Quantitative Cost of Quality Model in Manufacturing Supply Chain

Ehsan Ayati

Concordia Institue for Information Systems Engineering

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By: Ehsan Ayati

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Signed by the final examining committee:

Dr. S. Li Chair

Dr. K. Demirli Examiner

Dr. C. Wang Examiner

Dr. A. Schiffauerova Supervisor

Approved by _____
Chair of Department or Graduate Program Director

_____
Dean of Faculty

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Abstract

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Ehsan Ayati

In the present business environment where quality is a key factor and customer expectation of quality is ever-changing, measuring Cost of Quality (COQ) seems to be a critical factor for organizations in order to keep or grow their market share. However, until now the COQ has been measured almost exclusively only internally, i.e. within a company, while the role of a supply chain in delivering quality product to end users has been ignored. In this thesis we argue that all the entities within supply chain affect the quality of a product or a service and their quality related activities should thus be inevitably considered. Incorporating all the quality related costs of the supply chain entities into the COQ measurement will create a powerful measure of improvement in an organization. The objective of this research is to develop a mathematical model to estimate COQ as key performance measurement within manufacturing supply chain while considering quality Excellency status. Using classic PAF (Prevention-Appraisal-Failure) model classification to develop mathematical model and its integration with significant variables in supply chain entities are the key methodology in this work. Perceived quality is assumed as an appropriate definition of quality in manufacturing supply chain. Moreover, proposed model is examined against real time quality cost data of manufacturing supply chain in two intervals, first at quality immaturity period and then at quality maturity period. Statistical tools are used to validate the model and compare its behavior in the two intervals. The results are then analyzed and discussed, and possible future works are presented.

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1. Introduction

Recent trends in global market show that today it is supply chain which competes and not anymore a single firm. Despite all of the challenges within supply chain, like development chain contradictions and misalignment of objectives, the emergence of alliance and cooperation between supply chain entities play a critical role in today's market. All tiers of supply chain from suppliers to retailers could drastically affect the supply chain output. Thus there should be close cooperation between all entities to fortify the chain value.

In spite of different definitions of quality from manufacturer perspective and end-user perspective, delivering quality product is an ultimate objective of all supply chains. Cost of quality (COQ) could be used as one of the key measures to evaluate any system performance measurement. In the supply chain context COQ could be utilized as a key performance measurement tool. It gives an equal opportunity to supply chain stakeholders to examine supply chain performance in monetary terms.

There are numerous studies conducted in COQ measurement and analysis and supply chain performance measurement, but the integration of the two is a rare case among scholars. Some studies which study COQ in manufacturing supply chain recently appeared. However, no comprehensive COQ model for the supply chain has been proposed so far.

This research aims to develop a mathematical model which formulates COQ across manufacturing supply chain. The proposed model could be utilized as a performance measurement tool to evaluate supply chain effectiveness from quality cost point of view. Moreover, the model is able to estimate various COQ components (prevention costs, appraisal cost and failure costs) at different quality excellence level and their contribution to overall COQ. Also, this research aims to study and compare proposed model at two major COQ behaviors, first at Juran’s trade-off trend and the continuous improvement

trend. The proposed model is modified based on the characteristics of COQ at these behaviors.

In the second chapter of this work the comprehensive study of literature regarding COQ has been conducted. The most popular COQ models are studied in this chapter and their advantages and drawbacks are discussed.

In the third chapter, which is the research methodology, the problem definition, research hypotheses and data collection procedures are described in detail.

Fourth chapter described step by step procedures to develop mathematical model and in the fifth chapter statistical tools are used to externally validate proposed model.

Finally, the thesis is concluded in the sixth chapter, where the future works are discussed.

2. Literature Review

2.1 Literature on Cost of quality

2.1.1 Background on COQ

Juran (1951) and Feignebaum were the first scholars who urged the necessity of measurement of "Cost of Quality" (COQ) in quality related studies (Banasik 2009). Feigenbaum (1956) pointed out the excessiveness of quality cost for many companies and inevitability to measure it for the sake of business's market position improvement.

Based on the literature in 1950s, there were several factors which lead the quality authorities to measure quality costs. First of all, changes in the customer demands and request for more precise and reliable product have augmented the need of cost of quality measurement. On the other hand, the emergence of long life products, which imposed vast amount of repair, labor, maintenance and inventory costs on the manufacturer, made the provision of quality product more expensive than before. Furthermore, quality authorities needed a monetary language to express and motivate senior managers to participate in quality programs (Juran, Gryna 1993) .

Even though the formation of COQ committee in American Society of Quality (ASQ) in 1967 was the first step to the systematic and global definition and classification of COQ, the definition of COQ has still not been agreed upon globally by the researchers and quality involved organizations. It means that there is not a single definition which has been accepted widely (Machowski, Dale 1998) .

Bank and Solórzano (1978) have defined the COQ as a cost incurred to keep the whole system at the predefined quality level. Clark and Mclaughlin (1986) have divided COQ into two types of cost. First category refers to those costs which are related to the specifications in design and development phase and occur before delivery of product or service. The second category involves the costs which happen after the product delivery and are caused by the lack of conformance to the specified criteria.

The definition of Dale and Plunkett (1995) is the definition of COQ which is generally accepted by scholars. (Schiffauerova, Thomson 2006) have classified COQ into four categories. First includes the cost of planning, implementation and controlling any quality system in the organization, while the second category comprises the cost of resources which cross-functionally are committed to maintain or reach to specified quality level. The third category refers to the cost of quality failure, and, finally, the fourth one to the other quality related costs.

In general COQ is assumed as a sum of amount of cost which and organization is paying in order to achieve a good quality and amount of cost which has been incurred due to the bad quality. The first COQ component is known as quality conformance cost and the latter as quality nonconformance cost. (Schiffauerova, Thomson 2006).

British Standard Institution publication BS6143, (1981) developed its own definition of COQ. In 1990 they revised their definition and published "Guide to the Economics of Quality". The definition is comprised of two subdivisions. First is based on the process cost model and second is based on PAF model which will be defined later in this literature review. It defines COQ as "cost in assuring quality as well as loss incurred when quality is not achieved".

Loss of consensus over cost items in COQ is the fundamental reason why ambiguity exists in definition of COQ (Castillo-Villar, Smith et al. 2012). Dale and Plunkett (1991) stated that there is not an agreement between accountants in what to include as a COQ. Moreover it depends on the industry and also on the chief executive officer eagerness towards implementation of quality programs, because quality experts are adding more cost components or even dropping some cost components so as to signify their financial impact (Dale, Plunkett 1999) .

Implication in definition of quality also made the definition of COQ more complicated. Castillo- Villar, smith et al. (2012) indicated that new trends in definition of quality like Juran definition "fitness to use" or Garvin's new dimension of quality, not only complicated definition of COQ but even added more intangible cost component to the COQ.

As a result of these inconsistencies, quality authorities, as for example ASQ, define COQ simply based on nothing but cost components. They define COQ as a cost to prevent poor quality in product and service and not the cost incurred to achieve high quality. Literally they define COQ base on the COQ classification. Despite the inconsistency in the COQ definition, Feigenbaum's PAF classification of COQ to prevention (P), appraisal (A) and failure (F) costs is the worldwide accepted taxonomy used to classify COQ (Castillo-Villar, Smith et al. 2012). PAF model has gained universal acceptance amongst researchers and organizations like ASQ. There are some other classifications of COQ which will be discussed in the following sections.

2.1.2 COQ Models

COQ components are acquired through the COQ classification. Subsequently, the COQ classification is implied in the COQ models. Plunkett and Dale (1988) conducted extensive research on the COQ models. They studied several conceptual COQ models and also generated some COQ models based on the real data from industries. They have analyzed the relationship of COQ components and COQ behavior and concluded that, there is no consistency in the relationship of quality cost categories and they challenged the existence of unique COQ behavior. According to their findings, the COQ models could be divided into 3 distinct categories. In the first group there are the models which highlight a difference between their quality optimum point and COQ curve slope. The second group includes models which describe quality advancement over time and pointed out to quality milestones. Third group plotted actual quality costs obtained via industries and over time (Plunkett, Dale 1988, Castillo-Villar, Smith et al. 2012).

Banasik (2009) outlined the findings of Plunkett and Dale (1988) findings as follow:

1. The differences between authors' quality cost items leads to the generation of different COQ behavior and optimum COQ points.
2. Diverse COQ categories combinations proposed by different scholars and industries prevent appropriate analysis of each cost category impact and their interrelationships.

3. In some models the return on the investment seems unrealistic.
4. Top managers need to have a validated model which demonstrates their current COQ status and predicts their future changes impact. This issue caused the generation of several diverse COQ models.
5. The logic which implies that investment in prevention and effect would have effect on failure cost in time lags is ignored in many of the models.

Plunkett and Dale (1988) finally concluded that many proposed COQ models are inaccurate and misleading. Moreover, they claimed uncertainties over accuracy and validity of optimum quality levels.

First proposed classification of COQ divided modeling theories to six groups. Juran's model, Lesser's model, PAF model, the economics of quality, business management of COQ and Juran's revised model (SANDOVAL-CHÁVEZ, Beruvides 1998).

Schiffauerova and Thomson (2006) categorized COQ to four major categories of COQ: PAF model, opportunity cost model, process cost model and ABC model. Later on Castillo-Villar, smith et al. (2012) classified COQ with chronological order into ten groups: Juran's model, Lesser's contribution, PAF or Crosby's model, PQC model, accounting COQ model, process cost model, ABC approach, Juran's revised model, Opportunity cost model and capital budgeting model.

There are number of models and analyses which are not included in any of above classifications. Carr (1992) introduced the COQ model for service (the previous models were all intended for manufacturing). Ittner (1996) proposed the continuous improvement model as an alternative to Juran's classic model. Miller and Morris (2000) proposed the profit consideration COQ model. And Freiesleben (2004) proposed new continuous improvement COQ model.

The following sections provide further explanation on all of major COQ models which seem to have dominant impact on COQ evolution.

2.1.2.1 Juran's model

Juran (1951) presented a conceptual - graphical COQ model. The model is later used quite frequently by many researchers as a foundation for their newly proposed COQ models. In his model he classified COQ into avoidable quality costs and unavoidable quality costs. He has used the term of "gold in mine" where the gold refers to the avoidable quality costs which just need to be identified. He described the avoidable costs as costs which would totally disappear when there is no defect in the system.

He classified COQ into basic manufacturing costs to meet the specification, inspection costs, quality control costs and avoidable costs. Nevertheless, later Juran (1956) declared that the inspection costs are in fact avoidable as well.

He plotted the economics of quality against quality level. His model is shown in Figure 2.1. He claimed that the total quality cost is parabolic, and concluded that losses due to the defects will reduce exponentially as the total amount of cost spent on quality control per product increases. And this is the point where the quality is most economical, i.e. this is where the highest possible quality level can be reached for the lowest possible quality costs.

He claimed that this economic optimum point for quality is not a perfection but near to it. Based on this model, in order to achieve the complete perfection, i.e. zero defects, the conformance cost would be infinite (Juran 1951).

Later Juran (1962) presented this model as a COQ trade-off model. The model was designed based on the PAF, COQ classification. He emphasized on the opposite behavior of prevention and appraisal costs on one hand, and the failure costs on the other hand. The main objective of the model is to find the level of quality which minimizes the total quality cost per product (Schiffauerova, Thomson 2006).

Juran (1951 and 1962) demonstrated that there is an economic point for quality where a very high quality can be achieved for the minimum quality cost. From this point of view, expected benefit gains from reduction of non-conformance costs would be less than the investment in conformance activities in order to achieve higher quality level. No further

investments are thus justified. In most of the literature the model is known as COQ classical model.

Plunkett and Dale (1988) have presented practical cases which follow the Juran's classical COQ model trend. Also, Burgess (1996) simulated the model and validated it for the short run and static analysis of COQ in an organization. Freiesleben (2004) also proposed the model suitability for companies with low quality level, where practices to find root cause of errors are costly and thus achieving perfection is too expensive for them.

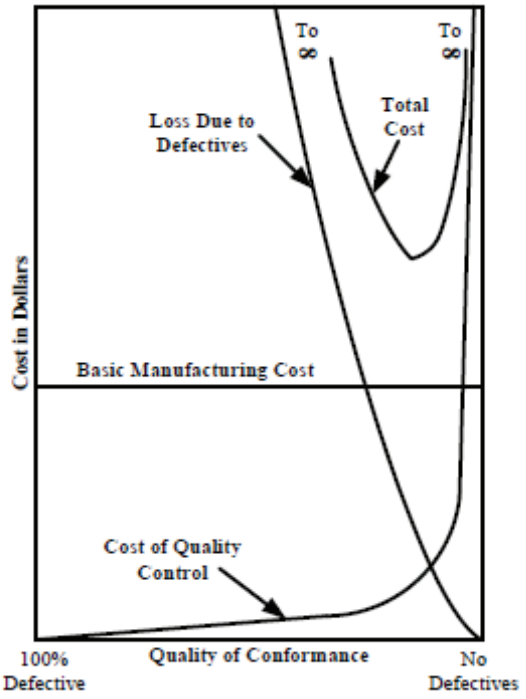

Figure 2.1 Economics of quality of Conformance Juran (1951)

2.1.2.2 Lesser's model

It has been mentioned in the literature that the first scholar who used PAF classification has been Lesser. (Castillo-Villar, Smith et al. 2012, SANDOVAL-CHÁVEZ, Beruvides 1998) Lesser (1954) proposed a model based on the PAF model.

He has classified the quality costs in manufacturing environment in order to identify quality costs and hidden quality costs. He aimed to contribute the quality costs

measurement as a tool to justify quality investments. In his proposal he classified quality costs to identifiable quality costs and hidden quality costs. Scraps, reworks, customer complaints due to defective products, inspections, testing and quality control costs were classified as identifiable and extra costs due to poor quality, delays in production and shipping due to defective components, business losses due to poor quality and inherited weakness in design were classified as hidden quality costs. (Banasik 2009, Castillo-Villar, Smith et al. 2012)

Banasik (2009) remarked his contribution to identify the impact of quality costs on utilized resources e.g. labor, material and etc.

2.1.2.3 PAF and Crosby model

Feigenbaum (1956) presented well-known PAF model. He divided quality costs to prevention, appraisal and failure costs. Banasik (2009) asserts that his work is the one which shows the relationship between prevention and appraisal costs on one hand and failure costs on the other hand. Feigenbaum (1956) described PAF components as follows:

Prevention Costs: The costs associated with any activities to avoid poor quality

Appraisal Costs: The cost of measuring, evaluating and auditing product and service to ensure their conformance to predefined specifications.

Internal Failure: Costs incurred due to the nonconformance of product and service to the specification before product or service is delivered to the customer.

External Failure: Costs of nonconformance to the specification after the product or service has been delivered to the customer

Feigenbaum (1956) illustrated the PAF model cost components interactions in the following four steps:

1. Modern quality practice (prevention costs) leads to the decrease of failure costs due to the reduction in number of defected components.

2. Lower defect rate means less necessity for inspection activity and thus lower appraisal cost.
3. Better inspection system and inspection equipment (prevention cost) also decrease appraisal costs.
4. The new inspection and audit system will prevent defects, i.e. the reduction in appraisal activity will lead to the reduction in defects.

Porter and Rayner (1992) concluded that the main concept of PAF model is that the increment in prevention and appraisal costs would lead to the decrease in failure costs. The advantage of PAF is not merely its universal acceptance among quality authorities and researchers, but also the fact that it helps in more precise identification and classification of quality costs (Castillo-Villar, Smith et al. 2012).

Moreover, PAF helps businesses to identify the contribution of each quality cost to total COQ at different intervals. This enables the detection of the cost category which needs to get more attention in order achieve higher quality level or to even reduce quality costs. Banasik (2009) claims that the use of PAF can facilitate businesses the quality budgeting which can be performed in accordance with their quality strategic objectives and not simply based on historical inspection costs. Also it allows companies to determine the return on their quality investment and to assess their investment impact on the quality.

Crosby's (1979) classification is also in accordance with the PAF model. It categorizes COQ to conformance and nonconformance costs. Conformance costs are defined as costs incurred in order to obtain conformity to design specifications and to meet customer requirements (e.g. prevention costs and appraisal costs). Nonconformance cost is the money wasted if a defective product reaches to the customer (e.g. rework costs and warranty costs) (Schiffauerova, Thomson 2006). Goulden and Rawlins (1995) claimed that Crosby's model is the same as PAF model but using different terminology.

2.1.2.4 Harrington's Poor Quality Cost (PQC) model

Harrington (1987) introduced the PQC (Poor Quality cost) model based on the PAF model. He asserted that PQC is aiming at the analysis of white-collar PQC and not the

PQC in manufacturing environment. Besides, he claimed that based on the management attitude towards quality, PQC would alerted them more than the COQ. To engage the attention of managers and white-collars workers towards quality costs in PQC model, he replaced the defect term with error and changed the quality target from optimum quality cost to error free point target (Castillo-Villar, Smith et al. 2012).

He claims that his modification of the original quality costs model, will predictably lead managers and employees towards the identification of improvement points. As a result they will involve more in implementing and measuring continuous improvement activities.

The concept of PQC is coming from the term “doing the things right at the first time”.

Harrington (1987) defined the PQC as “all the cost incurred to help the employee do the job right every time and the cost of determining if the output is acceptable, plus any cost incurred by the company and the customer because the output did not meet specification and/or customer expectations”.

In Harington's (1987) definition the PQC are both direct and indirect PQC. The direct PQC are controllable (prevention and appraisal), resultant (internal and external error) and equipment related costs. Indirect costs are the costs incurred by the customer, cost of customer dissatisfaction and loss of reputation. Although he claimed that indirect costs are not measured in the company ledger they are part of the PQC life cycle.

Figure 2.2 demonstrates Harrington's PQC model. It shows that the increment in the controllable costs will reduce the resultant costs and customer incurred costs. Additionally, instead of defining an optimum quality cost point the model proposes interim optimum operation point which dictates unavoidability of continuous improvement.

2.1.2.5 Godfrey-Pasewark accounting COQ model

This model is proposed by (Godfrey, Pasewark 1988) and represents a COQ model from accounting point of view. The model classified quality cost into three cost components including defect control costs (prevention and appraisal), failure costs (rework costs, lost

sales due the selling products at lower price due to their defects and return process costs) and costs due to lost sales. The model is very similar to the PAF model. Proposed model claims that there is an interrelationship between cost components. Authors criticized the American quality systems, because of their tendency towards minimizing individual cost instead of total quality costs.

They support the interrelationship argument through existence of cause and effect relationship between individual cost components. They argued that there is a cause and effect relationship between defect control costs and number of defective unit. Similarly, there is a cause and effect relationship between the number of defective units and costs due to the lost sales. As a result, there is an indirect relationship between defect control costs and costs due to the lost sales (Godfrey, Pasewark 1988).

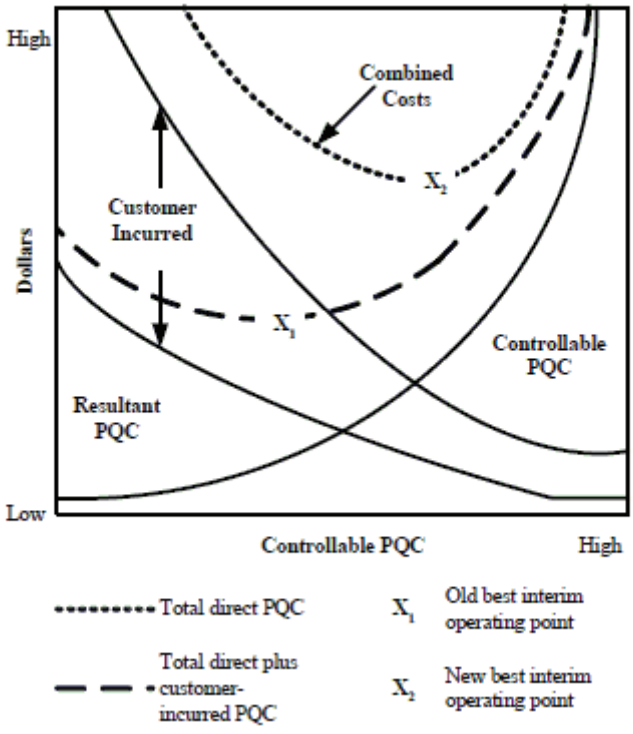

Figure 2.2 Harrington PQC model (Harrington 1987)

2.1.2.6 Process Cost Model

Process cost model was first developed by Ross (1977). He proposed this model as a computer-aided integrated program to model and analyze costs for the manufacturing

environment. The model seemed beneficial but not convenient to common users and managers (Schiffauerova, Thomson 2006, Castillo-Villar, Smith et al. 2012).

Marsh (1989) used the process cost model in COQ. He used a complex method to categorize COQ, define cost components based on the process flowchart and differentiate quality costs components for different processes (Schiffauerova, Thomson 2006). Model integrates conformance costs and non-conformance costs based on individual processes. His model is very useful in businesses which implement total quality management programs as the activities of these businesses are nothing other than interrelated processes. Consequently, the quality costs of each process can be identified instead of measuring a general or product based COQ. Moreover, the process cost model gives an opportunity to evaluate current and required prevention investment action plan, i.e. to increase or decrease the investment for each process as a prerequisite for new design development (Marsh 1989, Porter, Rayner 1992).

Crossfield and Dale (1990) suggested a mapping method for quality assurance activities and the related flow of information and activities in order to ease the classification of quality costs for each process. Goulden and Rawlins (1995) utilized integrated or functional flowchart to measure process's quality costs.

Even though process cost model facilitates the classification and the analysis of direct and indirect quality cost, and some scholars have highlighted its advantages over PAF, it has not been used extensively in COQ evaluations (Goulden, Rawlins 1995).

2.1.2.7 Juran's revised model

Juran's (1956) trade-off model which was discussed previously suggests that there is a quality economic point and that in order to achieve perfection the total quality cost tends to infinity. However, this idea has been challenged by Deming (1986) afterwards. He claimed that "Cost of selling bad quality product is too high that the best quality cost point is where we have zero defects, thus it is not required to measure quality cost and we have to produce zero defects". (Deming 1986)

Also, other researchers criticized the idea of the existence of quality cost economic point and argued that spending on prevention activities is justifiable as long as there is a defect in the system. (Schneiderman 1986, Plunkett, Dale 1988, Fox 1989, Porter, Rayner 1992, Shank, Govindarajan 1994). Freiesleben (2004) also criticized classic trade-off model by Juran. He claimed there is a problem with exponential increment of conformance costs. He argued;

1. As quality level tends to increase, the total number of good products increases. The conformance cost per product should thus not have incremental behavior.
2. As the sum of prevention costs increases, the sum for appraisal costs should decrease. Similarly then, the conformance should not have incremental behavior.

Freiesleben (2004) also criticized the model because it was constructed based on the time technological status when the quality has been poor comparing to recent progression. Finally, he asserted that the acceptance of this model is due to "inspection mentality" of managers.

Juran and Gryna (1993) revised the economic trade-off model. In the revised model they claimed that perfection is achievable in finite conformance costs. They eliminated the exponential behavior of prevention and appraisal costs. The comparison of classic and revised Juran model is showed in Figure 2.3. However, they limited the application of this model to the companies with high technological advancement and companies which the clients who are very wealthy and thus businesses care much about their expenses. In their revised model they stated that the 100% perfection is not reachable in short run and it should be a long term goal of businesses. Freiesleben (2004) challenged the model for not considering hidden costs. Also he claimed snap shot of perfection is not realistic as prevention has diminishing return and return on prevention depends on already achieved quality level, technological options and learning over time. Burgess (1996) used simulation to validate Juran's COQ classic and revised models. He stated that for the long run the revised model is justifiable. Also, Ittner (1996) presented empirical study which validated the Juran's revised model.

