Design Supply Chain Based on Cost of Quality with Consideration of Quality Level

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A Thesis
In The Department
of
Mechanical, Industrial & Aerospace Engineering

Presented in Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy (Industrial Engineering) at
Concordia University
Montreal, Quebec, Canada

March 2018

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CONCORDIA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

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Entitled: *Design Supply Chain Based on Cost of Quality with Consideration of Quality Level*

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Abstract

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In the contemporary global market, organizations are striving to survive and compete not only by satisfying customer's needs but also by fulfilling it with the least costs. Quality management experts determined that quality costs account for a substantial part of total production costs. Therefore, finding a way to improve the Quality Level (QL) while minimizing the Cost of Quality (COQ) is a crucial task. In the manufacturing industry, there are a variety of costs that are directly associated with the production; these costs can be considered as visible costs. However, another type of costs may indirectly arise during and after manufacturing processes or even after the product reaches the customer. These types of costs are considered as invisible (hidden) costs and in most cases are difficult to track. Measuring the effect of hidden costs such as the costs of unsatisfying a customer is not straightforward. Even though the hidden costs may have serious consequences for any organization if they are not considered in early stages, they are rarely incorporated in the COQ calculations.

Furthermore, the COQ models found in the literature rarely go beyond the costs incurred within an individual firm and seldom attempt to estimate cost elements related to the customers or suppliers. This, however, does not reflect the reality, since not all the quality costs are generated internally. Suppliers, subcontractors, agents, dealers and customers each contribute (sometimes significantly) to an organization's indirect quality costs. It is therefore proposed to

combine the internal measures of COQ with costs related to both upstream and downstream supply chain (SC) partners.

In this thesis, pursuing the aforementioned motivations, we focus on designing SCs in framework of various COQs and QLs. The previous literature lacks a work that integrates the opportunity cost (OC), COQ and QL into SC and Supply Chain Network Design (SCND). The main objectives of this thesis are to consider OC in the COQ analysis, to incorporate it into the Prevention, Appraisal, and Failure (PAF) model, and to analyze it together with various QLs in a manufacturer SC. The purpose is to find an optimum QL that matches the minimum spending on the COQ and. This work proposes a reliable COQ model, which can be used to measure COQ in the whole SC.

We carried out a case study in a manufacturing SC to collect the PAF data and the related data to OC i.e., customer satisfaction. The involved organization is an automobile manufacturing SC. A system dynamics model is used to simulate the COQ, while including OC and analyzing its effects at different QLs.

In addition, PAF, OC, and QL are mathematically modeled in an uncapacitated SC. Different proposed scenarios were developed to allocate the PAF, OC, and QL in the SC. The model determines the best scenario of allocating the COQ at each facility while minimizing the COQ and OC, and thereby optimizing the QL. Based on the COQ, the mathematical model also reveals the difference between the centralized and decentralized SC. Moreover, we address the effects of spending limitations of PA costs on F, OC, and QL at each facility and in the SC as a whole.

Afterwards, the thesis develops a mathematical model which is involved in designing of a capacitated SCND based on PAF, OC, and QL. The developed model is intended to highlight the importance of OC by show the difference between OC-included and OC-excluded SCND model. The SCND model is also used to determine the best improvement in the QL, i.e. the optimal value of investing in the COQ at each echelon.

Finally, a hybrid decision support system (DSS) model which combines the mathematical model and the simulation model for COQ, OC, and QL is developed. The model implements the optimum results of the mathematical model in the simulation model. This aim is to increase spending on PA costs beyond the optimal results of the mathematical model. The model is intended to decrease the OC (increase the number of new customeers). The results show how the combined methodologies can provide better decision support for upper management.

This research shows that COQ can be used as a meaningful measure of improvement not only in an organization but in the whole SC. The methods developed in this thesis will provide a powerful tool to management for assessing quality economics, facilitating quality programs and optimizing benefits of quality across SC.

