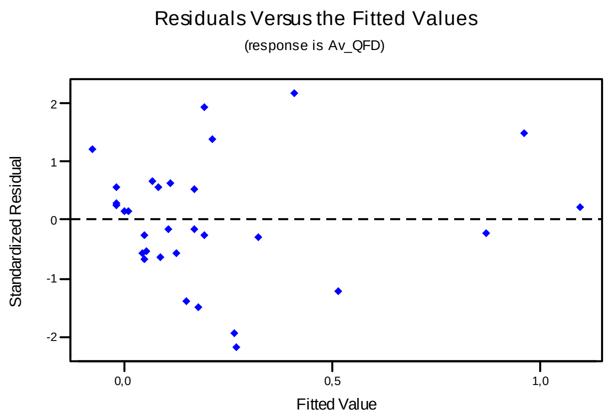


Figure N.2 Residuals-Fits graph of ANCOVA model

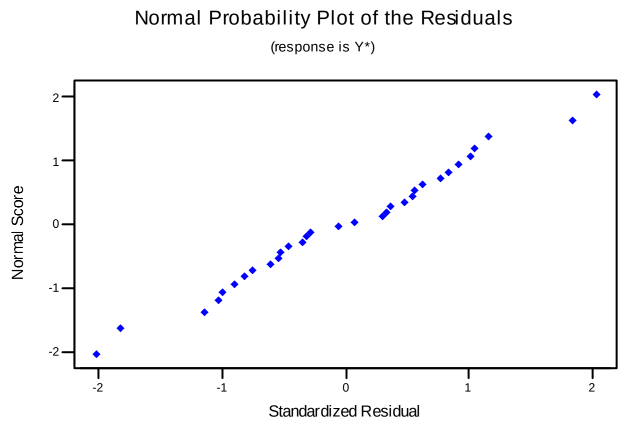


Figure N.3 Normal Probability Plot of the residuals of ANCOVA model for Y*

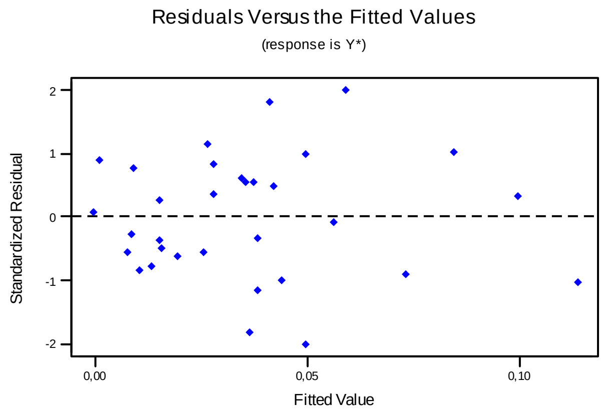


Figure N.4 Residuals-Fits graph of ANCOVA model for Y*

APPENDIX O

ANCOVA ANALYSIS

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General Linear Model: Y* versus CP4; CP3; ...
Factor   Type   Levels Values
CP4      fixed       2 1 2
CP3      fixed       2 1 2
CP2      fixed       2 1 2
AX4      fixed       2 1 2
AX3      fixed       2 1 2
AX2      fixed       2 1 2
AX1      fixed       2 1 2
AY4      fixed       2 1 2
AY3      fixed       2 1 2
AY2      fixed       2 1 2
AY1      fixed       2 1 2
AZ4      fixed       2 1 2
AZ3      fixed       2 1 2
AZ2      fixed       2 1 2
AZ1      fixed       2 1 2
PX4      fixed       2 1 2
PX3      fixed       2 1 2
PX2      fixed       2 1 2
PX1      fixed       2 1 2
PY3      fixed       2 1 2
PY1      fixed       2 1 2
PZ4      fixed       2 1 2
PZ3      fixed       2 1 2
PZ2      fixed       2 1 2
PZ1      fixed       2 1 2

Analysis of Variance for Y*, using Adjusted SS for Tests
Source    DF     Seq SS     Adj SS     Adj MS      F      P
PC1        1  0,0138588  0,0059948  0,0059948  15,25  0,011
CP4        1  0,0020070  0,0019010  0,0019010   4,84  0,079
CP3        1  0,0034739  0,0028907  0,0028907   7,35  0,042
CP2        1  0,0011978  0,0012366  0,0012366   3,15  0,136
AX4        1  0,0000028  0,0000089  0,0000089   0,02  0,886
AX3        1  0,0001970  0,0002236  0,0002236   0,57  0,485
AX2        1  0,0000253  0,0000705  0,0000705   0,18  0,689
AX1        1  0,0000539  0,0000327  0,0000327   0,08  0,784
AY4        1  0,0000724  0,0000225  0,0000225   0,06  0,820
AY3        1  0,0000062  0,0000000  0,0000000   0,00  0,995
AY2        1  0,0001625  0,0000931  0,0000931   0,24  0,647
AY1        1  0,0000857  0,0001126  0,0001126   0,29  0,615
AZ4        1  0,0000082  0,0000031  0,0000031   0,01  0,933
AZ3        1  0,0000311  0,0000355  0,0000355   0,09  0,776
AZ2        1  0,0006633  0,0007517  0,0007517   1,91  0,225
AZ1        1  0,0001933  0,0002510  0,0002510   0,64  0,460
PX4        1  0,0001346  0,0001419  0,0001419   0,36  0,574
PX3        1  0,0000208  0,0000278  0,0000278   0,07  0,801
PX2        1  0,0007136  0,0007214  0,0007214   1,84  0,233
PX1        1  0,0000000  0,0000015  0,0000015   0,00  0,953
PY3        1  0,0000448  0,0000486  0,0000486   0,12  0,739
PY1        1  0,0000226  0,0000272  0,0000272   0,07  0,803
PZ4        1  0,0000000  0,0000003  0,0000003   0,00  0,978
PZ3        1  0,0000271  0,0000296  0,0000296   0,08  0,795
```

```
PZ2        1  0,0000000  0,0000000  0,0000000    0,00  0,996
PZ1        1  0,0000322  0,0000322  0,0000322    0,08  0,786
Error      5  0,0019653  0,0019653  0,0003931
Total     31  0,0250001

Term           Coef   SE Coef        T      P
Constant  0,016330  0,006135     2,66  0,045
PC1       0,000065  0,000017     3,91  0,011

Unusual Observations for Y*
Obs        Y*        Fit      SE Fit  Residual   St Resid
  2  0,075902  0,058782    0,017910  0,017120      2,01R
  6  0,032512  0,049631    0,017910 -0,017120     -2,01R

R denotes an observation with a large standardized residual.
```