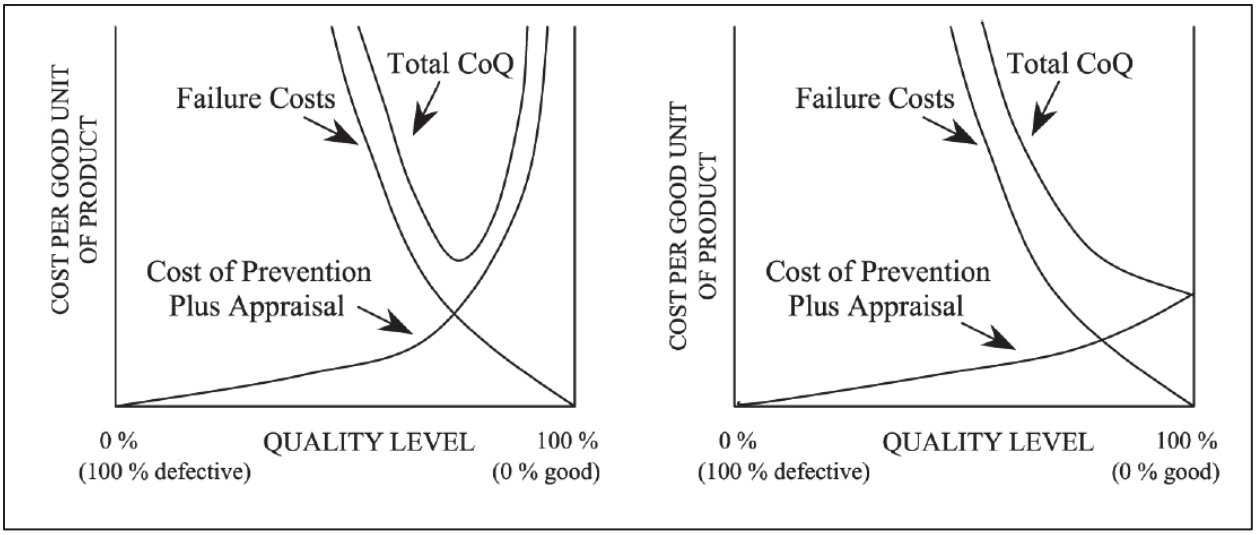

Figure 2.3 Classic COQ trade off model VS Revised Model (Schiffauerova, Thomson 2006)

2.1.2.8 Carr's service model

Classification of cost of quality in manufacturing and service is predictably different. Also the identification of COQ items is more challenging in services than in manufacturing environment as the differentiation between quality cost components and other type of cost is tougher in service.

Carr (1992) introduced the COQ model for the service industry for the first time. He implemented COQ measurement in the marketing and sale division of U.S Marketing group (USMG) as a part of its operation management system. (Carr 1992)

The main difference between his model and the PAF model is the classification of opportunity costs as a cost category. In his model he classified COQ into conformance, non-conformance costs and lost opportunity costs (Banasik 2009).

2.1.2.9 Opportunity Costs Model

Intangible costs have been considered by many authors. Lesser (1954) considered hidden costs and Harrington (1987) proposed indirect costs in their models as both are intangible costs. Tatikonda and Tatikonda (1996) defined the opportunity costs as the cost of lost customers when the defective product reaches the market (Tatikonda, Tatikonda 1996).

Opportunity costs are the costs of not earning profit as a result of losing customers (Schiffauerova, Thomson 2006). Provided that the customers do not receive good component or service at the time it is required it is expected that this sort of cost will be incurred by businesses.

Carr (1992) provided new definition for COQ which included opportunity costs. In his article he presented practical case of Xerox. Xerox was the first company which included opportunity costs in COQ measurement.(Castillo-Villar, Smith et al. 2012)

Albright and Roth (1992) and Castillo-Villar (2012) applied Taguchi's loss function to estimate the opportunity costs.

There are several components which could be counted as opportunity costs. Freiesleben (2004) outlined opportunity costs as follows:

1. Lost sales
2. Goodwill and warranty to the customer
3. Downtime of process during elimination of error
4. Slowdown of process due to inspection
5. Over-capacity due to certain sale goal
6. Opportunity costs due to management distraction

Sandoval-Chavez and Beruvides (1998) integrated the Juran's revised model and Carr's Service model. They proposed the inclusion of opportunity costs in COQ measurement. The first part of costs was the PAF model costs, and the second was the intangible costs. The result of their studies show that the more than 83% of the total loss in revenue and also more than 56% of loss in profit is due to intangible costs.

The model of Beruvides and Sandoval-Chavez (1998) is presented in Figure 2.4. As the model shows there is a difference between perceived COQ and actual COQ. The difference is the opportunity costs or intangible costs. Model assumes that when the opportunity costs are accurately considered, the model trend and behavior would be much similar to the Juran's revised model.

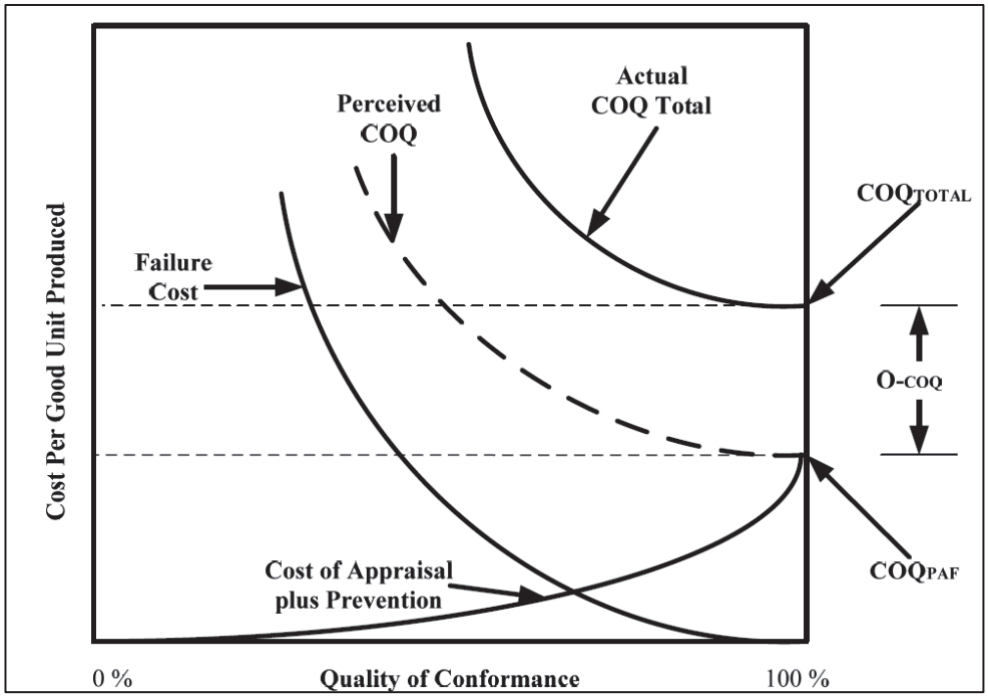

Figure 2.4 COQ considering opportunity costs (SANDOVAL-CHÁVEZ, Beruvides 1998)

2.1.2.10 Activity Based Costing (ABC) Model

Traditional accounting system has not been useful in COQ studies. It classified costs based on their category of expense instead of activity. Also there is not a consensus over a method to allocate overhead costs to COQ (Schiffauerova, Thomson 2006).

ABC is a classification of costs based of their relative activity. It was developed by Cooper (1988) and Cooper and Kaplan (1988). They suggests that quality costs studies need to classify costs based on processes and activities. ABC is not a COQ model but it is a useful method to classify costs. It traces back costs until the original source of costs can be attained. It is suggested that when it is integrated into COQ, it can give appropriate quality cost data and could help measuring the quality activity results (Cooper, Kaplan 1988, Schiffauerova, Thomson 2006) .

Integration of ABC accounting system into COQ was first performed by Tsai (1998). He presented a framework which measures quality costs based on ABC model. This classification extracts costs of various activates in the process and eventually aims to eliminate non-adding value and costs generating activities from the process.

2.1.2.11 Miller and Morris profit based COQ model

Freiesleben (2004) criticized existing COQ models because they were all based on the cost instead of profit. He claimed that COQ thus does not have meaning in the business context. He suggested that instead of decision making on the quality based on the cost, it is more realistic to do so based on the profit. Miller and Morris (2000) integrated the total benefits in the COQ model and suggested that the quality optimum point is where the marginal benefit is equal to the marginal COQ. Contrary to the former models the optimum quality level has been the point where the marginal COQ is equal to zero.

Their model is shown in Figure 2.5. The total benefit in their model is equal to the sum of tangible benefit and intangible benefit. Intangible benefit is the benefit of providing good component to the society and is similar to the intangible costs. As the model shows, when the profit increases, with augmentation of quality level the optimum quality cost should shift towards higher quality level and inevitably also higher quality costs.

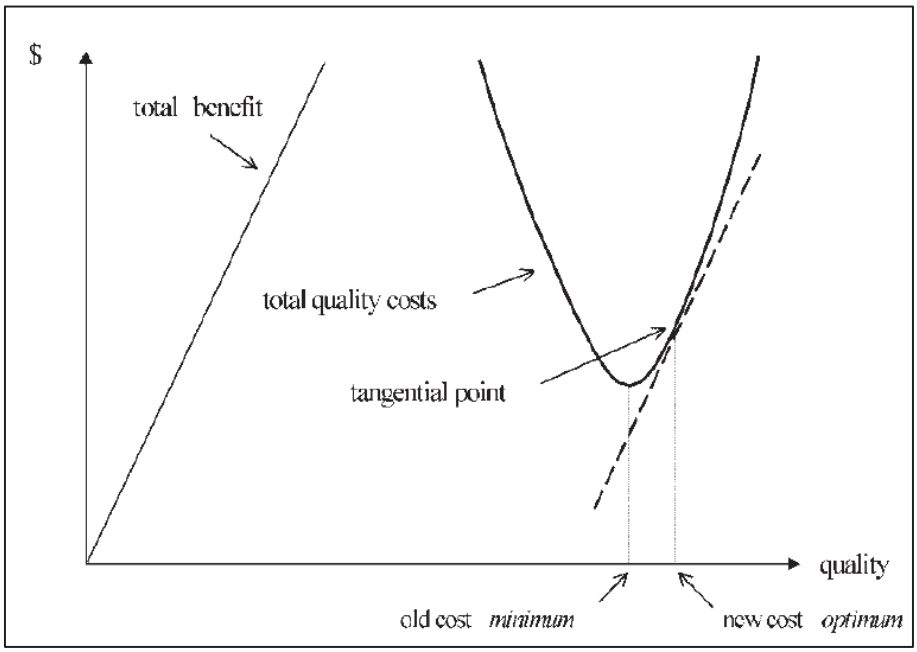

Figure 2.5 COQ model integrating profit

2.1.2.12 Capital Budgeting model

Beruvides and Chiu (2003) presented the capital budgeting COQ model. In their model they integrated Juran's trade-off model and opportunity cost model.

The model suggests that the smartest decision for businesses is not to achieve 100% conformance all the time. Their idea thus opposes the concept behind the Juran's revised model. They used the cost benefit analysis to study the return of investment in prevention and appraisal activities against failure costs for specific period of the time or specific quality program. In their model, there is a point which is named Economic Inflection Point (EIP), which determines the point of the decision whether to cease or continue quality programs or investment. This point varies between different industries and within different level of quality. The model is based on the net present value objective function. Function is comprised of three components:

1. Initial investment
2. Benefit gains through prevention and appraisal activities
3. Salvage value of investment at the end of study period

The analysis of the model of Beruvides and Chiu (2003) can be merely based on the estimated net present value or it can be based on the comparison of internal rate of return (IRR) against minimum attractive rate of return (MARR). Castillo-Villar, smith et al. (2012) stated that the main objective of this model is to demonstrate balance between return on the investment and quality level.

2.1.2.13 Continuous improvement model

Although Juran's revised model claims that the perfection is achievable within finite conformance costs, it does not suggest that the optimum economic quality level for all businesses happens is at perfection. Intuitively, the cost of reaching to 100% quality level would be inevitably too high for most of businesses. This may in fact push them out of profit margin if they want to keep perfection (Banasik 2009).

The idea of "continuous reduction in nonconformance costs can only happen if business invests continuously on conformance costs" has been challenged by some authors. Schneiderman (1986) and Harrington (1987) stated that the fixed level of conformance costs could cause continuous decrease in non-conformance costs in the continuous improvement environment, while in the continuous improvement process, each time the

root causes would be detected and removed without excessive investment in conformance costs. Another model suggested the use of multi-periodic COQ model in accordance with the organization's stage in quality improvement process. (Noz, REDDING et al. 1989).

Fine (1986) proposed a dynamic model which emphasizes on lessons learnt. He claimed that in his model, the lessons from former problem identification and correction would help organization to achieve quality assurance in lower costs.

Marcellus and Dada (1991) also claimed that any investment in prevention activities would provide learning opportunity to achieve less defective products in lower cost.

Ittner (1996) proposed the first continuous improvement COQ model against the classic COQ model. His model suggested that due to continuous improvement policy in his COQ model there would be point where with the same or a slightly higher spending on conformance costs one could achieve diminishing trend in non-conformance costs. Figure 2.6 shows his proposed model.

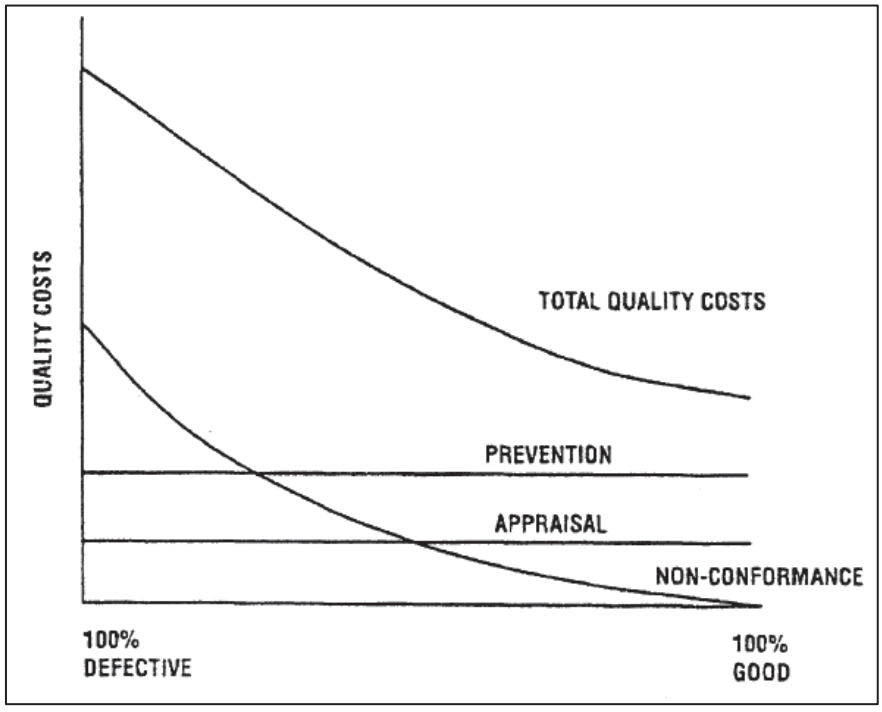

Figure 2.6 Ittner's Continuous improvement COQ model (Ittner 1996)

Freiesleben (2004) conducted explanatory studies on the classic and Juran revised model.

He argued that neither of the models determines optimum quality level in practice. He challenged the model static nature and claimed that the revised model perfection could not occur in a short run or a single interval. Therefore he proposed his model as a continuous improvement model of COQ.

In his model he focused on three critical elements in each stage of continuous improvement which would affect the COQ of upcoming stage;

1. Technical progress
2. Learning from former continuous improvement activities
3. Detection of root cause

Proposed model is shown in Figure 2.7. In the model he suggested several intervals. In each interval the root cause of problem would be identified and removed, and consequently the process improves to the certain level of quality. In the next intervals, as a result of the prevention investments in former stage, reaching to higher level of quality is achievable with lower COQ.

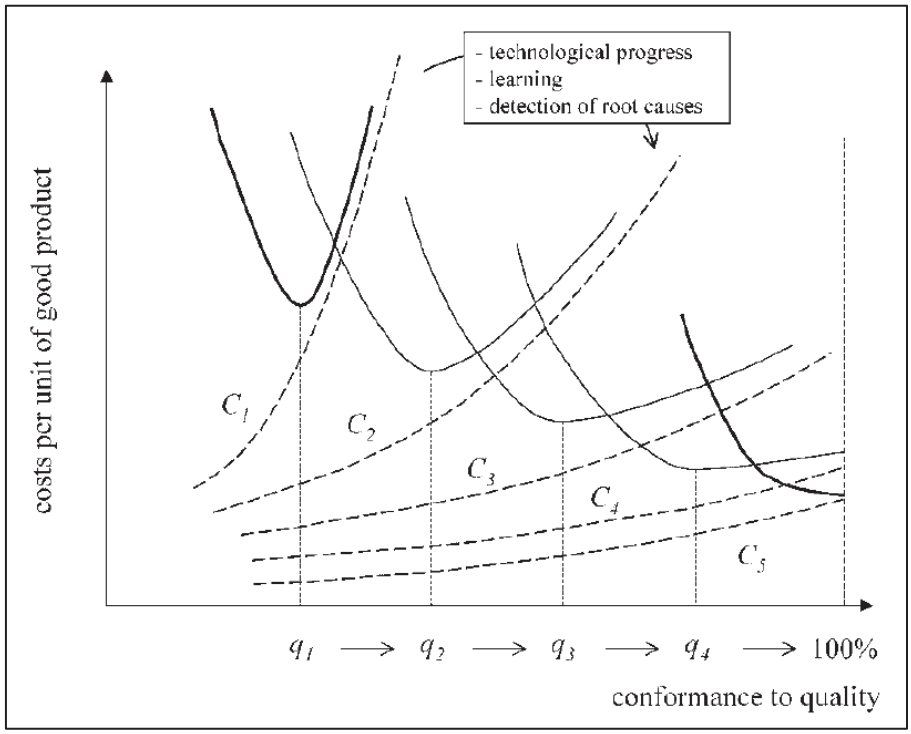

Figure 2.7 Freiesleben Continuous improvement COQ model (Freiesleben 2004)

2.1.3 Conclusion on COQ Models

Most of the above mentioned models are conceptual and COQ model is highly dependent on the type of COQ classification. They are not based on the accurate data, or they have not been validated against real data. Moreover classification of quality costs will dramatically affect the COQ behavior. Tsai and Hsu (2010) proposed a hybrid model based on decision-making trial and evaluation (DEMATEL) method and the analytic network process (ANP) which helps managers to choose the most relative COQ model in accordance to their industry, quality maturity and outcome expectations.

This study of COQ models literature is a chronological illustration of COQ models development. Some of them have been used in several studies afterwards and for some no further studies could be found. Based on the reviewed literature it can be concluded that despite the criticism Juran's revised model is the most applied model due to its flexibility and breadth.

2.1.4 COQ Metrics

Measurement of COQ does not necessarily result in quality improvement. It is a decision support measure which helps managers to evaluate their quality investment impact and prepare their strategic or operational quality plans. In order to be able to measure the COQ it is required to identify COQ metrics.

There are two types of COQ metrics in the literature, detailed metrics and global metrics. The first one measures each element of COQ and its performance individually. Cost of resources, cost of control tools, cost of defect manufacturing per unit, cost of return items and cost of lost customers due to poor quality are the examples of detailed metrics (Schiffauerova, Thomson 2006).

The global metrics measure global performance of system COQs. When we utilize global metrics in COQ, we consider all of the elements of COQ and measure the contribution of each element both individually and globally. This allows us to analyze the system performance at various time intervals. Practically, as opposed to the detailed metrics,

when deploying the global metrics we are able to measure and optimize the whole system performance. However, it seems impossible to obtain and estimate global metrics without consideration of detailed metrics. Table 2.1 shows some examples of global metrics in general (Schiffauerova, Thomson 2006).

(Tatikonda, Tatikonda 1996) state that, based on the literature on COQ metrics, "Return in Quality" (ROQ) is the most common COQ metric which has been suggested and used by many scholars. They suggest that most successful businesses implement ROQ method to measure their COQ performance. They also mention that ROQ measurement is an appropriate procedure to verify quality project success in most of the companies. This method can also be used to compare, prioritize and select between potential quality projects.

After determination of COQ parameters and detailed metrics we can estimate COQ global metrics and eventually construct COQ model and study its performance.

Global metrics	
Return in Quality (ROQ)	increase in profit/COQ improvement
Percentage of sale	COQ detailed costs/ total sale
Percentage of costs	COQ detailed costs/ total costs
Percentage of revenue	COQ detailed costs/ total revenue
Process Quality	(available time – rework time)/available time
Quality rate	(input – (quality defects)+start up defects + reworks)/input
First time quality	percentage of product with no rework

Table 2.1Global Metrics in COQ studies (Schiffauerova, Thomson 2006)

2.1.5 COQ Studies, Analysis Implementations

As it was mentioned previously, COQ is a tool which serves for the evaluation and measuring of performance of organization or even of a single process. Likewise COQ models development, There are numerous studies which used COQ measurement to study behavior of quality costs and quality level in specific industries. Also some authors used COQ in order to evaluate particular process or system performance.

(Blank, Solorzano 1978, Campanella, Corcoran 1983, Godfrey, Pasewark 1988, Ittner 1996, Sower, Quarles et al. 2007) studied the relationship of COQ as a tool for management improvement process. They asserted that the contribution of each quality cost category to total quality costs determines organization's quality maturity. Al-Tmeemy and Rahman et al (2012) conducted a qualitative research survey on the benefits of implementation of COQ on one hand and barriers which affect implementation of COQ between contractors on the other hand. They divided the barriers to three categories of cultural, system and company and declared "getting management attention and increase quality awareness" is the biggest advantage of measuring quality costs.(Al-Tmeemy, Rahman et al. 2012)

(Gardner, Grant et al. 1995, Burgess 1996, Clark, Tannock 1999, Kiani, Shirouyehzad et al. 2009, De Ruyter, Cardew-Hall et al. 2002, Omar, Sim et al. 2009, Omar, Murugan et al. 2010) have used Simulation techniques to assess impact of decision variables on total quality costs and its impact on quality improvement process.

Gardner and Grant et al. (1995) used simulation to analyze COQ model behavior in manufacturing process. They studied the impact of defective rate, inspection and defect removal strategy on total quality costs and eventually on quality improvement process. They used COQ as a performance measurement tool to evaluate quality improvement programs in two intervals. Burgess (1996) simulated system dynamic model of COQ and proposed justification for both Juran's traditional and revised COQ model. Clark and Tannock (1999) used simulation to estimate the impact of different cell-manufacturing systems and quality strategies on quality costs. De Ryter and Cardew-Hall et al. (2002) simulated COQ in the automotive stamping plant to analyze the impact of inspection and control error on the total quality costs. Their findings show significant effect of inspection error on the total quality costs. Kiani and Shirouyehzad et al. (2009) utilized system dynamics approach to model COQ. They used empirical study to validate their model. They studied the effect of cost factor on total COQ and concluded:

1. Prevention activity has more impact than appraisal activity on the decrease in total COQ.
2. Prevention and appraisal activities together would have higher effect on total COQ reduction than when they are implemented individually.

(Kiani, Shirouyehzad et al. 2009)) suggested COQ measurement to be conducted as a long-term process within any organization regardless of its size and industry.

Omar and Sim et al. (2009) utilized simulation to assess the impact of implementation of acceptance sampling on the incoming raw material on total COQ. Later, Omar and Murugan et al. (2010) extended the model to assess effect of inspection error rate and tolerance design on total COQ.

Schiffauerova and Thomson (2006) conducted a case study on measurement of COQ within companies. They studied four companies with different types of industry and concluded that despite the importance of COQ measurement it is not considered by many organizations. Sower and Quarles (2007) studied the role of COQ measurement and quality maturity on organization's performance. In their survey above 30% of companies measure COQ which is in accordance with former research findings. They concluded that "the total COQ will decrease as quality improvement processes implemented but the trend of decrease is diminishing".

They also studied the reasons of reluctance in most organizations towards COQ measurement. The claimed management unwillingness and lack of information system are the major reasons of not tracking COQ in most companies.(Sower, Quarles et al. 2007)

Desai (2008) utilized COQ as a performance measurement in small and medium sizes enterprises (SME). He emphasized on the role resource and knowledge shortage as main reason that lead SMEs to not commit to continuous improvement. Ability to construct a COQ budget gives an opportunity to SMEs to emphasis on failure costs in future improvement plan and thus increasing productivity and business performance. (Desai 2008)

Banasik (2009) conducted an extensive research on the application of COQ. He made an elaborate comparison between COQ in manufacturing environment and water utility plants. His finding showed that there is a big difference in all components of COQ between manufacturing plants and water utilities. Also the percentage of total COQ in water utilities is twice of manufacturing plants. He justified his findings with health risk issues and regulatory reason although declaring needs for further study on the causes.

Sim and Omar et al. (2009) and Tye and Halim et al. (2011) conducted a survey regarding implementation of COQ in Malaysian manufacturing industries. They studied both measurement of COQ and its impact on the quality achievement in the relative industry sector. Their findings showed high contribution of COQ measurement to non-conformance cost reduction and organization level improvement. (Sim, Omar et al. 2009, Tye, Halim et al. 2011)

Su Su and Shi et al (2009) studied the relationship of quality costs PAF model categories based on the case study of automobile industry. They studied trade-off between conformance costs and non-conformance costs by statistical analysis. Results challenged existence of trade-off between prevention activities costs and failure costs on one hand and appraisal activities costs and failure costs on the other hand. they estimated relative COQ (RCOQ). Based on the results the trade-off is significant when the time lag between conformance and non-conformance costs is considered. Outcomes underline on gradual influence of conformance investment in failure costs reduction.

Abdul-Kader and Ganjavi et al (2010) proposed statistical quality cost model which integrates tolerance model and investment model. The model aims to obtain optimum cost of rework and scrap for the off-specification products. They emphasized on process adjustment which leads to the reduction in scrap and rework, while improving the manufacturing process and reducing quality costs. The model optimizes the cost of process adjustment in order to avoid rejected products. They claimed that their model not only gives managers an opportunity to estimate the optimal quality investment but even prospect to compare the quality level and relative costs before and after the process adjustment.

Dror (2010) used "House of Quality" methodology to obtain and prioritize essential prevention and appraisal activities. He used two manufacturing case studies to validate his proposed methodology. The methodology is named the "The House of Cost of Quality" (HCOQ). The HCOQ translates desired improvement in the language of non-conformance costs to required effort in the language of conformance costs.

Cheah and Shahbudin et al (2011) proposed implementation of COQ as a quality improvement program. In their study they focus on methods in identifying hidden cost of quality and based on their case study they reveal that cutting the hidden costs would be more useful for businesses' profitability comparing to other routine cost cutting policies.

Liu and Li (2011) studied the relationship of reliability and COQ in coal industry in China. They developed COQ optimization model based on the neural fuzzy network and genetic algorithm.

2.2 Evaluation of COQ in Supply Chain

COQ reveal the implications of poor quality, quality improvement efforts and hidden quality costs and translates them to a comprehensible language in monetary terms to all of the system stakeholders (Castillo-Villar, Smith et al. 2012). However, COQ measurement is mostly implemented for a specific organization or business as Srivastava (2008) mentioned it as an in house measurement. There are numerous cases of measurement of COQ and its implementation in organizations individually. However, there are few studies which attempt to measure COQ in the whole supply chain networks. Srivastava (2008) was the first author who integrated COQ in supply chain performance measurement. The definition of COQ in supply chain based on Srivastava is:

"the sum of the costs incurred across a supply chain in preventing poor quality of product and/or service to the final consumer, the costs incurred to ensure and evaluate that the quality requirements are being met, and any other costs incurred as a result of poor quality" (Srivastava 2008) P.194.

He measured COQ at selected third party manufacturing sites for a pharmaceutical company. Ramudhin and Alzaman et al (2008) focused on integration of COQ in supply

chain. They claimed that when COQ is incorporated in supply chain the overall operation costs will decrease. Also they claimed that selection of supply chain network without considering COQ is accompanied by high risk of low quality suppliers' selection. They studied single product three echelon supply chain and aimed to minimize total operational costs and quality costs at the same time. They found that adding supplier quality costs to cost objective function will lead to 16% in cost function and change the solution considerably. Justification is because when the cost is estimated just based on the operational costs, the supplier selection would be merely on the operational costs regardless of their quality and COQ (Ramudhin, Alzaman et al. 2008).

Afterwards Alzaman and Bulgak et al (2009) proposed a heuristic approach to solve a mathematical model which combines quadratic COQ function, based on the defect ratio in all of the supply chain components. They validated their model by aerospace industry case study.

Castillo-Villar and smith et al. (2012) developed a mathematical comprehensive model which incorporates COQ in supply chain network. They assumed a single product three echelon supply chain and studied the impact of defect ratio and inspection error at the manufacturer, on total COQ and quality level. They found both Juran's trade-off and revised model behavior in their model in specific range of decision parameters. Later on, Castillo-Villar and Smith et al. (2012) studied the impact of cost of quality on the supply chain network design and solved their nonlinear model using Genetic Algorithm (GA) and Simulated Annealing (SA).

3. Research Methodology

3.1 Problem Definition

Based on my literature review, there are already some scholars who evaluated supply chain network performance measurement using COQ as a key concept (Srivastava 2008, Ramudin and Alzaman et al 2009, Castillo-Villar and smith et al 2012)

However, the former studies on performance measurement of supply chain using COQ have concentrated on a single entity in supply chain. Srivastava (2008), Ramudin and Alzaman et al (2009) and Castillo-Villar and smith et al (2012) focused on supply chain performance solely form manufacturer's point of view. In other words, their studies have considered just manufacturer performance parameters, while other supply chain entities influential factors in measurement are ignored. As the supply chain performance measurement aims to evaluate whole entities performance, focusing on single entity would not have any significant advantage over in-house performance measurement. Also, they have evaluated three echelon supply chain performance and neglected the critical role of distribution tier in supply chain. Distributers have significant role in today's supply chain performance and quality as they can both affect products defect rate and product delivery time. Thus elimination of their impact on performance does not seem logical.

Moreover, in the previous studies the definition of quality level is limited. They confined quality level to receiving "non-defective" measure. Voice of customer definition of quality is totally ignored in their definition. From customer point of view, there are some other critical factors like delivery time and availability of product which affect system wide quality.

Finally, none of the above mentioned studies validated their models against actual costs data. Thus their proposed models are merely conceptual and are validated internally based on the casual relationship between their model components.

3.2 Research Design

This research is classified as quantitative applied research. It develops a mathematical model and validates against actual manufacturing supply chain quality costs data, and provides COQ estimator for similar supply chains to achieve certain level of quality.

Research goal is to develop a comprehensive mathematical model in order to forecast quality costs in four echelon manufacturing supply chain. Model utilizes COQ as a performance measure of all of the entities within supply chain.

Consideration of customer perceived quality to define quality level is a key issue in the model and the time series effect of quality costs and quality level is examined against their functions parameters.

This research is basically inspired by Ramudin and Alzaman et al (2009) and Castillo-Villar and Smith et al (2012) works. The model has been developed and then evaluated against actual manufacturing supply chain data and is validated externally. Major hypotheses are defined to examine model validity.

Validation is carried on by utilizing statistical linear regression analysis for all of the quality costs components and subsequently Durbin-Watson test is used to examine the time series effect of independent variables. Based on the statistical analysis results the model modification and justifications would be presented.

3.3 Hypotheses

In this study, the proposed model is examined and validated against two sets of data points, quality immaturity data and quality maturity data. Classification of data to periods as quality maturity and immaturity periods is based on the observed COQ behavior over time.

Before the hypotheses testing, we have to verify whether if attributed quality costs behavior to each time interval is correct or not. It deems to examine if the first interval COQ data follows classic trade off behavior and the second interval COQ trend is in accordance with continuous improvement quality cost behaviors. In the first interval conformance expenditure should be increased over time to achieve ongoing decrease in

nonconformance costs and also existence of local economic COQ points is necessary to be classified as trade-off model. In the second interval ongoing decrease in nonconformance costs can be achieved by maintaining or even reducing existing conformance costs and also non-existence of economic COQ point is crucial to categorize the COQ behavior at this interval similar to continuous improvement model.

Evaluation of whether if the dataset follows classic trade off or continuous improvement COQ behavior is conducted through drawing trend-line on COQ data points in both intervals.

After the verification of distinction between COQ behaviors in two intervals the COQ function is examined against decision parameters. In this model five major hypotheses need to be examined in order to statistically validate proposed model. As the behavior of COQ and quality level is studied for two datasets to verify validation results, each of major hypotheses would have its own sub-hypotheses. Major hypotheses firstly aim to study possible relationship between COQ function and quality level then to acknowledge relationship between relative decision variables and parameters and cost function.

To validate proposed model set of major hypotheses is defined. Each hypothesis tests statistical significance of the model in the following order:

1. The correlation between independent variables is tested using Pearson-coefficient test. As the coefficient value for full dependency of variable is zero and in the real data analysis it seems unrealistic, model's desired value for coefficient is between -0.5 and 0.5 for pair variables to be considered uncorrelated
2. Linear regression analysis would be conducted on all of the costs sub-functions for each datasets
3. R^2 Values are examined against criteria. Due to the domain of study context, $R^2>$ 0.4 is acceptable for regression model if the homogeneity of duplicated tests is met. This value is used to obtain the sample size and is not used to accept or reject the hypotheses.
4. p - values are examined against criteria. 95% confidence interval is predefined criteria based on the former studies and type of industry

5. Residual analysis would be performed to assess fitness of linear regression
6. Durbin-Watson statistic test is performed to determine the presence of autocorrelation within the regression's residuals in order to detect time series effect. The accepted value for the test statistic is dependent to the confidence level, sample number, number of variables. Table 3.1 shows the acceptable range of DW statistics.

Sample Size	Variables including intercept	auto correlated DL	Non-auto correlated DU	Inconclusive
32	2	DW<1.37	DW>1.50	1.37<DW<1.50
	3	DW<1.31	DW>1.57	1.30<DW<1.57
48	2	DW<1.49	DW>1.57	1.49<DW<1.57
	3	DW<1.45	DW>1.62	1.45<DW<1.62
80	2	DW<1.61	DW>1.66	1.61<DW<1.66
	3	DW<1.58	DW>1.68	1.58<DW<1.68

Table 3.1 Durbin-Watson statistic critical values

Major hypotheses are shown in the Table 3.2. Proposed model is examined against quality maturity and immaturity intervals in order to achieve external validity with anticipated duplicated results. First major hypothesis examines relationship between total COQ and quality level. As COQ function aims to predict quality costs for specific quality level value, independency of these variables leads to COQ function uselessness.

Other four major hypotheses test the parameters of COQ functions. COQ function is comprised of parameters and each parameter is consisting of several input parameters and decision variables. These hypotheses test the accuracy of relationship between cost function as a dependent variable and parameters as independent variables directly. Consequently they examine cost function and variables (decision and input) relationship indirectly.

Validation process objects to examine if the model is capable of generalization within all the same manufacturing supply chain scenarios considering model assumptions – regardless of quality maturity status- or not.

Internal validity of the model is achieved as proposed relationships are based on the casual relationship between dependent and independent. External validity of the model is highly dependent on the attributes of collected data. In the other words, if all of the model assumptions are met and all of model constrains are considered comparable results could be expected.

Purpose	Hypothesis
To determine if there is a linear relationship between total quality costs and quality level	$\boldsymbol{Hypothesis_{1a}}$: There is a positive relationship between quality costs and quality level in quality immaturity period. $\boldsymbol{Hypothesis_{1b}}$: There is a negative relationship between quality costs and quality level in quality maturity period.
To assess relationship between prevention costs as a dependent variable and number of actual good products and lead-time deviation as an independent variables	$\boldsymbol{Hypothesis_{2a}}$: Actual good product percentage has positive effect and lead-time deviation has negative effect on prevention costs in quality immaturity period. $\boldsymbol{Hypothesis_{2b}}$: Actual good product percentage has positive effect and lead-time deviation has negative effect on prevention costs in quality maturity period.
To assess relationship between inspection error rates and appraisal costs	$\boldsymbol{Hypothesis_{3a}}$: There is negative relationship between inspection error rate and appraisal costs at quality immaturity period.

	$\boldsymbol{Hypothesis_{3b}}$**:** There is negative relationship between inspection error rate and appraisal costs at quality immaturity period.
To study if the predicted internal failure costs is a good estimator of actual internal failure cost	$\boldsymbol{Hypothesis_4}$ **:** Predicted internal failure cost is a good estimator of quality costs for both quality maturity and immaturity periods.
To study between external failure costs as a dependent variable and actual defective products and lead-time deviation as independent variables.	$\boldsymbol{Hypothesis_{5a}}$: Actual defective products percentage and lead-time deviation have positive effect on external failure costs in quality immaturity period. $\boldsymbol{Hypothesis_{5b}}$: Actual defective products percentage and lead-time deviation have positive effect on external failure costs in quality maturity period.

Table 3.2 Major Hypotheses

4. Model Development

As it was mentioned in literature review, former studies examined manufacturer decision parameters impact on supply chain performance. Performance measurement system for a supply chain should satisfy all of the supply chain entities even if their objectives are conflicting. Measurement results has to be beneficial to all of the stakeholders within supply chain, though this will not happen except performance measurement focuses on individual product or process.

This Model represents a product based supply chain. It analyses quality costs as a performance measurement for an individual product. In order to obtain more accurate results we have constrained our model. These constraints will decrease the external applicability of the model, but due to the inherent challenges in supply chain, e.g. conflict of interests, development chain and large network seems inevitable. Model assumptions are as follow:

1. Product demand is constant throughout the whole supply chain from supplier to end-user
2. The model is suitable for the existing manufacturing firms and does not suit to establish new supply chain.
3. There are two 100% Inspections during the whole product delivery process. First one is when the component is delivered to the manufacturer and the other one is when the final products are about to be shipped. Both of the inspection processes belong to the manufacturing authorities. Sample inspections and testing during the manufacturing process and product delivery to retailers is not considered as an inspection process.
4. Inspection errors are error type I and error type II. Error type I is the manufacturer risk or risk of rejecting true null hypothesis. Error type II is the customer risk and is defined as a risk of accepting false null hypothesis. Error type I in this context is the classification of good component as a defective one and error type II is the classification of defective component as a good component. In this model error

type I and II exist in supplier stage inspection, but since error type II is complex to measure it is assumed to be equal to error type I. Error type II is the only inspection error assumption in the manufacturing stage as the rework would be accomplished at the same place and error type II could be highly negligible.

5. Time value of the money should be ignored to prevent the model to generate biased results and compare the results based on quality costs only.
6. All of the scraped parts at the manufacturing stage could be sold at lower price.
7. Defective products during distribution and retailing process are recoverable, but the cost of products return is not considered.

PAF classification of quality costs is used in this model due to its universal acceptance. The model includes four entities in the supply chain; supplier, manufacturer, distributer and retailer. Thus the model is four echelon supply chain. Model is based on single entity supply chain and it is assumed that for each level of supply chain only one entity is considered.

The model aims to estimate the total quality cost in supply chain of a specific product while calculating each of the prevention, appraisal, internal failure and external failure costs separately as a key performance measurement. The total COQ is nothing other than the sum of all the cost categories.

Also, as opposed to an existing supply chain the model is not a static snapshot of supply chain which incorporates COQ. This model dynamically represents COQ evolution in time series. The model aims to predict total quality cost at different time intervals considering quality level of processes. Thus appropriate definition of quality level and quality maturity status is required in order to achieve this goal.

Model's conceptual process flowchart map is shown in Figure 4.1. Model shows the flow of products in the whole supply chain network form supplier to the end users. To develop a mathematical model two types of variables and a set of parameters are defined as Input parameters, Decision variables and Model parameters.

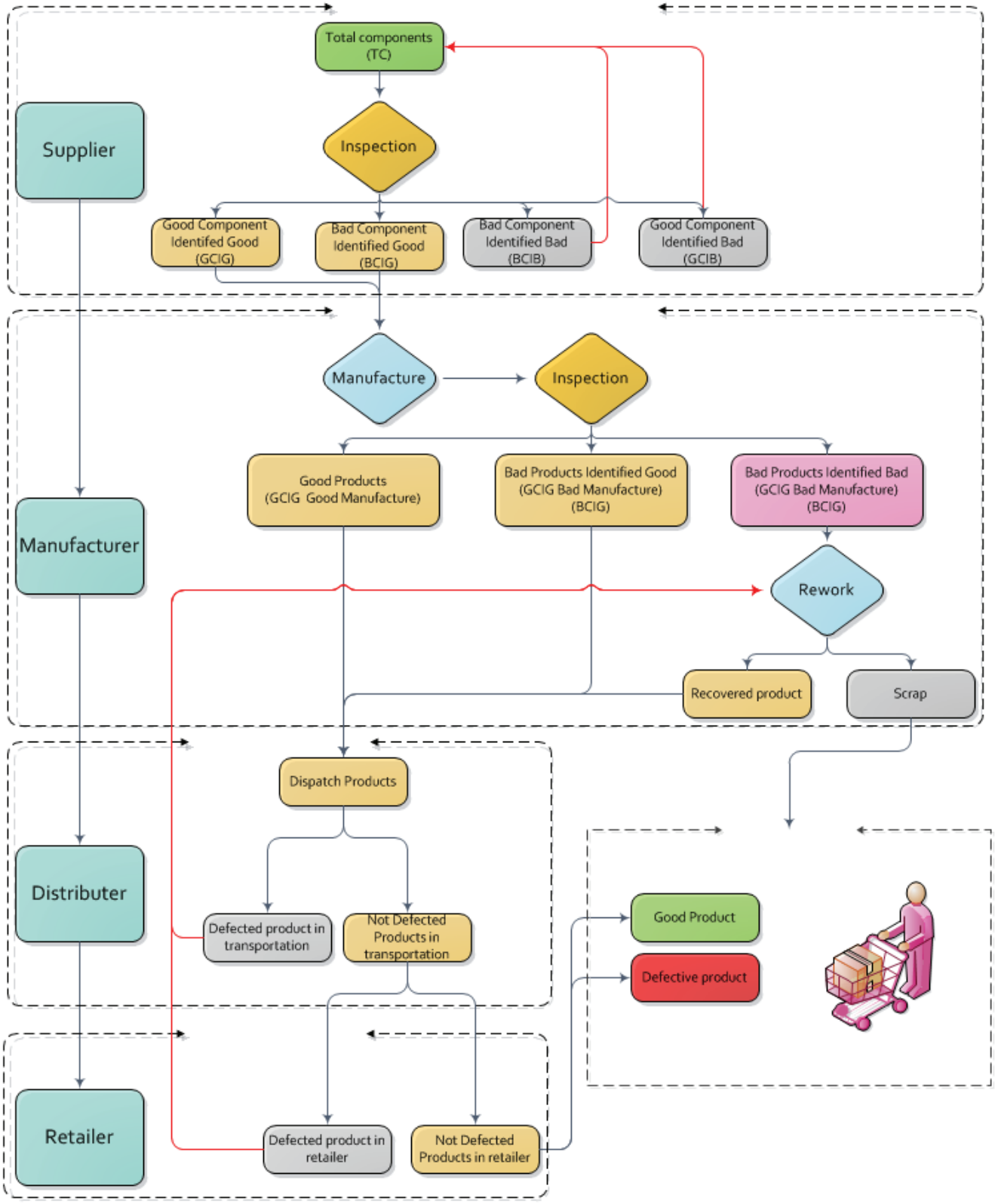

Figure 4.1Supply Chain Network process flow chart considering COQ

4.1 Input Parameters

These variables are varying in different intervals and may affect the final result, but they are not the ones which the model targets, i.e. their impact on the objective function is not assessed. Table 4.1 shows the model input parameters acronyms and their relative definitions

No	Input Parameters	Definition
1	D	Average demand of product
2	P	Average Price of product at retailer
3	SP_m	Average Discounted price of product
4	ARC_s	Average rework cost if component is defective at supplier
5	ARC_m	Average rework cost if component is defective at manufacture
6	ARC_d	Average rework cost if component is defective before delivery to retailer
7	ARC_r	Average rework cost if component is defective before delivery to customer

Table 4.1 Input parameters definition

4.2 Decision Variables

Decision variables are the variable which could vary during the time interval and could have a critical impact on the objective function. Decision variables change if the process characteristics like production process, inspection process and others change. Amendment in these variables could result in quality level and status changes. This is however not true for input parameters. Table 4.2 shows the model decision variables and their acronyms and definitions.

4.3 Model parameters

Model parameters are shown in the boxes of process flow chart. In each tier of supply chain there are parameters which are obtained from decision variables and input parameters. Each of these parameters should be defined in accordance with its tier level in the supply chain.

No	Decision Variables	Definition
1	DR_s	Defect rate at supplier
2	DR_m	Defect rate at manufacturer
3	DR_d	Defect rate during delivery
4	DR_r	Defect rate at retailer
5	IER_{sm}	Inspection error rate between supplier and manufacturer (Error Type I, II)
6	IER_{md}	Inspection error rate between manufacturer and distributer (Error Type II)
7	RR_m	Rework rate at manufacturer
8	LTD	Total lead-time deviation from customer order to product deliver (days)

Table 4.2 Decision variables definition

4.3.1 Tier 1: Supplier

Good components identified good (GCIG): these are the components which are good and classified good after the inspection at the supplier stage.

$$GCIG = D(1 - IER_{sm})(1 - DR_s) \quad \textbf{Equation 4.1}$$

Bad components identified good (BCIG): This category of components refers to the components which is defective but during the inspection they are classified as good components.

$$BCIG = D(IER_{sm})(DR_s) \quad \textbf{Equation 4.2}$$

Good components identified bad (GCIB): These are the good components which are classified as bad due to the inspection error of the manufacturer.

$$GCIB = D(IER_{sm})(1 - DR_s) \quad \textbf{Equation 4.3}$$

Bad components identified bad (BCIB): The components in this category are defective, and the inspection identified them as defective components, so would not be accepted by the manufacturer.

$$BCIB = D(1 - IER_{sm})(DR_s) \quad \textbf{Equation 4.4}$$

4.3.2 Tier 2: Manufacturer

Good manufactured products (GMP): These are the products which are acquired through appropriate manufacturing process on components which supplied in a good condition.

$$GMP = D(1 - DR_m)(1 - IER_{sm})(1 - DR_s) \quad \textbf{Equation 4.5}$$

Bad Manufacture products identified good (BMPIG): This category involves the products which are defective due to the bad production process or the components supplied as defective, but they are classified as good products as a result of inspection error at the manufacturing stage.

$$BMPIG = D(IER_{md})[(1 - IER_{sm})(1 - DR_s)(DR_m) + (IER_{sm})(DR_s)] \quad \textbf{Equation 4.6}$$

Bad manufactured products identified bad (BMPIB): Here we have the products which are defective as a result of bad manufacturing or components supplied as bad. These products may be sent for a rework process.

$$BMPIB = D(1 - IER_{md}) * [(1 - IER_{sm})(1 - DR_s)(DR_m) + (IER_{sm})(DR_s)] \quad \textbf{Equation 4.7}$$

Recovered products (RP): These are the products which could be assumed as good products after the rework process. These products are acquired through multiplication of BMPIB product with rework rate.

$$RP = D(RR_m)(1 - IER_{md}) * [(1 - IER_{sm})(1 - DR_s)(DR_m) + (IER_{sm})(DR_s)] \quad \textbf{Equation 4.8}$$

Scarp: Scrap refers to the products which are not recoverable and would be sold at a reduced price.

$$Scrap = D(1 - RR_m)(1 - IER_{md}) * [(1 - IER_{sm})(1 - DR_s)(DR_m) + (IER_{sm})(DR_s)] \quad \textbf{Equation 4.9}$$

4.3.3 Tier 3: Distribution

Dispatched products: Sum of good products, assumed good products and recovered products is referred to here as dispatched products. These products are loaded to distributer's facilities and should be shipped to retailers.

Although the scrapped parts are being sold as well they are not included in this category. The reason is that the model of supply chain is for the final good product and scrap is thus not considered in the supply chain model.

$$\begin{aligned} Dispatched\ Products =\ & GMP + BMPIG + RP \\ & = D\{(1 - DR_m)(1 - IER_{sm})(1 - DR_s) \\ & + (IER_{md})[(1 - IER_{sm})(1 - DR_s)(DR_m) + (IER_{sm})(DR_s)] \\ & + (RR_m)(1 - IER_{md})[(1 - IER_{sm})(1 - DR_s)(DR_m) \\ & + (IER_{sm})(DR_s)]\} \end{aligned}$$

Equation 4.10

Not defected products in transportation: These are the products which do not become defective during the whole distribution process.

These products must be delivered and unloaded at the retailers. Defective products would be returned to the manufacturer for the rework process.

$$Not\ defected\ products\ in\ transportation\ = (1 - DR_d) * Dispatched\ Products$$

Equation 4.11

4.3.4 Tier 4: Retailer

Not defected products in retailer: products which are not get defected at retailer inventory are in this category. Defected products at retailer would be returned to manufacturer for rework.

$$Not\ defected\ products\ in\ retailer\ =$$

$$(1 - DR_r) * \ Not\ defected\ products\ in\ transportation = \quad \textbf{Equation 4.12}$$

$$(1 - DR_r)(1 - DR_d) * \ Dispatched\ Products$$

4.3.5 Tier 5: Customer

All of the products which do not become defective in retailer and are calculated in Equation 4.12 shall reach to the end-users. These products are essentially comprised of two types of products which are as follows:

Actual good products: This is the sum of good manufactured products and reworked products which do not become defective at distributer and retailer stages.

$$Actual\ Good\ products =$$
$$D(1 - DR_r)(1 - DR_d)$$
$$\{(1 - DR_m)(1 - IER_{sm})(1 - DR_s) \quad \textbf{Equation 4.13}$$
$$+ \ (RR_m)(1 - IER_{md})[(1 - IER_{sm})(1 - DR_s)(DR_m)$$
$$+ (IER_{sm})(DR_s)]\}$$

Actual defective products: These are the assumed good products which are defective and could reach to the end user due to the inspection errors.

$$Actual\ Defective\ products =$$
$$D(1 - DR_{r)}(1 - DR_d)(IER_{md})[(1 - IER_{sm})(1 - DR_s)(DR_m) \quad \textbf{Equation 4.14}$$
$$+ (IER_{sm})(DR_s)]$$

4.4 Mathematical Functions

Quality level function and cost function are the central part of the model. They are the model output and any judgment about supply chain performance regarding COQ should be perpetuated based on these two outputs. This model aims to calculate quality cost and quality level at different levels of quality maturity. It is also able to forecast the probable outcome on the quality investment.

4.4.1 Quality level

Quality level in cost of quality does not have an agreed upon definition. Most of authors who studied quality level in cost of quality in supply chain, defined quality level based on the number of defective products. They proposed a range from 0 to 100 percent as representation of quality level, where 100% quality level refers to the state when there are no defective products in the system (Ramudhin, Alzaman et al. 2008, Castillo-Villar, Smith et al. 2012, Castillo-Villar, Smith et al. 2012).

However, the definition of quality based on the defective products, does not seem to be a comprehensive definition of quality level. Garvin (1996) defined quality in eight dimensions of performance, features, reliability, conformance, durability, serviceability, aesthetics and perceived quality.

Each of these dimensions has its own definition and addresses a specific requirement of a customer. Presumably all of these dimensions will not apply to all of services and products but the definitions of quality level considering Garvin's framework will allow a systematic identification and prioritization of quality requirements for various processes.

Applying all of the quality dimensions in defining quality and measuring quality level seems idyllic, but in the conceptual supply chain model, quality could be defined as perceived quality as each product would have different quality dimension and quality priority. If the model is defined for specific process or product then other dimension could be considered. Mahanty and Naikan et al. (2012) proposed a combined effect of product quality, lead-time and time delivery as quality perception for COQ performance measurement in supply chain.(Mahanty, Naikan et al. 2012)(Mahanty, Naikan et al. 2012)(Mahanty, Naikan et al. 2012)

In this study the perceived quality is determined as a base to define and measure quality level. It is defined as a multiplication of actual good component parameter in Equation 4.15, and lead-time deviation variable as follows:

$$QL = \left[\frac{Actual\ Good\ Product}{D} * \left(1 - \frac{Actual\ Lead\ Time}{Expected\ Lead\ Time}\right)\right]\% \qquad \textbf{Equation 4.15}$$

Where actual good product defined in Equation 4.13 and average expected lead-time could be calculated from historical data.

4.4.2 Quality Cost Function

Feigenbaum's PAF model is utilized to classify quality cost components in this model. The quality cost is divided to four major groups: prevention costs, appraisal costs, internal failure costs and external failure costs. In each tier of supply chain, i.e. supplier, manufacturer, distributer and retailer, these costs will be calculated. Proposed model is validated statistically in the upcoming chapter. Table 4.3 shows the cost components of the model.

4.4.2.1 Prevention Costs

Prevention cost in supply chain must consider all of the prevention activities investment in each tier of supply chain. None of the variables and parameters can define prevention cost directly. Castillo-Villar and Smith et al (2012) claimed that the prevention cost is the function of number of good product. They divided the prevention cost in relationship to good product to three scenarios; supplier prevention activities, manufacturer prevention activities and mutual prevention activities between supplier and manufacturer. They argued that the number of good product is related to prevention activities, since as the number of good products increases the overall quality level will increase as well and these products do not need to be reworked.

Evidently, prevention cost is hence dependent on the number of good products which come out of manufacturing process. Nevertheless, in our model we proposed this relationship in terms of the good products which reach to the customer instead. The reason is that we are considering the whole supply chain as a system beneficiary and not just the manufacturing entity. Moreover, the definition of quality of Castillo-Villar and Smith et al. (2012) is based on the number of good products in the whole system, which is the reason why their analogy seems to be correct. But in our model the definition of quality is based on the consideration of whether the product is defective and whether it was delivered on time.

No	Quality Cost Components	Definition
1	COQ_{SC}	Cost of Quality in supply chain
2	P_{SC}	Prevention costs in supply chain
3	A_{SC}	Appraisal costs in supply chain
4	IF_{SC}	Internal failure costs in supply chain
5	PIF_{SC}	Predicted internal failure costs
6	IF_S	Internal failure costs in supplier
7	IF_M	Internal failure costs in manufacturer
8	IF_D	Internal failure costs in distributor
9	IF_R	Internal failure costs in retailer
10	EF_{SC}	External failure cost in supply chain

Table 4.3 Quality cost components definitions and abbreviations

As a result, in our model we propose prevention costs as an independent variable and the number of good products and lead-time as dependent variables as follow:

$$P_{SC} = \alpha_1 * Actual\ Good\ products + \beta_1 * LTD + \gamma_1 \quad \textbf{Equation 4.16}$$

Where $\alpha_1$is the coefficient of actual good products and β_1 is the coefficient of lead-time deviation and γ_1 is the fixed amount of prevention costs.

4.4.2.2 Appraisal Costs

Former works focused on the relationship of appraisal costs and inspection error rate.(Ramudhin, Alzaman et al. 2008, Castillo-Villar, Smith et al. 2012). In our model the appraisal costs is defined based on its dependency on the inspection error rate at supplier and the inspection error rate at manufacturer. The reasoning behind this is based on the assumption that when the appraisal costs increase the inspection error should decrease and there is thus a relationship between these components.

$$A_{SC} = \alpha_2 * IER_{sm} + \beta_2 * IER_{md} + \gamma_2 \quad \textbf{Equation 4.17}$$

Where α_2 is the coefficient of the inspection error at the supplier stage, β_2 is the coefficient of the inspection error at the manufacturing stage and γ_2 is the fixed value interpreted as appraisal fixed costs.

4.4.2.3 Internal Failure Costs

These are the costs incurred in the supply chain as a result of manufacturing defective products. However, defective products are identified at inspection and test stations within the supply chain and would not be delivered to the end-users. Internal failure costs for the supply chain in this model are calculated based on the predicted internal failure costs. Predicted internal failure costs are equal to the sum of the internal failure costs at each tier of supply chain. Contrary to prevention cost and appraisal costs in the manufacturing supply chain, the internal failure costs are calculable at each stage of supply chain separately. They are therefore calculated based on the probable amount of defective products at each tier of supply chain and their relative rework costs. The number of defective products could be estimated from the defect rate at each stage, but due to the significant variance in the rework cost of defective components the average rework costs at each stage is used.

After estimation of predicted internal failure costs value, the actual internal failure cost is calculable from predicted internal failure costs:

$$IF_{SC} = \alpha_3 * PIF_{SC} + \gamma_3 \qquad \textbf{Equation 4.18}$$

Where α_3 is the coefficient for predicted internal failure costs and $\gamma_3$is the constant value which could be interpreted as internal failure fixed costs.

The predicted value for internal failure costs has four components which are internal failure costs at supplier, manufacturer, distributer and retailer. The predicted internal failure cost is comprised of 4 components shown in Equation 4.19.

$$PIF_{SC} = IF_S + IF_m + IF_d + IF_r \qquad \textbf{Equation 4.19}$$

$\boldsymbol{IF_S}$: The first component of the predicted internal failure cost refers to all of the internal failure costs incurred due to the bad component manufacturing. The defective products are identified and classified as defective by manufacturer. Due the model inspection

condition at supplier level, where both of the inspection error types (I and II) exist, the good components identified bad (GCIB) in Equation 4.3 and bad components identified bad (BCIB) in Equation 4.4 would be sent for rework. Nonetheless, as a result of supplier self-inspection - which is considered out of the supply chain model – it is assumed that the GCIB shall not go through rework process.

Thus the value of internal failure at supplier is equal to the multiplication of BCIB value and average rework cost at supplier level.

$$IF_S = ARC_s * BCIB \qquad \textbf{Equation 4.20}$$

$\boldsymbol{IF_m}$**:** Internal failure costs at the manufacturer are in this model are comprised of two components. The first component is similar to the internal failure costs at supplier level and is equal to multiplication of total number of defective products to average rework cost at manufacturing level. Total number of defective products at manufacturing stage is equal to Bad manufactured products identified bad (BMPIB) which is shown in Equation 4.6. The second component of internal failure costs at manufacturer level is the cost of selling irrecoverable products or scrap at discounted price, which essentially is the lost profit instead of cost. The amount of scrap parts is shown in Equation 4.9. Also due to large variance of product's discounted price the average discounted price is considered in the model. The final equation of internal failure is as follow:

$$IF_m = ARC_m * BMPIB + (P - SP_m) * scrap \qquad \textbf{Equation 4.21}$$

$\boldsymbol{IF_d}$**:** Internal failure costs at the distributer are equal to the multiplication of total number of defective products at the delivery stage by relative average rework cost. Total number of dispatched products to the distribution stage is shown in Equation 4.10. Multiplication of defect rate at distributer to this value would give the total number of defective products at this stage. The value of internal failure at distributor is shown in the following equation:

$$IF_d = DR_d * Dispatched\ Products * ARC_d \qquad \textbf{Equation 4.22}$$

IF_r: Using the Equations 4.11 and 4.12 with analogy used to generate internal failure costs at distributer tier in Equation 4.22, the internal failure costs at retailer would be as follow:

$$IF_r = DR_r * Not\ defected\ products\ in\ transportation * ARC_r \quad \textbf{Equation 4.23}$$

4.4.2.4 External Failure Costs

External failure costs are the most challenging quality costs to be measured. Like prevention costs it seems impossible to generate a function which could directly calculate external failure costs from input parameters and decision variables. Apparently there is a relationship between the numbers of defected products that reach to the end users and the external failure costs. Also, based on the definition of quality in this model there could be a relationship between external failure costs and lead-time deviation. In this model external failure costs are assumed to be dependent variable and actual defective product in Equation 4.14 and lead-time deviation as independent variables. The following equation shows the external failure function:

$$EF_{SC} = \alpha_4 * Actual\ Defective\ products + \beta_4 * LTD + \gamma_4 \quad \textbf{Equation 4.24}$$

Where α_4 is the coefficient of actual defective products, β_4 is the coefficient of lead-time deviation and γ_4 is the fixed external failure costs.

4.4.2.5 Total COQ Function

The total COQ function for supply chain is nothing but the sum of PAF components of quality costs in the whole supply chain demonstrated in former equations. Equation 4.25 shows the COQ function.

$$COQ_{SC} = P_{SC} + A_{SC} + IF_{SC} + EF_{SC} \quad \textbf{Equation 4.25}$$

Relative cost component functions are shown in Equations 4.16, 4.17, 4.18 and 4.24 respectively.

4.5 Data Collection

In order to conduct external validation of the proposed model an updated manufacturing supply chain COQ data is required. Due to the existence of overlap between COQ data and businesses' financial data and also because of financial data confidentiality for most of businesses, the accurate data collection was the toughest challenge of this research. Furthermore, the demanded data is not just confined to a single entity within supply chain, because data should be collected from all the tiers of supply chain from suppliers to retailers. As a consequence, the data collection process needed an extensive interaction with supply chain entities.

Moreover, another challenge is due to the fact that the COQ data is not limited to finance or quality departments – if they exist - but it comprises of broad spectrum of the data from ranging from the defect rate at shop floor to quality plans investments. The collection of such data required highly interactive cross-functional collaboration with organizations' authorities.

Collected data for current research is from a manufacturing supply chain and by virtue of confidential nature; name of the company must not be disclosed. Studied supply chain product is automobile flywheel. Flywheel is used in the engine of automobile motor and is considered as a critical engine part.

Flywheel could be manufactured via different casting processes like sand casting and die casting or CNC machining. Focused part is manufactured through die casting and machining processes, and the final product is delivered to a spare part retailer for sale. In the studied manufacturing supply chain, supplier provides casted components and the machining process is performed at the manufacturer. Both the suppliers and the manufacturer are involved in other production processes other than flywheel, but as it was mentioned in the literature review, supply chain performance measurement should focus on specific product or service, and other processes are thus disregarded.

As a result this study merely focuses on the flywheel supply chain. Supply chain considerations are centered on the manufacture entity although all of the entities are reflected. Considerations are as follow:

1. Supply chain demand is equal to flywheel production capacity at manufacturer
2. Defect rate, inspection error rates and rework costs are estimated based on the manufacturer historical data
3. Final selling price and scrap discounts are determined through manufacturer and retailers agreement, and are available in both manufacturer's and retailers' historical data
4. Lead-time deviation is the variation between the actual replenishment time and the planned replenishment time between retailers and manufacturer.

Also, as it was mentioned earlier, Cost figures do not have conclusive meaning in the business context and they have to be evaluated against other monetary values like revenue, profit and etc. Thus the costs are considered as a percentage of total supply chain sales.

The data is collected in tight collaboration with suppliers, manufacturer, distributer and retailers. Categorization of quality costs was the first step to be done. In this study, the quality costs are classified based on the PAF model. The classification is shown in Table 4.4.

Table 4.4 Costs components classification based on PAF model

No	Cost Component	Cost Item
1	Suppliers Prevention Costs	Supplier training Supplier auditing Supplier certification
2	Manufacturer Prevention costs	Quality planning and programs Quality planning training Audits Certifications
3	Distributer Prevention Costs	Distributers auditing Distributers certification
4	Retailers Prevention Cost	Retailers Training

		Retailers auditing
5	Supplier Appraisal Costs	Outgoing Inspection Equipment test and calibration
6	Manufacturer Appraisal Costs	In process testing field audit equipment test and calibration outgoing inspection
7	Suppliers Internal Failure Costs	Corrective actions
8	Manufacturer Internal Failure Costs	Discounting sub optimal products Rework Re-inspection of rework Scrap setup changes (till the point of first good product) Sorting and screening of sub optimal products
9	Distributer Internal Failure Costs	Defected component after manufacturing
	Retailers Internal Failure Costs	Defected component after delivery
10	External Failure Costs	Goodwill, reputation damage Lost sale penalties recall Refund/compensation/allowance Returned products Warranty costs

4.5.1 Sample Size

The context of research is applied research and the method used to validate the proposed model was determined to be linear regression analysis as we want to study the impact of

decision variables and supply chain parameters on COQ value and study their relationship. Utilizing design of experiments or ANOVA could be helpful, but the numbers of influential variables were limited to two in each equation which justifies multiple regression application.

There are several conventional rules proposed in the literature to calculate the sample size in linear regression. However, none of these rules is validated and proved to be a method which could be generally accepted by all the scholars.

In this research the sample size is determined by statistical power method for multiple regressions proposed by Cohen (1983). Method is based on the rejection of null hypothesis, which is the existence of relationship between dependent and independent variables. (Null Hypothesis:$\beta_1, \beta_2, \beta_3, \dots, \beta_n = 0$, where β_i is the independent variable coefficient). In this test statistical power is the probability of rejecting this hypothesis.

It has to be mentioned that the higher statistical power value does not guarantee stable coefficient and means that the regression model is not necessarily extensible to other samples from the same population and stability of coefficient must be testified through other parameters.

In order to estimate sample size the following parameters should be determined:

Effect size (f^2): Effect size is the measure of relationship between two variables. In the multiple regressing it can be calculated through Equation 4.26. Estimation of effect size is the main challenge in identifying sample size in multiple regressions (Maxwell 2000). Maxwell (2000) stated that based on the rule of thumb for each independent variable there should be 10 samples. As a result in our work the minimum sample size must not be less than 20 samples.

$$f^2 = \frac{R^2}{1 - R^2} \qquad \textbf{Equation 4.26}$$

In the Equation 4.26, R^2 is coefficient of determination and in the multiple regressions and determines how the obtained outcomes are replicated by the model. Based on the research context and in order to obey rule of thumb stated above in this study, desired R^2

is 0.4 or above if the homogeneity of R^2 value on the similar samples is met. Consequently the f^2 value is equal to 0.67.

Statistical significance (α): As the confidence interval in whole study is 95% the statistical significance is equal to 0.05

Statistical power $(1-\beta)$: Statistical power is the probability of Null hypothesis rejection when it is false. Statistical power is not directly calculable and is calculated through β value which is error type II or is the probability of accepting false Null hypothesis. In this research desired β value is equal to 0.05 and is higher than most of studies value which is 0.20.

Number of predictors: Is the number of independent variables in multiple regressions. In our model the maximum number of predictor per regression is two. A-priori analysis technique used SAS system software determine 30 samples as a minimum samples size, for model regressions to be significant.

4.5.2 Data Characteristics

In total eighty quality cost samples were collected from the manufacturing supply chain. Sampling starting point is close to initiation of quality management system implementation by manufacturer and subsequent samples are quality costs for the following months. First interval includes 32 samples and the second interval is comprised of 48 sample. Both of them are thus above the minimum accepted sample size which was determined as 30.

Each sample involves is the total quality cost for the relative month. Cost data are presented in a percentage of total gross sales of the product due to the data confidentiality. Thus to ease the model calculation the actual good components and actual bad components are calculated as a percentage of demand in the validation process.

Descriptive statistics of prevention costs, appraisal costs, internal failure cost, external failure costs, total quality costs and quality levels are shown for the whole sample in Table 4.5, for the first interval in Table 4.6 and for the second interval in Table 4.7.

	QL	Prevention Cost Percentage	Appraisal Cost Percentage	Internal Failure Cost Percentage	External Failure Cost Percentage	Total Quality Cost Percentage
Mean	0.725079	0.066771767	0.054333562	0.066173733	0.019771009	0.207050072
Median	0.750065	0.072272077	0.056027401	0.063453708	0.017450247	0.207240745
Standard Deviation	0.074819	0.011227299	0.008871089	0.009509474	0.005299194	0.009258943
Sample Variance	0.005598	0.000126052	7.86962E-05	9.04301E-05	2.80815E-05	8.5728E-05
Range	0.282758	0.040567937	0.040181685	0.038647192	0.019185565	0.044109925
Minimum	0.528659	0.037085036	0.03074034	0.050726602	0.012814319	0.184530926
Maximum	0.811417	0.077652973	0.070922024	0.089373793	0.031999884	0.228640851
Count	80	80	80	80	80	80

Table 4.5 Whole Sample Descriptive Statistics

	QL	Prevention Cost Percentage	Appraisal Cost Percentage	Internal Failure Cost Percentage	External Failure Cost Percentage	Total Quality Cost Percentage
Mean	0.660832	0.055881978	0.048511637	0.075517145	0.025121339	0.2050321
Median	0.676319	0.05720283	0.049234947	0.073660157	0.025969402	0.203847364
Standard Deviation	0.077507	0.010529068	0.009916476	0.007395285	0.004366949	0.010359913
Sample Variance	0.006007	0.000110861	9.83365E-05	5.46902E-05	1.90702E-05	0.000107328
Range	0.270542	0.035855098	0.034746157	0.022869791	0.01417389	0.038364184
Minimum	0.528659	0.037085036	0.03074034	0.066504003	0.017825994	0.184530926
Maximum	0.799201	0.072940134	0.065486496	0.089373793	0.031999884	0.222895111
Count	32	32	32	32	32	32

Table 4.6 First Sample Descriptive Statistics

	QL	Prevention Cost Percentage	Appraisal Cost Percentage	Internal Failure Cost Percentage	External Failure Cost Percentage	Total Quality Cost Percentage
Mean	0.76791	0.074031627	0.058214845	0.059944792	0.016204123	0.208395386
Median	0.773007	0.074337825	0.058368858	0.060031462	0.016352804	0.208481319
Standard Deviation	0.027623	0.002046073	0.005380911	0.004106597	0.001462556	0.008287606
Sample Variance	0.000763	4.18641E-06	2.89542E-05	1.68641E-05	2.13907E-06	6.86844E-05
Range	0.111371	0.007986347	0.021987591	0.01661073	0.006196463	0.036282891
Minimum	0.700046	0.069666626	0.048934433	0.050726602	0.012814319	0.19235796
Maximum	0.811417	0.077652973	0.070922024	0.067337332	0.019010782	0.228640851
Count	48	48	48	48	48	48

Table 4.7 Second Sample Descriptive Statistics

As the data graph shows in Figure 4.3, two different behavior of quality cost are observable through these 80 points. Figure shows the total COQ as the percentage of total gross sale of supply chain -COQ metric- in relative points with their trend lines and for two intervals subsequently.

Sample number 33, is where the highest COQ is observed and this point is chosen as a borderline between the two sample intervals. From the first sample to the sample 32 the behavior of quality costs is almost similar to Juran trade-off COQ. Likewise, from sample 33 to sample 80 the COQ trend is similar to the continuous improvement model. These two incoherent intervals are named in this thesis quality immaturity and quality maturity periods, respectively.

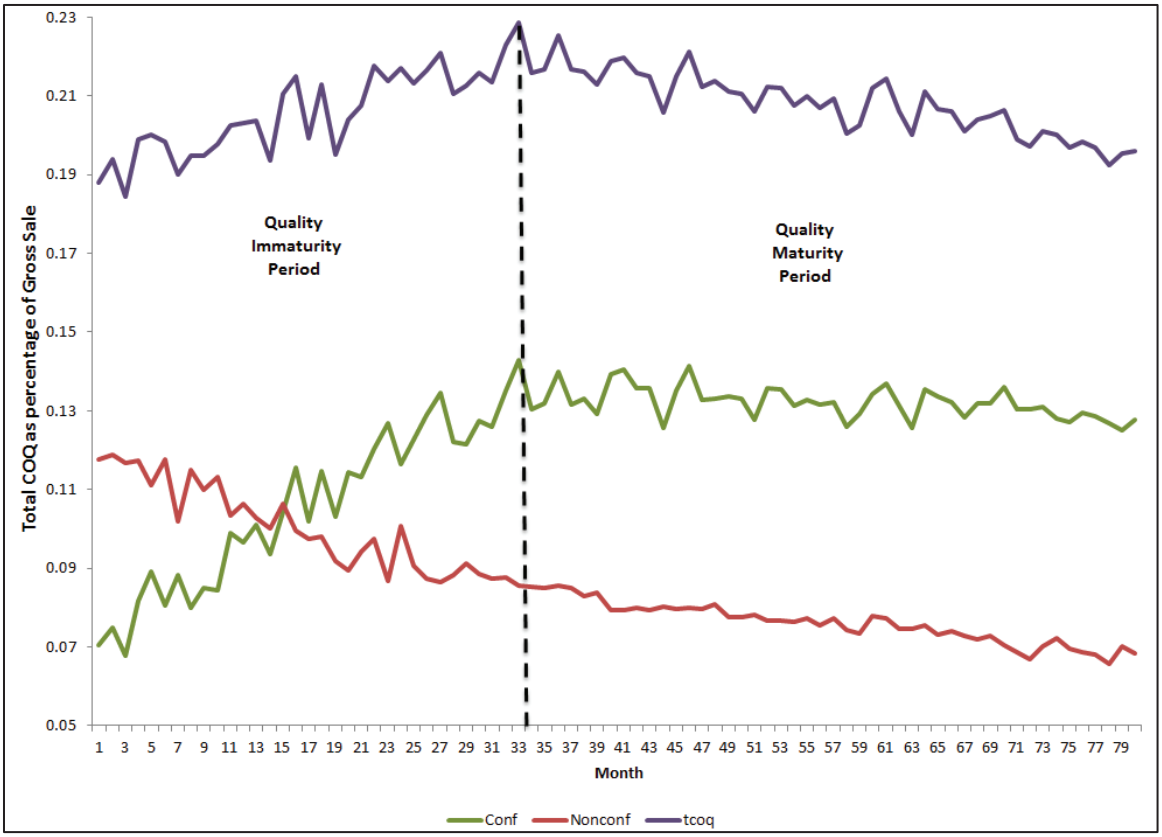

Figure 4.2 Total COQ for whole samples

Tables 4.6, 4.7 and 4.8 show the descriptive statistics of these variables for the whole sample and for the subsamples.

DR_s_	DR_s	DR_m	DR_d	DR_r	IER_{sm}	IER_{md}	RR_m	LTD
Mean	0.047563	0.040475	0.038725	0.030088	0.035463	0.025163	0.291063	5.875
Median	0.045	0.037	0.036	0.03	0.035	0.024	0.2995	5
Mode	0.03	0.034	0.033	0.03	0.037	0.023	0.299	4
Standard Deviation	0.016154	0.009821	0.007046	0.004276	0.003789	0.00513	0.031887	3.00369
Sample Variance	0.000261	9.65E-05	4.96E-05	1.83E-05	1.44E-05	2.63E-05	0.001017	9.022152
Range	0.052	0.038	0.027	0.019	0.018	0.019	0.153	13
Minimum	0.028	0.029	0.03	0.022	0.029	0.017	0.2	1
Maximum	0.08	0.067	0.057	0.041	0.047	0.036	0.353	14
Count	80	80	80	80	80	80	80	80

Table 4.8 Descriptive statistics of decision variables for whole sample

DR_s_	DR_s	DR_m	DR_d	DR_r	IER_{sm}	IER_{md}	RR_m	LTD
Mean	0.064563	0.049906	0.045781	0.033219	0.037625	0.030313	0.275938	7.90625
Median	0.063	0.0485	0.046	0.032	0.0375	0.0305	0.2765	7.5
Mode	0.057	0.042	0.049	0.03	0.037	0.028	0.2	7
Standard Deviation	0.009827	0.008996	0.005835	0.004709	0.004324	0.003207	0.046639	3.813045
Sample Variance	9.66E-05	8.09E-05	3.4E-05	2.22E-05	1.87E-05	1.03E-05	0.002175	14.53931
Range	0.029	0.032	0.024	0.019	0.018	0.012	0.153	13
Minimum	0.051	0.035	0.033	0.022	0.029	0.024	0.2	1
Maximum	0.08	0.067	0.057	0.041	0.047	0.036	0.353	14
Count	32	32	32	32	32	32	32	32

Table 4.9 Descriptive statistics of decision variables for first sample

DR_s_	DR_s	DR_m	DR_d	DR_r	IER_{sm}	IER_{md}	RR_m	LTD
Mean	0.036229	0.034188	0.034021	0.028	0.034021	0.021729	0.301146	4.520833
Median	0.034	0.034	0.034	0.028	0.034	0.0215	0.3015	4
Mode	0.03	0.034	0.033	0.028	0.037	0.023	0.299	4
Standard Deviation	0.006855	0.002796	0.002119	0.002231	0.002547	0.002711	0.003837	0.945079
Sample Variance	4.7E-05	7.82E-06	4.49E-06	4.98E-06	6.49E-06	7.35E-06	1.47E-05	0.893174
Range	0.023	0.011	0.01	0.008	0.009	0.01	0.014	4
Minimum	0.028	0.029	0.03	0.024	0.029	0.017	0.294	3
Maximum	0.051	0.04	0.04	0.032	0.038	0.027	0.308	7
Count	48	48	48	48	48	48	48	48

Table 4.10 Descriptive statistics of decision variables for second sample

Decision variable data as defined in the model development section is collected for the corresponding eighty COQ points. Collected data is based on the available historical data at suppliers, manufacturer and retailers and missing data were collected through interview with senior engineers. As the data points are time series, in order to have more accurate study of COQ and quality level, the time value of money is not considered in data.

Furthermore, input parameters are cost values which vary drastically and are dependent on several internal and external factors which identified at tactical and strategic levels like market demand, production practices and etc. In this study, their evaluation is based on the average estimation of field managers as there were not sufficient historical accurate recorded data for them for the whole study period. Several interviews have been conducted with field engineers, production supervisors and senior managers at manufacturer and supplier and they played an interactive role in whole data collection and data analysis. Also in some cases field tests have been conducted to examine the conformity of obtained data. These values are assumed to be constant throughout the sampling period. Tables 4.6, 4.7 and 4.8 show the descriptive statistics of these variables for the whole sample and for the subsamples.

5. Data Analysis

In this chapter the set of hypotheses which were presented in the previous chapteris examined through statistical analysis. The first hypothesis is related the relationship of COQ and quality level and the following hypotheses are for testing of the proposed mathematical model in both time intervals.

Before performing hypotheses testing assumed trends for subsamples should be verified. Otherwise, data sub-grouping which was proposed in this thesis is meaningless and the subsamples cannot be categorized as different groups of the data for different quality maturity states, despite their similar descriptive statistics characteristics. Trend- line analysis is considered sufficient to test asserted behavior for subsamples, hence for the major hypotheses multiple regression analysis technique is conducted using SAS software. Regression test validity method and assumptions have been shown in previous chapters.

5.1 Subsamples Trend Verification

At this point we will test whether the collected data in the first time interval follows Juran's trade-off pattern or not. In Juran's trade-off model, quality costs data should have two following characteristics (Juran 1962):

1. Increasing in conformance costs will lead to the diminishing trend in non-conformance costs.
2. There is an economic COQ point, i.e. the point at which the quality cost corresponding to a certain quality level is lowest.

Other assertion that the second quality costs subsamples are following continuous improvement model should be examined. Continuous improvement COQ model should have also the following characteristics (Ittner 1996):

1. Decreasing in non-conformance costs is achieved while maintaining or even decreasing the amount of conformance costs.

2. There is no economic COQ point at any quality level and the lowest COQ is obtained at the point at which perfection is achieved.

To verify claimed trend for first subsample, plot of COQ data over time is required. Figure 5.1 shows the COQ value as a percentage of gross sales over 32 months. As the linear trend shows in the figure, the total COQ is increasing over time. Also decreasing in non-conformance costs is achieved through augmentation of conformance costs. Thus we can assert that the first subsample has met the first condition of trade-off model.

For the second condition, although there is not a single COQ optimized economic point, there are some local optimized points. In general month 14 is the relative optimized COQ economic point and we can consider points 3,7, 19,24 and 28 as local optimized COQ economic point. Thus the second condition is met too. As the two conditions are met in the first subsample, the assertion that first subsample follows the Juran's trade-off model is supported.

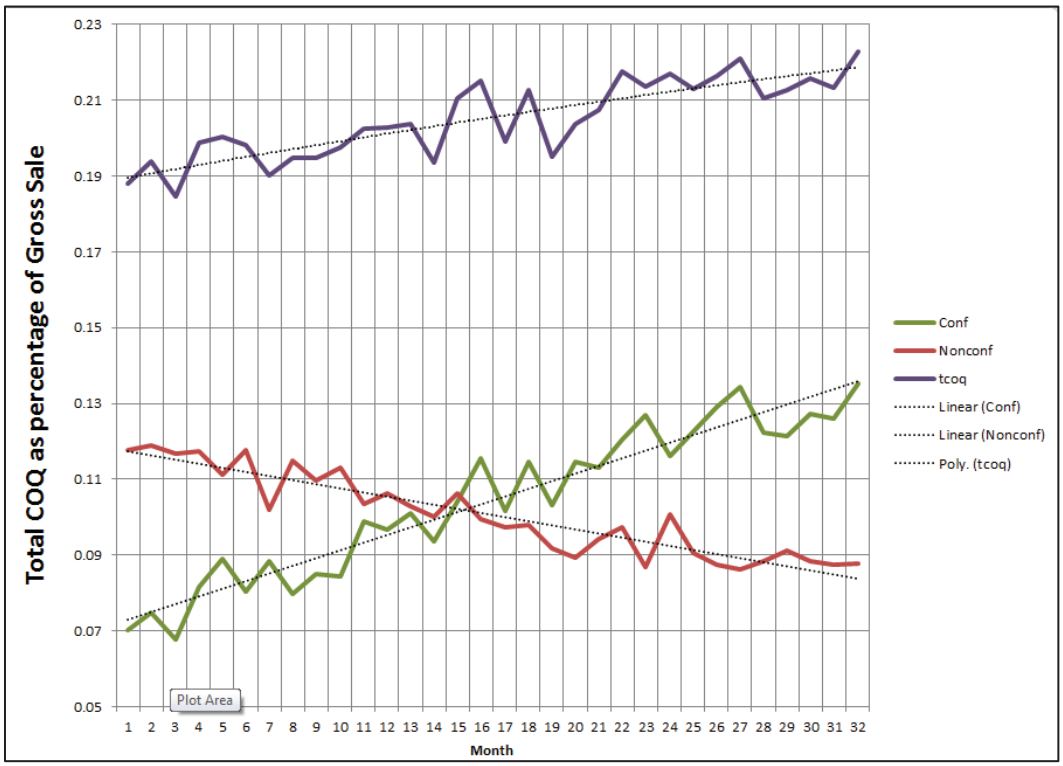

Figure 5.1 COQ trend in the first subsample

For the second subsample also the two conditions of continuous improvement trend should be satisfied. As the trend shows in Figure 5.2, the total quality costs are constantly decreasing hence the non-conformance costs are decreasing too. This could be justified as a result of continuous improvement nature where the effect of root problem solving effect in former stages and advancement in knowledge and processes leads to achieve lower non-conformance costs while maintaining same or lower investment in conformance costs. As a result we can say that the first condition is met.

Also based on the CoQ graph trend in Figure 5.2, there is no optimized or even local optimized COQ economic point in collected data in second subsample, subsequently the second condition is met too. Finally, based on our trend lines in second subsample, the corresponding COQ trend could be considered as continuous improvement COQ model.

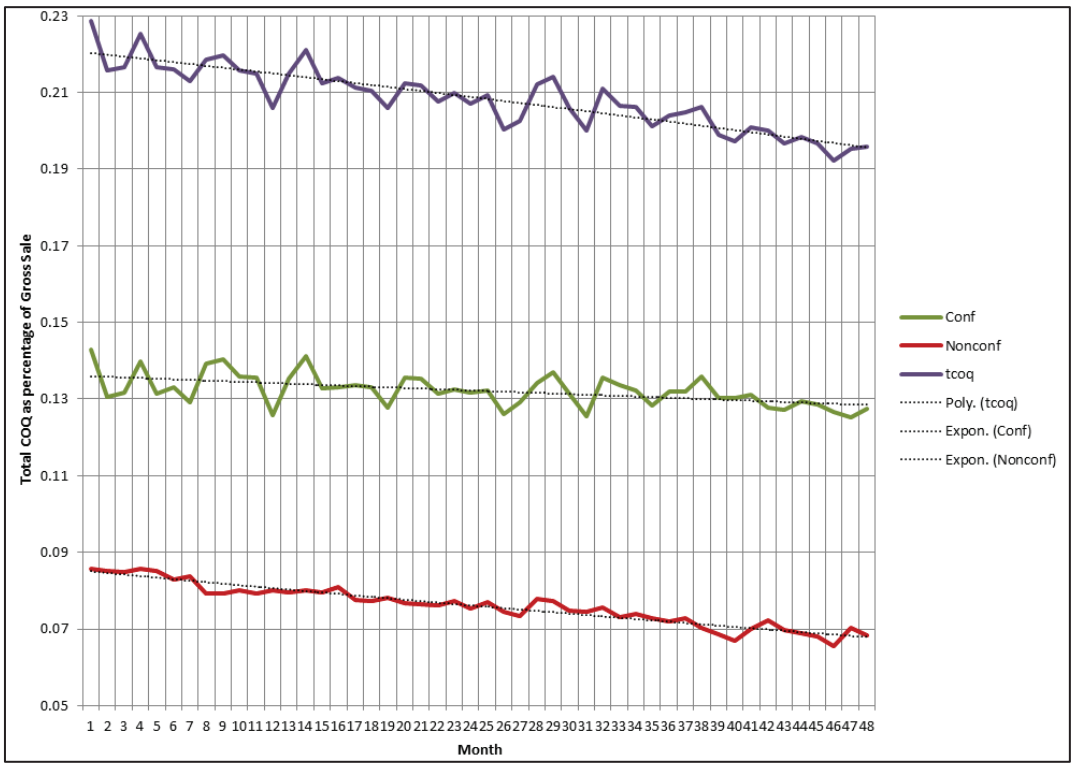

Figure 5.2 COQ trend in second subsample Major Hypotheses Testing

5.2 Major Hypotheses Testing

As it was mentioned previously, linear regression analysis is utilized to examine the proposed hypotheses. Within the major hypotheses, the fifth hypothesis, similarly as the

four explanatory hypotheses, is a prerequisite for data subgrouping. It examines the effect of COQ on quality level and their significant relationship in two subsamples. This hypothesis is constructed based on explanatory hypotheses results which acknowledged presence of different COQ behaviors. Test is required to be conducted in order to signify the subgrouping through examination of relationship between COQ and quality level in different quality maturity status.

Hypotheses 1 to 5 statistically test model components. Using simple or multiple regression analysis, residual analysis and Durbin-Watson test are the steps in these hypotheses testing.

$\boldsymbol{Hypothesis_{1a}}$:

H_0:There is a positive relationship between quality costs and quality level in quality immaturity period.

H_1:There is not a positive relationship between quality costs and quality level in quality immaturity period.

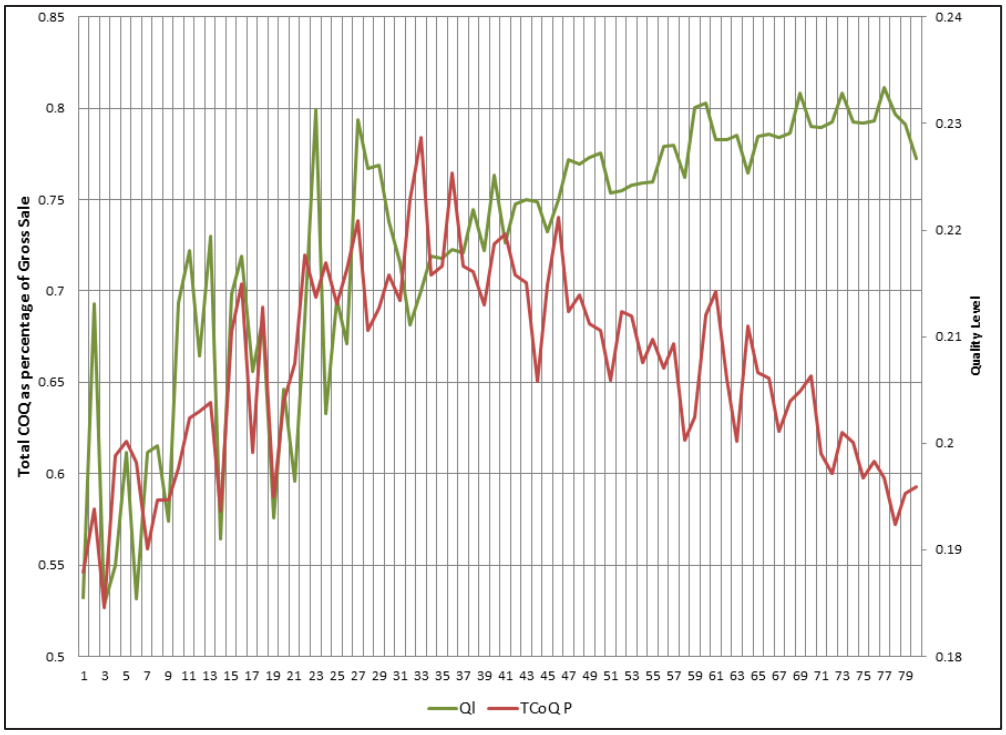

Figure 5.3 Quality Level and COQ trend in whole samples

In this hypothesis the COQ is assumed as independent variable and quality level as dependent variable. The first subsample with the quality immaturity period data is demonstrative of Juran's trade off model and based on the characteristics of this model, the existence of positive relationship between quality level and quality costs is necessary. Figure 5.3 shows the trend of COQ and Quality level over the whole subsamples. Based on the graph the increasing trend for quality level and COQ is observable. The results of regression analysis are shown in Table 5.1.

Variable	Coefficient	P-value <0.05	R^2	Significance F <0.05	DW test
Intercept	-0.41872	0.044056	0.49	6.99585E-06	1.92
COQ percentage	5.265307	7E-06			

Table 5.1 Regression analysis for total quality costs and quality level in immaturity period

Based on the regression analysis results all of the expected values are within the acceptable range. In the next step residual analysis is conducted to testify normality of residuals and their independency. Figure 5.4 shows standardized residual plot of COQ as a dependent variable and Fit plot of quality level and COQ in 95% confidence level. Comprehensive study of residual plots is shown in Appendix 1.

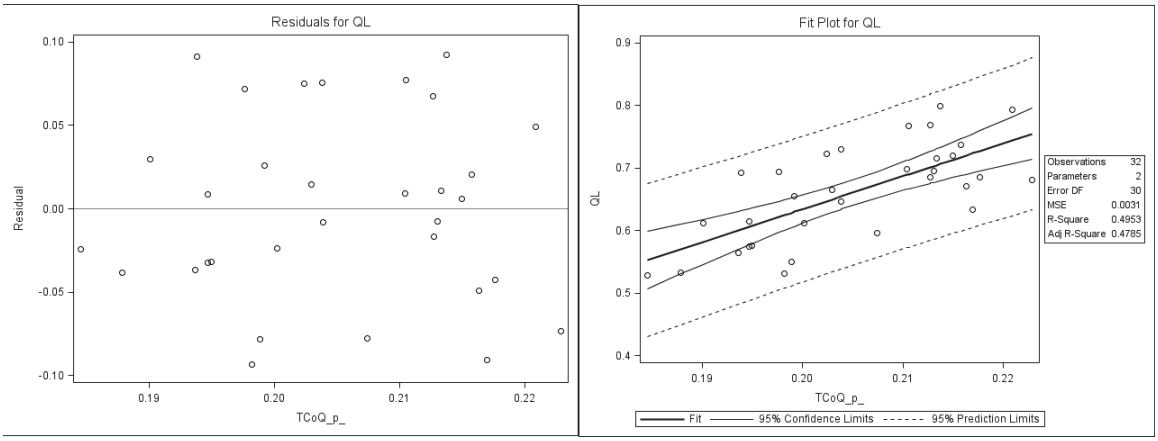

Figure 5.4 Residual plot and fit plot for quality level and COQ regression in immaturity period

Based on the Figure 5.4 the residuals are scattered around zero value without any identifiable pattern. This proves the independency of residuals. Also, based on the normal

probability plot of residuals in Appendix 1, residuals are quite normal. As result of the regression and the positive value of the independent variable, and also the residual analysis, it could be concluded that we cannot reject null hypothesis and there is not sufficient evidence to support the alternative hypothesis.

$\boldsymbol{Hypothesis_{1b}}$:

H_0: There is a negative relationship between quality costs and quality level in quality maturity period.

H_1: There is not a negative relationship between quality costs and quality level in quality maturity period.

Similarly as in the previous hypothesis the independent variable is COQ and the dependent variable is quality level. As the COQ data in maturity period asserted to follow continuous improvement COQ model, there should be a negative correlation between COQ and quality level. As it is shown in Figure 5.3, the trend of COQ in the maturity period is decreasing while quality level is diminishing. Statistical analysis of data using regressions is conducted and the results are shown in table 5.2.

Variable	Coefficient	P-value <0.05	R^2	Significance F <0.05	DW test
Intercept	1.303763	2.55E-24	0.59	1.39E-10	1.38
COQ percentage	-2.57133	1.39E-10			

Table 5.2 Regressions analysis for total quality costs and quality level in maturity period

Obtained statistics are within the acceptable range except the Durbin-Watson test statistic. The value of DW is 1.38 which based on the DW statistic critical value table presented in methodology chapter is within inconclusive range. It means that we cannot claim existence or absence of autocorrelation in samples. Although test statistic is still acceptable as there is not proven autocorrelation within sample, but existence of autocorrelation in this hypothesis is not necessarily unpredictable, as the time is a key factor which affects COQ and quality level. It means that the time series effect is inevitable in this regression model and would not affect results conclusion.

Residual analysis is conducted in the next step in order to assess normality of residual and their independency. Elaborate graph of residual analysis for this hypothesis is presented in Appendix 2. Figure 5.5 shows the fit plot of quality level and COQ in 95% confidence interval and standardized residuals against COQ. Based on fit graph there is an outlier in data but is insignificant considering test statistics. Also there is not any pattern in residual, thus we cannot reject the null hypothesis and there is a negative relationship between COQ and quality level at quality maturity period which subsequently affirms the continuous improvement COQ behavior of this period.

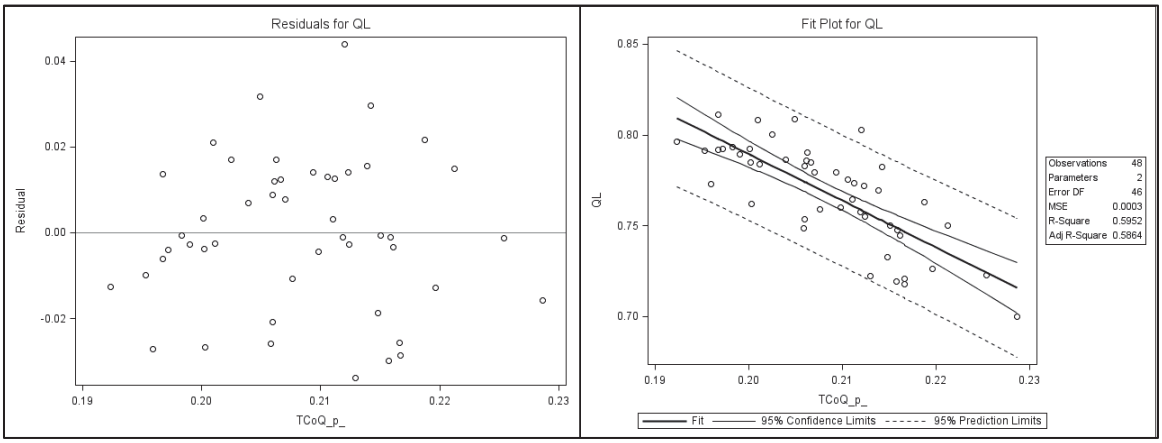

Figure 5.5 Residual plot and fit plot for quality level and COQ regression in maturity period

$\boldsymbol{Hypothesis_{2a}}$:

H_0: Actual good product percentage has positive impact and lead-time deviation has negative effect on the prevention costs in quality immaturity period.

H_1: Actual good product percentage does not have positive impact or lead-time deviation does not have negative effect on the prevention costs in quality immaturity period.

This hypothesis examines the first component of total quality cost function based on the PAF model, which is prevention cost. In our model, the prevention cost as a percentage of supply chain gross revenue is assumed to be a dependent variable while the ratio of actual good products and the amount of lead-time deviation are considered as independent variables. It is expected that the ratio of actual good products should have

positive impact and the lead-time deviation should have negative impact on the prevention costs.

As there are two independent variables in the proposed model, in order to justify linear regression model there should not exist correlation between independent variables. Pearson Correlation Coefficient is used to study the correlation between independent variables.

As it was revealed earlier, the satisfactory range of Pearson-Coefficient value to assert uncorrelated variables is between -0.50 to 0.50. Table 5.3 shows the correlation matrix for dependent and independent variables in prevention cost function at quality immaturity period. Based on Pearson-Coefficient value between actual good products and lead-time deviation, we can affirm uncorrelated relationship between independent variables.

	Prevention Costs	**Actual Good Product**	**LTD**
Prevention Costs	1		
Actual Good Product	0.926087616	1	
LTD	-0.586693755	-0.494972482	1

Table 5.3 Correlation matrix of actual good product, lead-time and prevention costs in immaturity period

In the next step, multiple regression analysis is performed. Results of the regression analysis are shown in table 5.4. As it demonstrates a positive sign of actual good product coefficient and a negative sign of lead-time deviation, attest the proposed relationships between dependent and independents variables. Also test statistics values are within the acceptable range which signifies proposed relationship. Durbin-Watson test statistic is very close but lower than 1.57 which is critical value to confirm non-autocorrelation within sample data. But this value still does not confirm existence of the autocorrelation within the sample data which means that the existence of time series effect in the first subsample - actual good product and lead-time deviation – is not evident.

Variable	Coefficient	P-value <0.05	R^2	Significance F <0.05	DW test
Intercept	-0.281220393	5.26E-10	0.88	4.75E-14	1.53
Actual Good Product	0.425666123	3.49E-12			
LTD	-0.000469263	0.029471			

Table 5.4 Multiple regressions analysis for prevention costs in immaturity period

Comprehensive residual analysis graphs are shown in Appendix 3. Normal distribution of residuals is shown in the graphs. Also, Figure 5.6 shows the standardized residuals against both of the independent variables. No specific pattern of distribution is apprehensible for both of the independent variables. Results of the multiple regression analysis and the residual analysis lead us to not rejecting null hypothesis in favor of the alternative hypothesis. As a result, the number of actual good products has a positive impact on the prevention costs and the lead-time deviation has a negative impact on the prevention costs simultaneously in the quality immaturity period.

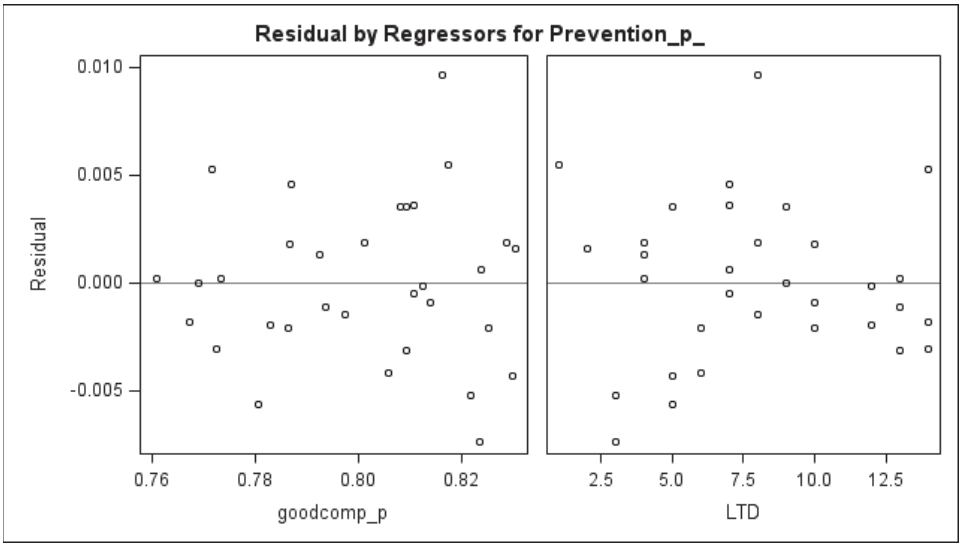

Figure 5.6 Residuals plot for independent variables in quality immaturity period

$Hypothesis_{2b}$:

H_0: Actual good products percentage has positive impact and lead-time deviation has a negative effect on prevention costs in quality maturity period.

H_1 : Actual good products percentage does not have positive impact or lead-time deviation does not have a negative effect on prevention costs in quality maturity period.

In this hypothesis the same assertion as in the previous hypothesis is examined, but now it is studied in quality maturity period, i.e. in the second subsample. The same steps as in the previous hypothesis testing should be taken in order to verify the proposed hypothesis.

The study of independent variables correlation using Pearson correlation coefficient is performed. Results of the correlation study are shown as a correlation matrix in Table 5.5. Based on the table there is a correlation between actual good product percentage and lead-time deviation as independent variables which challenges the significance of the proposed multiple regression analysis for prevention costs in quality maturity period.

	Prevention	**Actual Good Product**	**LTD**
Prevention Costs	1		
Actual Good Product	0.900176038	1	
LTD	-0.686056557	-0.734928178	1

Table 5.5 Correlation matrix of actual good product, lead-time and prevention costs in maturity period

Alternative solution is to run simple regression analysis for each independent variable separately and study the results. Simple regression analysis results for each independent variable are shown in Tables 5.6 and 5.7.

Variable	**Coefficient**	**P-value <0.05**	R^2	**Significance F <0.05**	**DW test**
Intercept	0.080746402	7.88E-50	0.47	7.376E-08	-
LTD	-0.001485296	7.38E-08			

Table 5.6 Regression analysis results for prevention costs and lead-time deviation in maturity period

Variables' coefficient signs in both regressions prove the positive impact of good products and negative impact of lead-time deviation on prevention costs. Challenging issue in the LTD regression is the value of R^2.

Variable	Coefficient	P-value <0.05	R^2	Significance F <0.05	DW test
Intercept	-0.046202896	4.13E-06	0.80	9.995E-18	1.681
Actual Good Product	0.140880444	1E-17			

Table 5.7 Regression analysis results for prevention costs and actual good product in maturity period

Based on the test statistics the R^2 value in the first simple regression is slightly above critical value but due to homogeneity of R^2 value condition mentioned in earlier chapter, it is not significant comparing to other regression value which is 0.80. In other words the regression analysis results shows higher dependency of the prevention costs on the number of actual good products rather than lead-time deviation or even their aggregation at quality maturity period.

All of the test statistics are at the desired range, specifically the Durbin-Watson test statistic which is higher than critical value of 1.57 and prove thereby the non-existence of autocorrelation within the sample data.

DW test statistic in second regression is justifiable based on the obtained data and comparing quality immaturity and maturity lead-time deviation trends. Lead-time deviation in the quality immaturity period is evidently declining as a result of supplier and distributor certification and training. This trend at quality maturity period does not continue as lead-time deviation is almost reached to a desired low value at the beginning of this period, based on the acquired data and management assertion.

As a result, prevention costs could be highly influenced by the number of good products at quality maturity period without significant effect on lead-time deviation.

Elaborate residual analysis graphs of the second simple regression are shown in Appendix 4. Also, Figure 5.7 shows the standardized residual plot against actual good products and fit plot of prevention costs and actual good components.

Based on these graphs the normality of residuals' distribution and the independency of residuals is evident. Also, based on the fit plot at a 95% confidence level there is just one outlier which does not have significant impact on the analysis results.

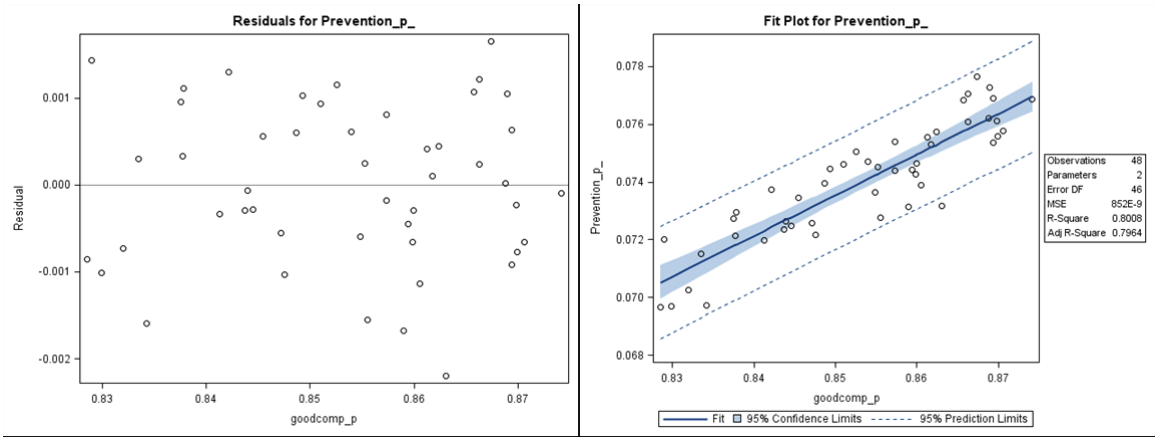

Figure 5.7 Residual plot and fit plot of residual for prevention cost at maturity period

Based on the results of correlation analysis and regression analysis, we can reject the null hypothesis in favor of alternative hypothesis. Alternative hypothesis assert that the prevention costs at quality maturity period is merely dependent on the number of actual good products and this variable has a positive impact on prevention costs.

$Hypothesis_{3a}$:

H_0: Inspection error rates have negative impact on appraisal costs at quality immaturity period.

H_1: Inspection error rates do not have negative impact on appraisal costs at quality immaturity period.

This hypothesis examines the relationship between appraisal costs and inspection error rate at supplier and at manufacturer. Presumably appraisal costs should have negative impact on the inspection error rates. It means that as much as a firm invests in their appraisal activities it should eventually reduce inspection errors. In the proposed model appraisal costs is assumed as dependent variable and inspection errors independent variables.

At the first step of multiple regression analysis, the correlation of independent variables should be studied. Correlation matrix of appraisal costs and independent variables is shown in Table 5.8. According to the table we can conclude that the independent variables are uncorrelated.

	Appraisal Costs	Inspection Error at Supplier	Inspection Error at Manufacturer
Appraisal Costs	1		
Inspection Error at Supplier	-0.3402	1	
Inspection Error at Manufacturer	-0.8375	0.206458	1

Table 5.8 Corroleation martix of appraisal costs

Regression analysis is performed in the next step. Results of the regression analysis are presented in Table 5.9. For both of the inspection error rates, i.e. at supplier and at manufacturer, the coefficient sign is negative which confirms the diminishing impact of appraisal costs on inspection error rates.

Challenging issue in this analysis is the p-value of inspection error rate at supplier which is 0.087 and is slightly greater than p-value at 95% confidence level which is 0.05. As the p-value is the likelihood of coefficient to be insignificant, increasing the confidence interval to 90%, will lead to not rejecting the null hypothesis. It means that at 90% confidence level the inspection error rate coefficient is significant.

Also, the critical value to affirm the presence of autocorrelation is 1.31, but the Durbin-Watson test statistic is not greater than 1.57 to assert non-autocorrelation. As a result, cannot conclude about the existence of autocorrelation within the sample data.

Variable	Coefficient	P-value <0.05	R^2	Significance F <0.05	DW test
Intercept	0.138703	4.41E-13			
IER_{sm}	-0.40079	0.087	0.730	5.49E-09	1.496
IER_{md}	-2.47792	5.68E-09			

Table 5.9 Regression analysis results for appraisal costs at immaturity period

Plot of residuals is shown in Figure 5.8. Also in Appendix 5, elaborate graphs of residual analysis are presented. Based on these graphs, no pattern for residuals is observable and the residual distribution is quite normal.

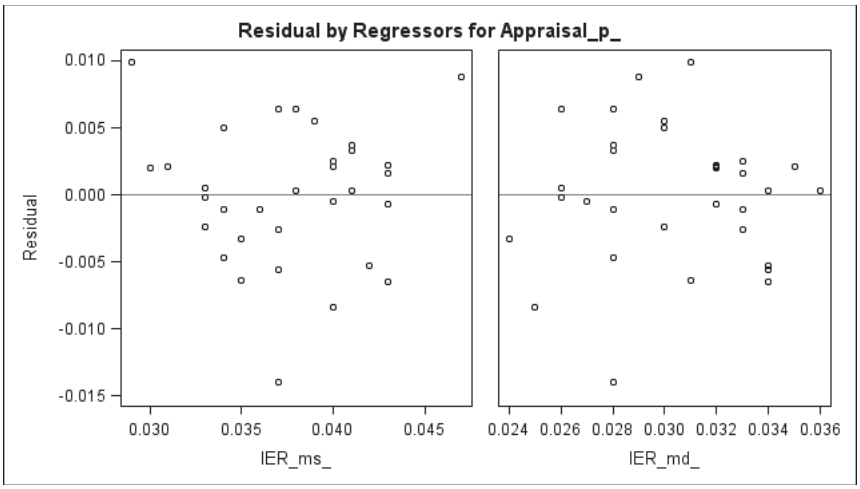

Figure 5.8 Residual plot of appraisal costs at immaturity period

Based on the results of regression analysis and considering the exception for the confidence interval modification, we will not reject null hypothesis and we can assert that the inspection error rate at manufacturer and supplier have negative impact on appraisal costs, and impact of inspection error rate at manufacturer is more weighty.

$\boldsymbol{Hypothesis_{3b}}$:

H_0: Inspection error rates have negative impact on appraisal costs at quality maturity period.

H_1: Inspection error rates do not have negative impact on appraisal costs at quality maturity period.

Assumption of this hypothesis is quite similar to the previous hypothesis and the only difference is that now it is examined in quality maturity period. Similarly to the previous hypothesis testing, the dependency of independent variables should be tested as a first step. Table 5.10 presents the correlation matrix of variables. Based on this table there is a high correlation between independent variable which prevent us from multiple regression analysis. As a result, simple linear regression is performed for both independent variables.

	Appraisal Costs	Inspection Error at Supplier	Inspection Error at Manufacturer
Appraisal Costs	1		
Inspection Error at Supplier	0.637103	1	
Inspection Error at	0.732252	0.764856	1

Table 5.10 Correlation matrix of variables for appraisal costs at qualitymaturity

Regression analysis results for both variables are shown in Tables 5.11 and 5.12. Low p-value for the first regression proves the insignificancy of inspection error rate at supplier as an appropriate predictor of appraisal costs. In Table 5.12 on the other hand the regression results confirm that the inspection error rate at manufacturer is an appropriate predictor of appraisal costs in the quality maturity period.

Variable	Coefficient	P-value <0.05	R^2	Significance F <0.05	DW test
Intercept	0.01243	0.135913	0.41	1.1234E-06	-
IER_{sm}	1.345795	1.12E-06			

Table 5.11 Regression analysis results for appraisal costs and inspection error rate at supplier in maturity period

Variable	Coefficient	P-value <0.05	R^2	Significance F <0.05	DW test
Intercept	0.026636	2.02E-07	0.54	3.325E-09	2.01
IER_{md}	1.453296	3.33E-09			

Table 5.12 Regression analysis results for appraisal costs and inspection error rate at manufacturer in maturity period

Interesting point here is the sign of the independent variable coefficient. It shows that decrease in the inspection error rate will lead to the decrease in the appraisal costs at quality maturity period. This could be justified through the fact that at quality maturity period both appraisal costs and inspection error rate are decreasing due to the former

investment in conformance costs. In other words, by keeping the same diminishing rate of appraisal costs we could still expect reduction in the inspection error rate.

Also, based on the regression results, at quality maturity period, the appraisal cost is very dependent on the inspection error rate at manufacturer. This is also reasonable as the inspection error rate at supplier has dramatically reduced in quality immaturity period due to the training and audits, and conformance costs by manufacturer. As a result, the appraisal cost is much related to the in-house quality control at quality maturity period in manufacturer firm, and there would not be significant amount of appraisal costs for suppliers.

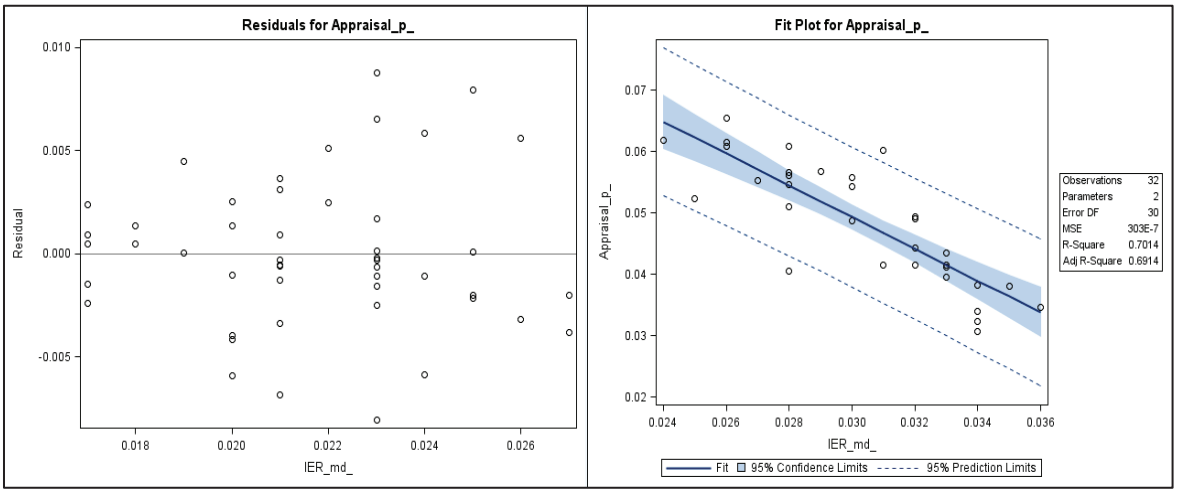

Figure 5.9 Residual plot and fit plot of regression analysis for appraisal costs in maturity period

Elaborate graphs of residual analysis are shown in Appendix 6. Figure 5.6 shows the fit plot and standardized residual plot against inspection error rate at manufacturer as independent variable. Two outliers in 95% confidence level are identified, but they are not found significant to affect the significance of regression. Also, based on the residual analysis graphs, independency of residual and their normality in distribution are evidently observable.

Based on the regression analysis result we reject the null hypothesis in favor of alternative hypothesis. It means that the inspection appraisal costs are only dependent on the inspection error rate at manufacturer at quality maturity level. By decreasing the

appraisal costs we can achieve the reduction in inspection error rate at manufacturer as a result of former and continuous conformance activities.

$\boldsymbol{Hypothesis_4}$:

H_0: Predicted internal failure cost is a good estimator of quality costs for both quality maturity and immaturity periods.

H_1: Predicted internal failure cost is not a good estimator of quality costs for both quality maturity and immaturity periods.

Predicted internal failure costs value could be calculated based on the Equation 4.19 presented in the model development chapter. It uses input parameters and decision variables to estimate internal failure costs.

The model asserts that the predicted internal failure costs are a good estimator of actual internal failure costs. Moreover, it is proposed that this is valid for any quality maturity level. As a result the hypothesis testing is performed for whole sample once as the predicted internal failure costs is nothing other than a function of decision and input parameters.

In the model there are two components which comprise internal failure costs. The first component is internal failure variable costs which are dependent to internal failure predicted value, and the other component is internal failure fixed costs. In order to prove that the proposed model is a good estimator, two conditions should be fulfilled in the regression model. First, the independent variable should be a highly accurate predictor of the dependent variable (i.e. the value of R^2 should be high), and, second, the value of the intercept should be close to the internal failure fixed costs.

Table 5.13 shows the linear regression analysis results. As it shows predicted internal failure costs have a positive correlation with internal failure costs. However, due to the lack of historical data regarding internal failure fixed costs, we cannot have a conclusion about the intercept value. From the statistics point of view, P-value and F value are extremely above acceptable range and the R^2 value is very high, thus we can conclude

that the predicted internal failure costs are a good estimator of actual internal failure costs.

Variable	Coefficient	P-value <0.05	R^2	Significance F <0.05	DW test
Intercept	18521.79	2.02E-31	0.96	2.31E-58	1.434
Predicted IF Costs	1.109772	2.31E-58			

Table 5.13 Regression analysis results for internal failure costs

Durbin-Watson test statistic proves the auto-correlation within the data sample, as it is lower than critical value of 1.58. in order to resolve autocorrelation issue, the test has been performed for both samples separately. No significant change was observed in the regression analysis, where the R^2 value has dropped slightly to 0.90 in the first subsample and to 0.92 in the second subsample. These values are also highly significant. Although within the first subsample the DW test statistic is decreased to 1.46 but as the sample size is decreases (from 80 to 32) the critical value diminishes too.

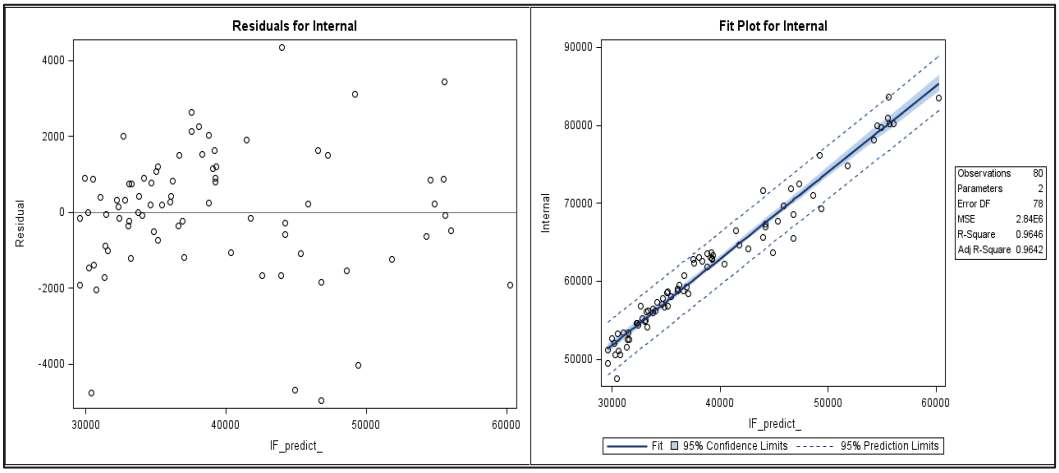

Figure 5.10 Residual and fit plot for internal failure costs regression

In this test, the critical value of 1.37 is a condition to prove the existence of autocorrelation, thus we cannot confirm the existence of autocorrelation in sample data. Remarkably in the second subsample the DW test statistic has increased significantly to 1.91, which is significantly above the critical value of 1.57, and we can hence confirm the non-autocorrelation within this subsample.

Comprehensive residual analysis is shown in Appendix 7. Figure 5.10 shows the residual plot against predicted internal failure as an independent variable. From the Appendix 7 and this graph we can assert that the residuals are distributed normally and are independent. Also, fit plot shows few outliers in 95% percent confidence interval, which however do not challenge the model significance.

As a result of analysis we cannot reject null hypothesis in favor of alter and we can conclude that the predicted internal failure costs are precise predictor of actual internal failure costs, regardless of supply chain quality status.

$\boldsymbol{Hypothesis_{5a}}$:

H_0: Actual defective products percentage and lead-time deviation have positive effect on external failure costs in quality immaturity period.

H_1: Actual defective products percentage or lead-time deviation does not have positive effect on external failure costs in quality immaturity period.

Based on the defined model, both actual bad products and lead-time deviation have positive impacts on the external failure costs in both time intervals.. In the model actual bad products and lead-time deviation are assumed as independent variables and external failure costs as dependent variables.

The independency of independent variables needs to be tested prior to performing the multiple regression analysis. Correlation matrix of all the variables is shown in table 5.14. According to the coefficients values, independent variables seem to be uncorrelated and we can step forward to the multiple regression analysis.

	External Failure Costs	**Actual Bad Products**	***LTD***
External Failure Costs	1		
Actual Bad Products	0.750214	1	
LTD	0.448529	0.452118	1

Table 5.14 Correlation matrix of variables in external failure costs in immaturity period

Results of multiple regression analysis are shown in Table 5.5. The p-value of LTD variable is critical issue in the analysis. It is much higher than the critical value of 0.05, thus the results related to the impact of lead-time deviation on external failure costs are disputed.

To resolve the issue linear regression is required for each variable separately. Results of the linear regression analysis are shown in Tables 5.16 and 5.17.

Based on the Table 5.16, the impact of lead-time deviation is entirely insignificant as the R^2 value is very lower than acceptable value.

Variable	Coefficient	P-value <0.05	R^2	Significance F <0.05	DW test
Intercept	0.011520738	1.61E-05	0.58	3.71E-06	-
Actual Bad Product	9.251777098	1.99E-05			
LTD	0.000157403	0.318008			

Table 5.15 Multiple regression analysis of external failure costs in immaturity period

Variable	Coefficient	P-value <0.05	R^2	Significance F <0.05	DW test
Intercept	0.021060016	9.4E-14	0.20	3.325E-09	-
LTD	0.000513685	0.010032			

Table 5.16 Regression analysis of external failure costs with LTD in immaturity period

Nonetheless, the results of linear regression analysis in Table 5.17 affirm the high dependability of external failure costs to actual bad products. Moreover, the high value of Durbin-Watson test statistic confirms the non-autocorrelation of the sample data.

Variable	Coefficient	P-value <0.05	R^2	Significance F <0.05	DW test
Intercept	0.011649357	1.23E-05	0.56	7.66E-07	1.79
Actual Bad Product	10.08727643	7.66E-07			

Table 5.17 Regression analysis of external failure costs with actual bad product in immaturity period

Residual analysis for this regression is performed in the next step. Complete graphs of residual analysis are presented is Appendix 8.

Also Figure 5.11 shows the plot of residuals against actual bad product as an independent variable. Based on the residual analysis we can confirm the normal distribution of residuals and at the same time their independency.

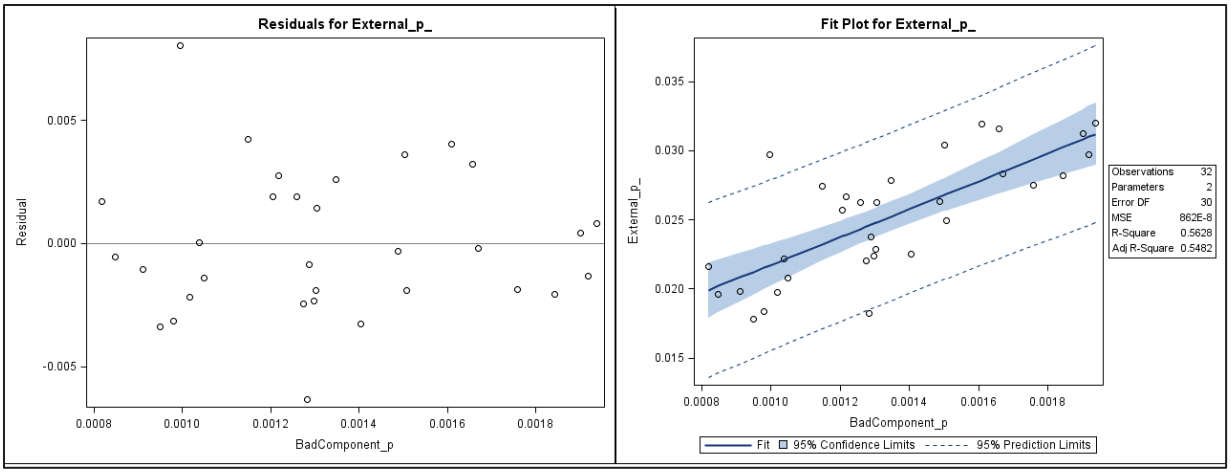

Figure 5.11 Residual plot and fit plot in immaturity period

Also, fit plot does not show any significant range of outliers which would cast doubt on regression analysis result.

As a result of these analyses we can reject the null hypothesis in favor of alternative hypothesis. Alternative hypothesis claim that the external failure costs.

$Hypothesis_{5b}$:

H_0: Actual defective products percentage and lead-time deviation have positive effect on external failure costs in quality maturity period.

H_1: Actual defective products percentage or lead-time deviation does not have positive effect on external failure costs in quality maturity period.

In this test, the dependent and independent variables remain the same as in the former hypothesis testing. The only change in this hypothesis is the sample. In this test we want to find out whether we can duplicate the same results with a different sample or not. In

another words, we want to determine whether the actual bad products and lead-time are appropriate predictors of external failure costs at quality maturity period or not.

Similarly as in the previous hypotheses, in order to be able to perform multiple regression analysis we need to examine the independency of independent variables.

Correlation matrix is shown in Table 5.18. As a result of this table, independent variables are correlated and we cannot step forward with multiple regression analysis.

	External Failure Costs	**Actual Bad Products**	***LTD***
External Failure Costs	1		
Actual Bad Products	0.893366	1	
LTD	0.571766	0.663212	1

Table 5.18 Correlation matrix of variables in external failure costs in maturity period

Consequently, for each independent variable simple linear regression is performed. Results of regression analyses are shown in Tables 5.19 and 5.20. According to Table 5.19 based on the R^2 value, we can conclude that the lead-time deviation is insignificant in prediction of external failure costs at quality maturity period, which is the same as the results obtained in quality immaturity period.

Variable	**Coefficient**	**P-value** **<0.05**	R^2	**Significance F** **<0.05**	**DW test**
Intercept	0.012204	2.44E-18	0.32	0.00002	-
LTD	0.000885	2.19E-05			

Table 5.19 Regression analysis of external failure costs with LTD in maturity period

On the other hand, the results of regression analysis in Table 5.20 show significant dependency of external failure costs on actual bad products. Also with the obtained value of Durbin-Watson test statistic, the existence of autocorrelation within sample data is highly unlikely.

Variable	Coefficient	P-value	R^2	Significance F	DW test
		>0.05	>0.4	>0.05	
Intercept	0.009407	8.87E-23	0.80	1.358E-17	1.79
Actual Bad Product	10.00062	1.36E-17			

Table 5.20 Regression analysis of external failure costs with Actual bad product in maturity period

Residual analysis of the regression is shown in the Appendix 9. Also Figure 5.12 demonstrates residual plot and fit plot of the model regression.

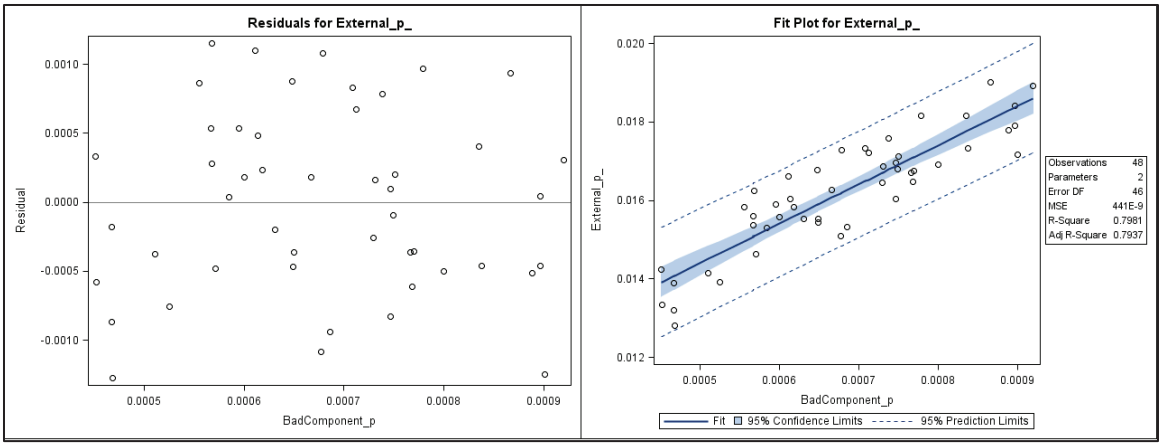

Figure 5.12 Residual plot and fit plot in maturity period

According to the residual analysis data and graphs we can assert normal distribution of residuals and their independency as there is no pattern in their distribution. Also fit plot in Figure 5.12 shows no outlier within the data in 95% confidence interval.

As a result we will reject the null hypothesis as there is no dependency of external failure costs to lead-time deviation and it is solely dependent on actual bad products.

Justification for the insignificance of the lead-time deviation on external failure costs for both of quality maturity and immaturity period could be the time lag effect of external failure costs.

External failure costs are the loss of profit due to poor quality by definition. It occurs when the customer is not eager to remain in the system. As a result, due to the characteristics of external failure costs, it could not be interpreted immediately with

influential variable. An assessment with a proper time lag between costs value and the variable might lead to more realistic results.

5.3 Model Modification

According to the results of data analysis total quality cost function may be modified to two distinct models for quality immaturity period and quality maturity period. Equation 5.1 shows the total quality costs at quality immaturity period.

$$COQ_{Sc} = (\alpha_1 * Actual\ Good\ products + \beta_1 * LTD + \gamma_1) + (\alpha_2 * IER_{sm} + \beta_2 * IER_{md} + \gamma_2) + (\alpha_3 * PIF_{SC} + \gamma_3) + (\alpha_4 * Actual\ Defective\ products + \gamma_4)$$

Equation 5.1

Also Equation 5.2 shows the total quality costs at quality maturity period.

$$COQ_{Sc} = (\alpha_1 * Actual\ Good\ products + \gamma_1) + (\beta_2 * IER_{md} + \gamma_2) + (\alpha_3 * PIF_{SC} + \gamma_3) + (\alpha_4 * Actual\ Defective\ products + \gamma_4)$$

Equation 5.2

6. Summary and Conclusions

In this research we have developed a mathematical model which could predict the total quality costs at different quality levels in manufacturing supply chain. Proposed model is examined and validated against manufacturing supply chain data in two intervals, which we call quality immaturity and quality maturity periods, respectively. The PAF classification of quality costs has been used to develop mathematical model for total quality costs. The definition of quality level is based on the definition of quality level in the product supply chain. Based on the results the quality level is increasing when the COQ increases in quality maturity period and, also, increments in quality level are not necessarily accompanied by higher quality costs in quality maturity period.

Prevention cost group is different in quality immaturity and quality maturity periods. The investment in prevention activities in quality immaturity period has a drastic role in lead-time reduction, but due to the quality excellence in maturity period lead-time variation would be insignificant and prevention costs at this period is solely dependent on the number of actual good products.

In the appraisal costs category, the inspection error rates at manufacturer and supplier have impact on appraisal costs in quality immaturity period, but inspection error rate at supplier is not significant at quality maturity period as supplier evaluation and certification occur in immaturity period. As a result, appraisal costs would be merely dependent on inspection errors at manufacturer at maturity period, and surprisingly they decrease simultaneously as a result of continuous improvement efforts.

Furthermore, according to the data analysis results, predicted internal failure costs are a precise estimator of total internal failure costs regardless of quality excellence status. In another words, the predicted amount of internal failure costs could be assumed as internal failure variable costs.

Finally, contrary to our hypothesis, external failure costs are merely dependent on the actual number of bad products which reach to the hand of customers, and they are not dependent on the lead-time deviation in any quality maturity status. As it was proposed in

the data analysis chapter to observe the impact of lead-time deviation on external failure costs it is recommended to study their relationships in time lags.

6.1 Future works

Considering the model assumptions and limitations, future works could be lied in different ways. Consideration of model for variant demand condition and integrating demand forecasting techniques in COQ could be one of the alternatives. Also, modification of quality level definition to include more quality dimensions is another possible key point remaining for future investigation. Furthermore, the proposed model is suitable for currently established supply chain, thus the cost of switching between suppliers and distributers or retailers is not considered in the model development. .Subsequently the consideration of cost of switching between supply chain entities is another work that can be done in future. Moreover, inventory costs as a quality issue could be deliberated in future works, because due to the the available data they were completely omitted in this work. Finally, in the context of data analysis, utilizing robustness test and techniques will enhance analysis results validity. This could be done through random continuous event simulation or any other statistical tool.

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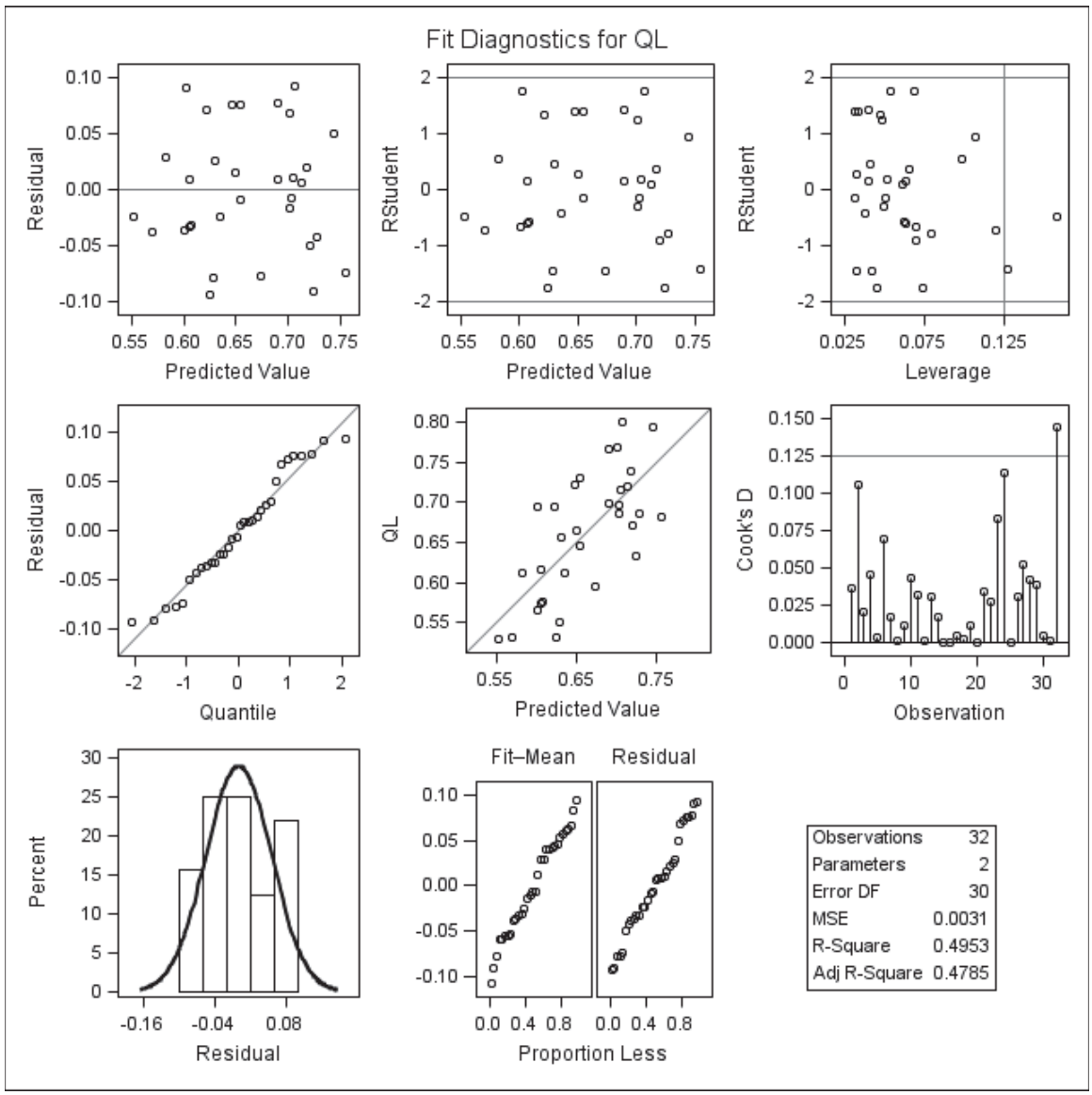
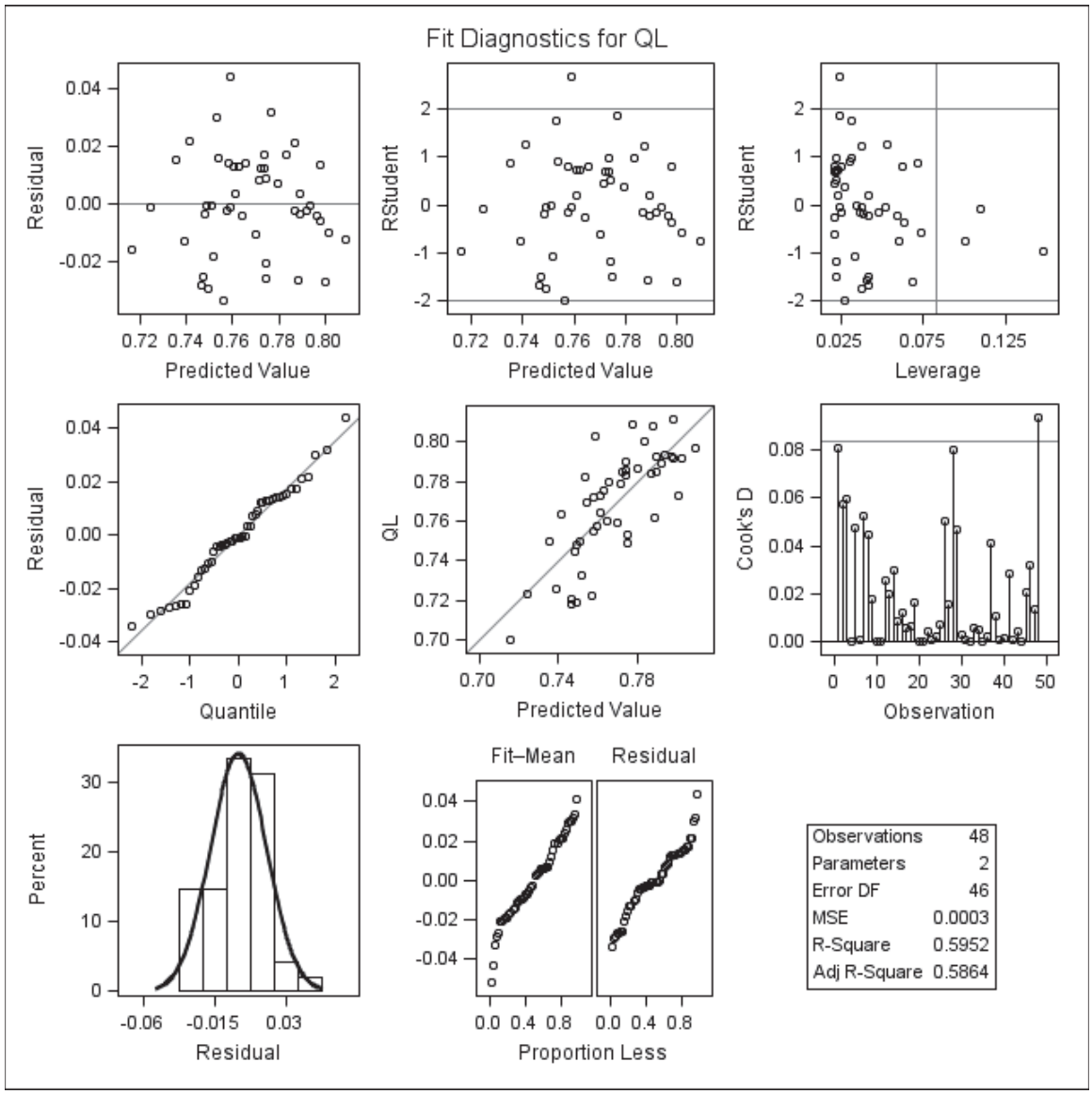
Appendices

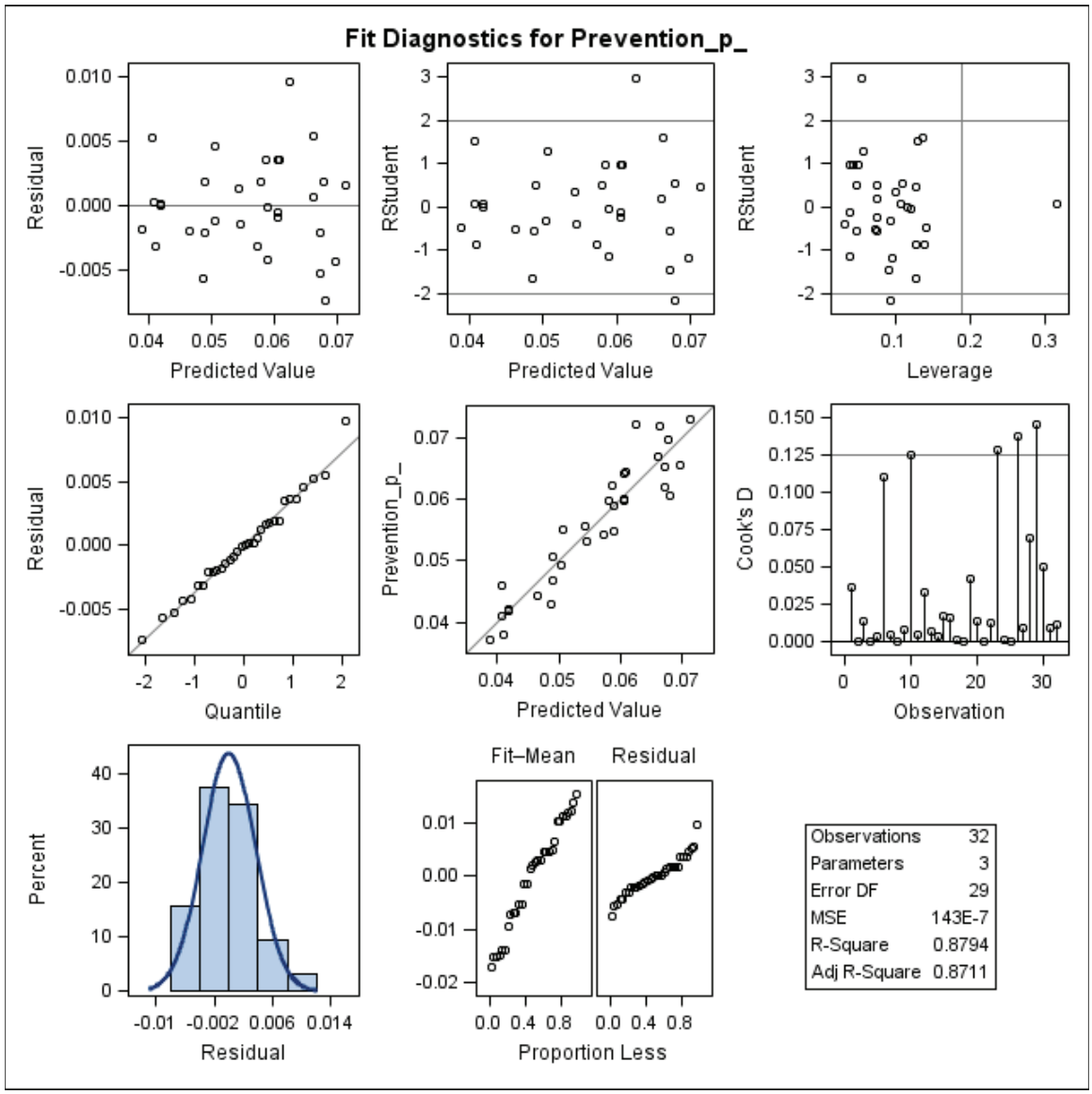
1- Residual analysis results for Quality level and total COQ in immaturity period



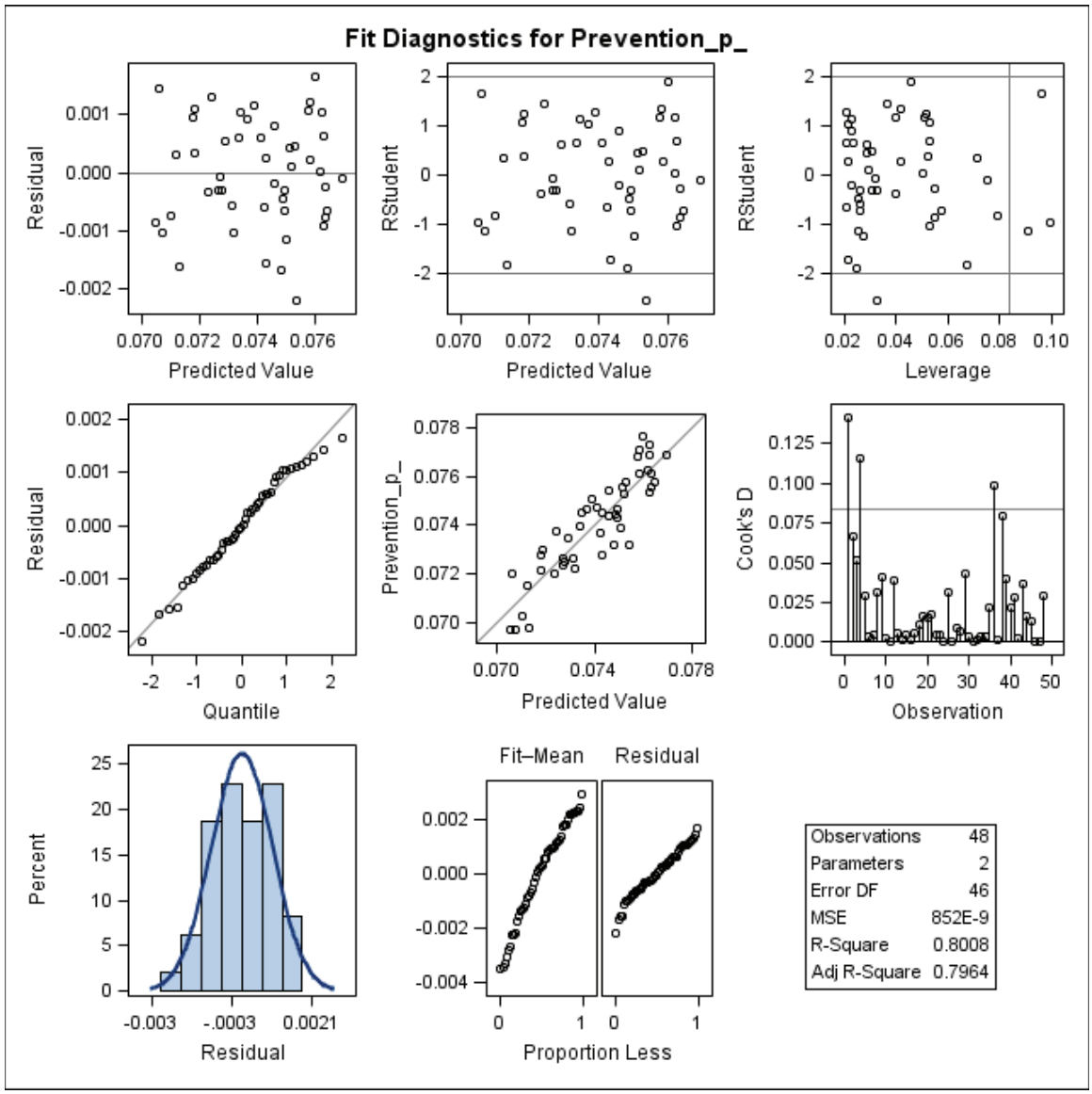
2- Residual Analysis Results for Quality level and total COQ in maturity period



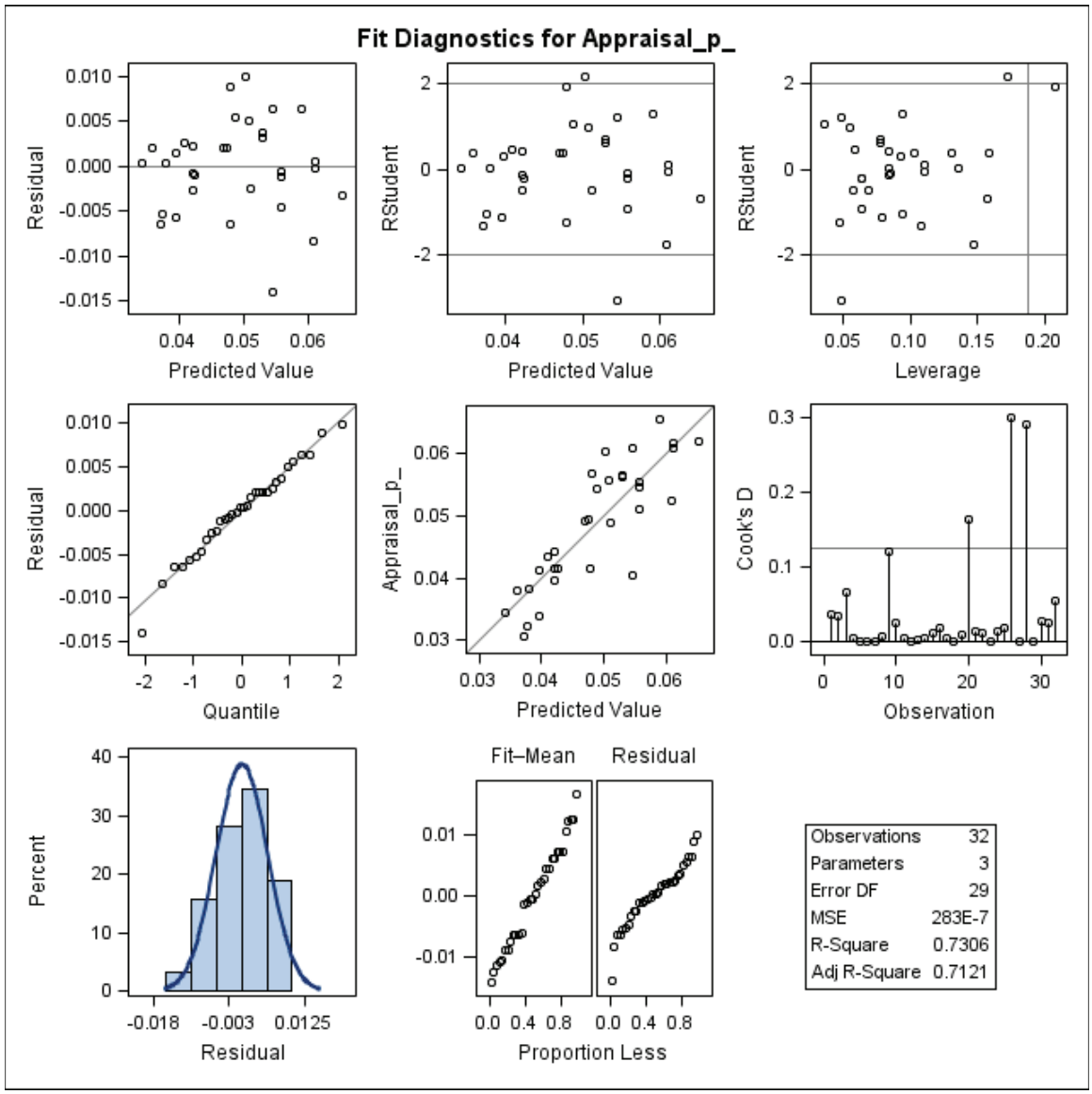
3- Residual analysis results for prevention costs at quality immaturity period



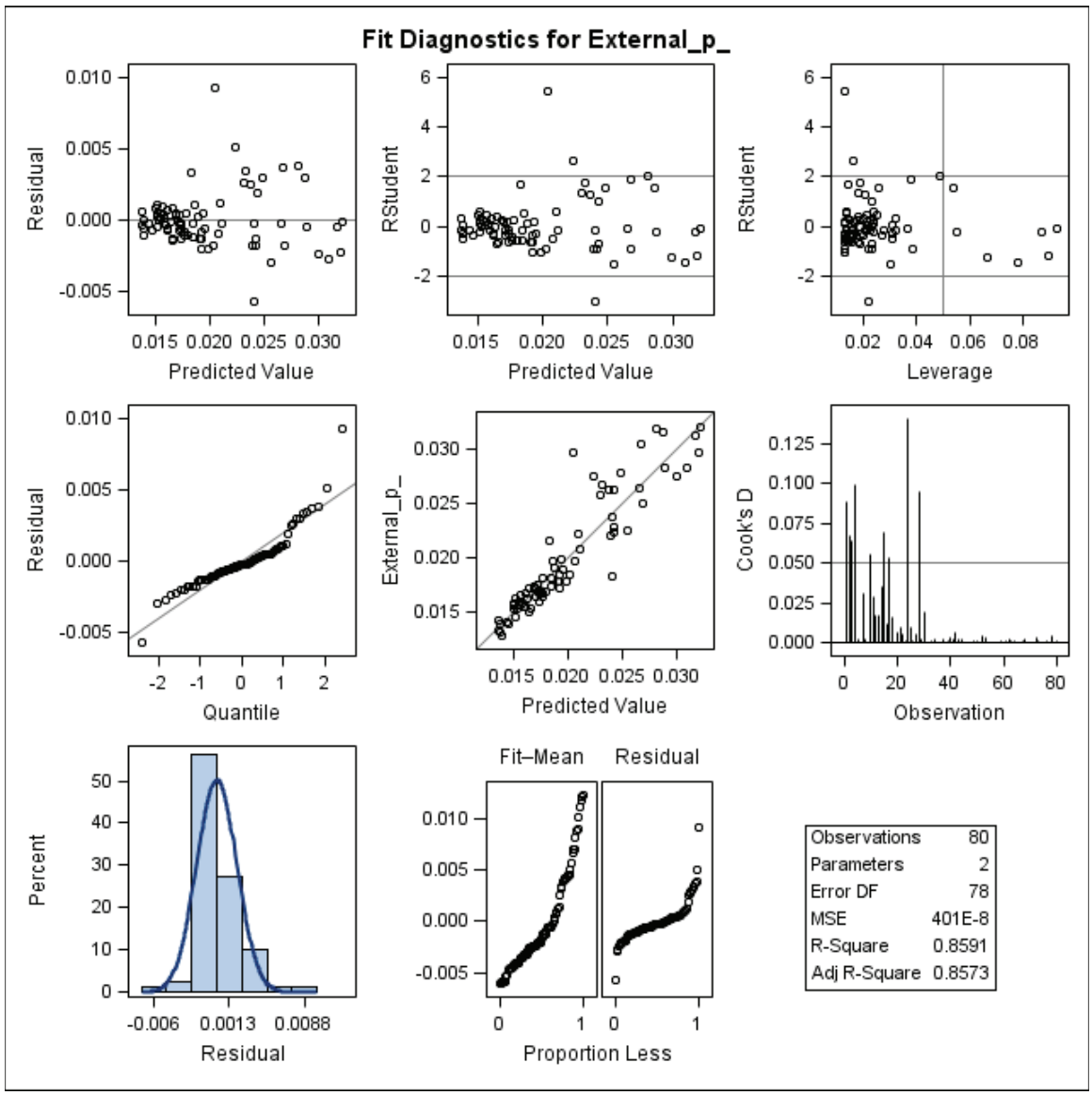
4- Residual analysis results for prevention costs at quality maturity period



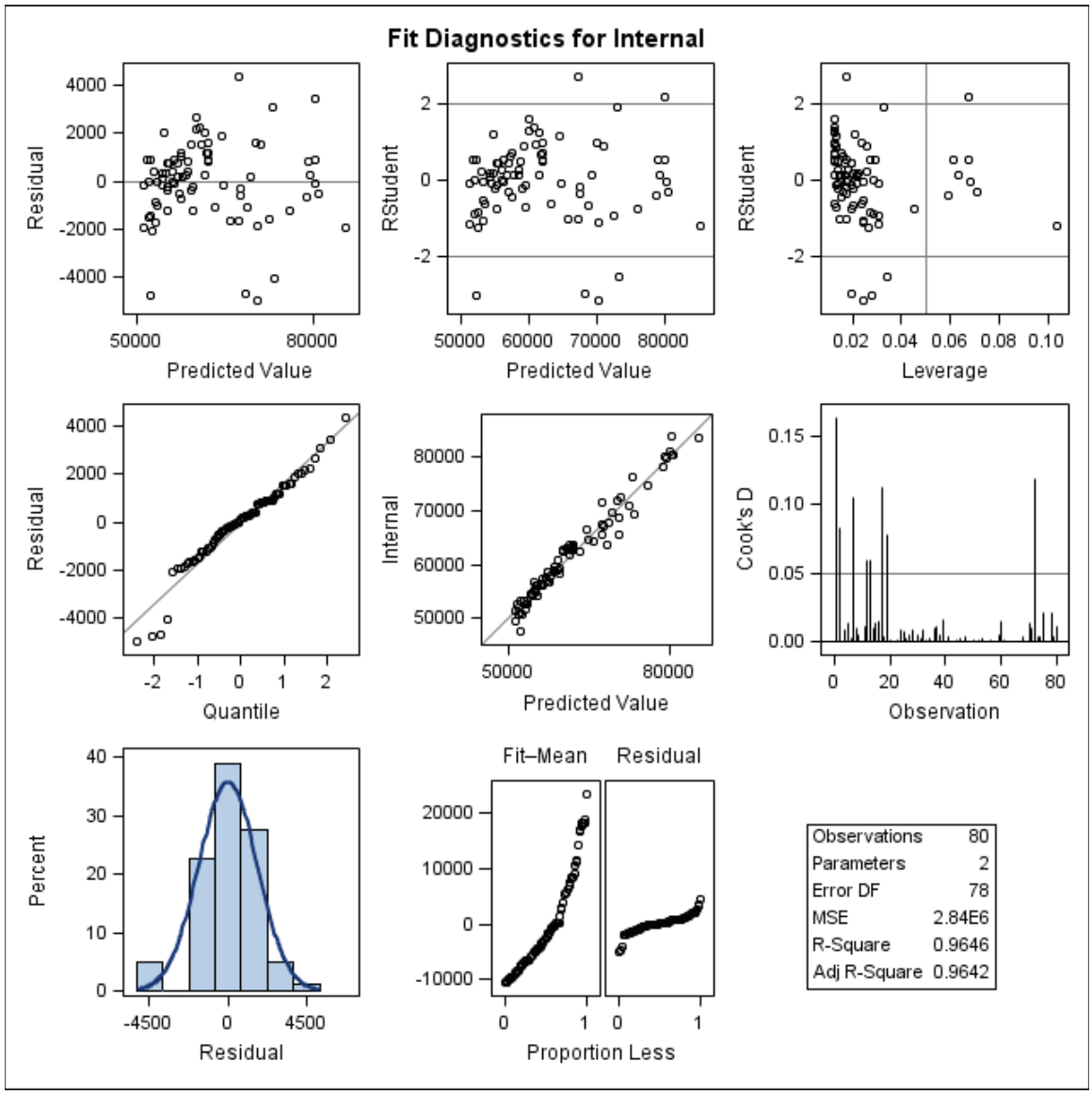
5- Residual analysis results for appraisal costs at quality immaturity period



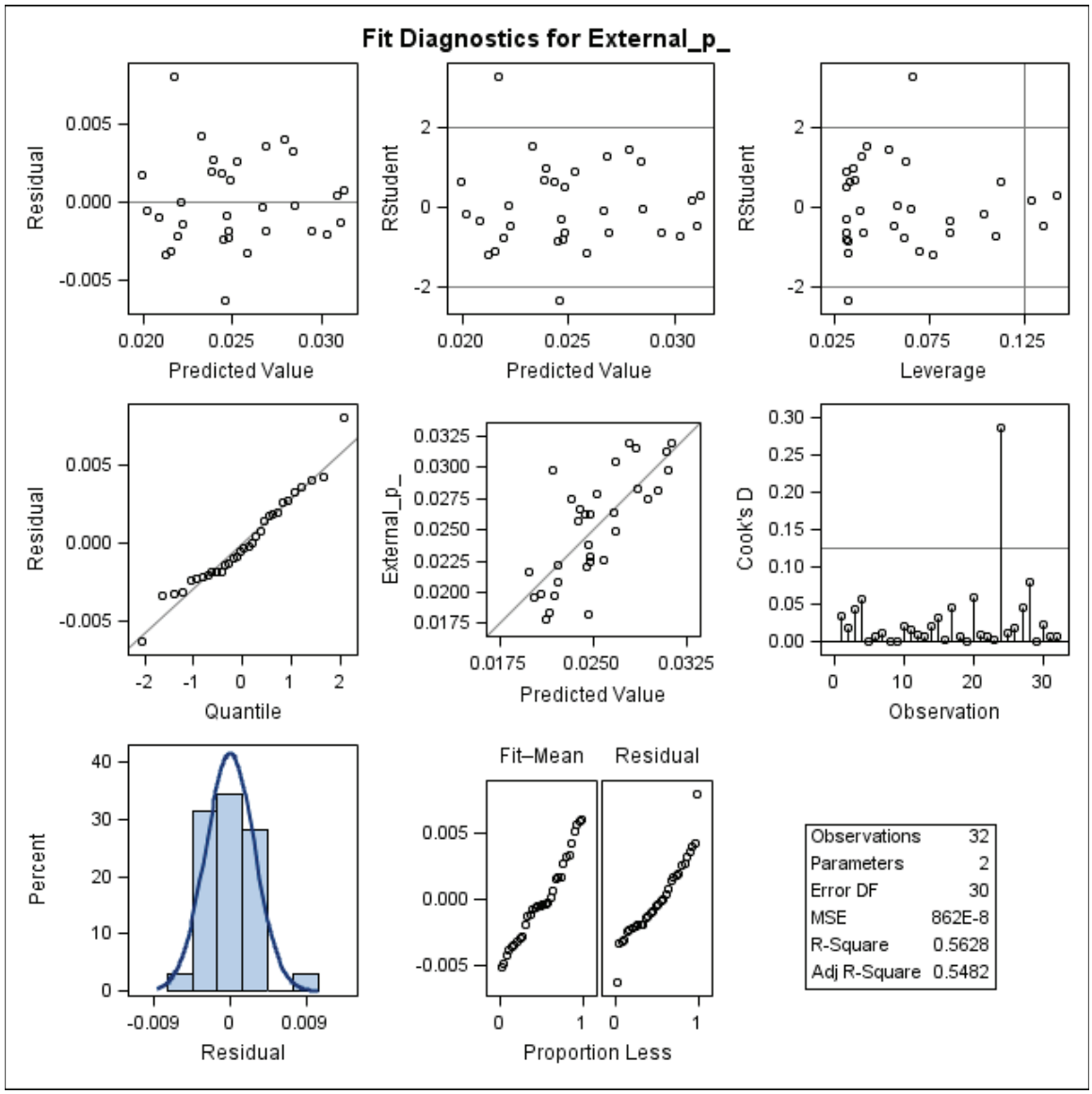
6- Residual analysis results for appraisal costs at quality maturity period



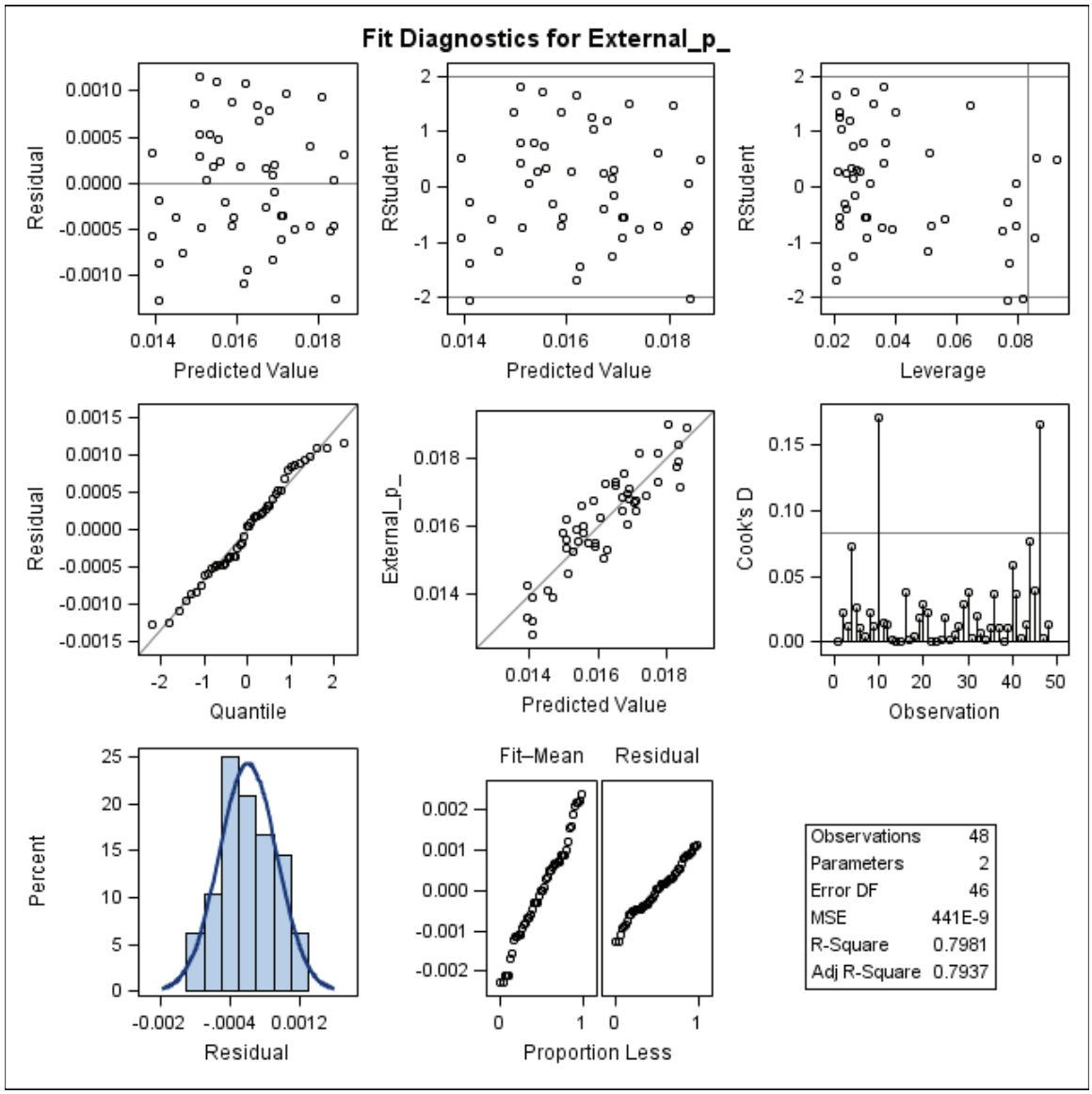
7- Residual analysis results for internal failure cost



8- Residual analysis results for external failure costs at immaturity period



9- Residual analysis results for external failure costs at maturity period



10- SAS program code

```
data ehsan.subsample1; set ehsan.subsample1; drop QL goodcomponent goodcomp_p IF_s_ IF_m1_ IF_m2_ IF_d_ IF_r_ IF_predict nonconf_predict;
run;

data ehsan.subsample2; set ehsan.subsample2; drop QL goodcomponent goodcomp_p IF_s_ IF_m1_ IF_m2_ IF_d_ IF_r_ IF_predict nonconf_predict;
run;

data ehsan.sample; set ehsan.sample; drop QL goodcomponent goodcomp_p IF_s_ IF_m1_ IF_m2_ IF_d_ IF_r_ IF_predict nonconf_predict;
run;


%macro ehsan(T);

    data ehsan.&T;

      set ehsan.&T;


D=6240;

Price=150;

GROSS_REVENUE= 936000;


goodcomponent     =     D*(1-DR_r_)*(1-DR_d_)*((1-DR_m_)*(1-IER_ms_)*(1-DR_s_)+(RR_m_)*(1-IER_md_)*((1-IER_ms_)*(1-
DR_s_)*DR_m_+(IER_ms_*DR_s_)));

goodcomp_p    = goodcomponent/D;

IF_s_         = ARC_s_*D*(1-IER_ms_)*DR_s_;

IF_m1_                          =   ARC_m_*D*(1-IER_md_)*((1-IER_ms_)*(1-
DR_s_)*DR_m_+IER_ms_*(DR_s_));

IF_m2_                    =   (Price-SP_m_)*D*(1-IER_md_)*((1-IER_ms_)*(1-
DR_s_)*DR_m_+IER_ms_*(DR_s_))*(1-RR_m_);
```

```
IF_d_          = D*DR_d_*((1-IER_ms_)*(1-DR_s_)*(1-DR_m_)+(IER_md_)*((1-
IER_ms_)*(1-DR_s_)*DR_m_+(IER_ms_*DR_s_)         )+RR_m_*(1-IER_md_)*((1-
IER_ms_)*(1-DR_s_)*DR_m_+IER_ms_*(DR_s_)))*ARC_d_;

IF_r_                    =  DR_r_*(D-(D*DR_d_*((1-IER_ms_)*(1-DR_s_)*(1-
DR_m_)+(IER_md_)*((1-IER_ms_)*(1-DR_s_)*DR_m_+(IER_ms_*DR_s_)
)+RR_m_*(1-IER_md_)*((1-IER_ms_)*(1-
DR_s_)*DR_m_+IER_ms_*(DR_s_)))))*ARC_r_;

IF_predict_    = (IF_s_+IF_m1_+IF_m2_+IF_d_+IF_r_);

QL             = ((1-(ltd/45))*goodcomponent)/D ;

BadComponent        =    D*(1-DR_r_)*(1-DR_d_)*(IER_md_)*((1-IER_ms_)*(1-
DR_s_)*DR_m_+IER_ms_*DR_s_);

BadComponent_p=          D*(1-DR_r_)*(1-DR_d_)*(IER_md_)*((1-IER_ms_)*(1-
DR_s_)*DR_m_+IER_ms_*DR_s_)/D;

conf           = prevention+appraisal;

nonconf        = internal+external;

tCoQ           = conf+nonconf;

prevention_p_  = prevention/gross_revenue;

appraisal_p_   = appraisal/gross_revenue;

internal_p_    = internal/gross_revenue;

external_p_    = external/gross_revenue;

conf_p_        = prevention_p_+appraisal_p_;

nonconf_p_     = internal_p_+external_p_;

tCoQ_p_        = conf_p_+nonconf_p_;


run;

%mend ehsan;
```

```
************************
*** REGRESSIONS *********
************************;
%macro REG_all(T);
      proc reg data=ehsan.&T; model  internal             =  IF_predict_
/dw;                    run;
      proc  reg  data=ehsan.&T;  model  Prevention_p_    =  goodcomp_p  LTD
/dw;                    run;
      proc   reg   data=ehsan.&T;   model   Prevention_p_     =   goodcomp_p
/dw;                    run;  *only for subsample2;
      proc  reg  data=ehsan.&T;  model  appraisal_p_     =  IER_ms_  IER_md_
/dw;                    run;
      proc   reg   data=ehsan.&T;   model   appraisal_p_         =   IER_md_
/dw;                    run;  *only for subsample2;
      proc   reg   data=ehsan.&T;   model   appraisal_p_         =   IER_ms_
/dw;                    run;  *only for subsample2;
      proc reg data=ehsan.&T; model external_p_     = BadComponent_p LTD
/dw;                    run;
      proc  reg  data=ehsan.&T;  model  external_p_       =  BadComponent_p
/dw;                    run;
%mend REG_all;

%macro REG_1(T);
      proc reg data=ehsan.&T; model  internal             =  IF_predict_
/dw;                    run;
      proc  reg  data=ehsan.&T;  model  Prevention_p_    =  goodcomp_p  LTD
/dw;                    run;
      proc   reg   data=ehsan.&T;   model   Prevention_p_     =   goodcomp_p
/dw;                    run;  *only for subsample2;
```

```
      proc reg data=ehsan.&T; model appraisal_p_    = IER_ms_ IER_md_
/dw;                    run;

      proc  reg  data=ehsan.&T;  model  appraisal_p_       =  IER_md_
/dw;                    run;  *only for subsample2;

      proc  reg  data=ehsan.&T;  model  appraisal_p_       =  IER_ms_
/dw;                    run;  *only for subsample2;

      proc reg data=ehsan.&T; model external_p_    = BadComponent_p LTD
/dw;                    run;

      proc reg data=ehsan.&T; model external_p_      = BadComponent_p
/dw;                    run;

%mend REG_1;


%macro REG_2(T);

      proc reg data=ehsan.&T; model  internal             =  IF_predict_
/dw;                    run;

      proc reg data=ehsan.&T; model Prevention_p_   = goodcomp_p LTD
/dw;                    run;

      proc  reg  data=ehsan.&T;  model  Prevention_p_     =  goodcomp_p
/dw;                    run;  *only for subsample2;

      proc reg data=ehsan.&T; model appraisal_p_    = IER_ms_ IER_md_
/dw;                    run;

      proc  reg  data=ehsan.&T;  model  appraisal_p_       =  IER_md_
/dw;                    run;  *only for subsample2;

      proc  reg  data=ehsan.&T;  model  appraisal_p_       =  IER_ms_
/dw;                    run;  *only for subsample2;

      proc reg data=ehsan.&T; model external_p_    = BadComponent_p LTD
/dw;                    run;

      proc reg data=ehsan.&T; model external_p_      = BadComponent_p
/dw;                    run;

%mend REG_2;
```