ACKNOWLEDGEMENTS

Alhamdulillah *(all praise and thanks are due to Allah) for the blessing, patience, and perseverance that he has given me, to complete my study, Ph.D. in industrial engineering. Verily, this thesis would have never been accomplished without the will and blessing of Allah, the most generous, gracious and the most merciful.*

I thank the person *who has given me endless support and enthusiasm, who enlightens my life day after day, my wife,* ***Zakia****. I could not have asked for as much soul mate like her. Even though she is in hardship and difficult times, she has constantly been giving all her love, dedication and sacrifice to support me.*

I also wish to acknowledge *my Lovely Kids,* ***Soliman****,* ***Salease*** *and* ***Muhammad*** *who were the strong motivation for me to complete this research.*

I won't forget to thank my great Parents and Siblings*, for providing their endless support and supplication, who have been presenting with their love and perpetual encouragement. Truly, my* ***Parents*** *are the people who are cared and suffered the most about me and for my higher study abroad. For sure, they are the closest people to me. Their support was precious in finalizing this thesis.*

I would also like *to extend my* ***appreciations to*** *my third family; the family of my wife for their continues infinite love and support. To them, I acknowledge fervent thanks.*

My profound ***gratitude*** *goes to my valued thesis supervisors, Dr. Andrea Schiffauerova and Onur Kuzgunkaya for their continuous support and valued advice for the past five years. Thank you for the great guidance, motivation, and for your ever-positive attitude. Through thick and thin, you have always offered me your full support, for which I will always be appreciative. I also, thank my,* ***lab mates****: Ehsan, Jaipuneet, Gita, Nuha, and Elise. Thanks to all* ***my friends and colleagues*** *at Concordia University for their assistance and support.*

Finally*, I thank the members and chair of my examinations committee, namely*
Dr. Onur Kuzgunkaya, Dr. Andrea Schiffauerova
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October 2017, Montreal, Canada

Preface

This thesis has been prepared as manuscript-based under the co-supervision of Dr. Andrea Schiffauerova from the department of Concordia Institute for Information Systems Engineering (CIISE), Concordia University and Dr. Onur Kuzgunkaya from the department of Department of Mechanical, Industrial & Aerospace Engineering (MIAE). This research was financially supported by the Ministry of Higher Education, Libya. All the articles which presented in this thesis were co-authored and reviewed before submission for publication by Dr. Andrea Schiffauerova and Dr. Onur Kuzgunkaya. The author of this thesis performed as the principal researcher, he performed the methodologies, the mathematical model's development, the simulation models, programming of the solution algorithms, sensitivity analysis and validation of the results, along with organizing and writing the first drafts of the articles.

The first article entitled "Analyzing the Cost of Quality within a Supply Chain Using System Dynamics Approach" co-authored by Dr. Andrea Schiffauerova and Dr. Onur Kuzgunkaya was published in *Total Quality Management & Business Excellence* in November 2017 (ISI Impact Factor 1.37).

The second article entitled "Managing Quality Decisions in Supply Chain" co-authored by Dr. Onur Kuzgunkaya and Dr. Andrea Schiffauerova was submitted to *International Journal of Production Economics* (ISI Impact Factor 3.493) in March 2018.

The third article entitled "Supply Chain Network Design Based on Cost of Quality and Quality Level Analysis" co-authored by Dr. Onur Kuzgunkaya and Dr. Andrea Schiffauerova was submitted to *International Journal of Production Research* (ISI Impact Factor 2.32) in February 2018.

The forth article entitled “A Decision Support System for Cost of Quality in Supply Chain” co-authored by Dr. Onur Kuzgunkaya and Dr. Andrea Schiffauerova was submitted to *Decision Support Systems* (ISI Impact Factor 3.222) in March 2018.

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List of Acronyms

COQ	___	Cost of Quality
SC	___	Supply Chain
PAF	___	Prevention, Appraisal and Failure costs
PA	___	Prevention and Appraisal costs
F	___	Failure costs
OC	___	Opportunity Costs
SD	___	System Dynamics
COPQ	___	Cost of Poor Quality
CLD	___	Causal Loop Diagram
SCND	___	Supply Chain Network Design
QL	___	Quality Level
DSS	___	Decision Support System
A	___	Appraisal Costs
ABC	___	Activity Based Costing
PA_C	___	Prevention and Appraisal costs
F_C	___	Failure Costs
O_C	___	Opportunity Costs
MINLP	___	Mixed Integer Nonlinear Programming

Chapter 1 – Introduction

1.1. Overview

Quality has been long documented as an important feature for consumers when similar products are available in the market. However, it is not only high-quality which attracts customers; it is the high quality along with a low price that attracts them and eventually enables companies to outperform the competition (Chopra & Singh, 2015). In order to gain more customers, organizations must therefore consider not only the products quality level (QL) but also the cost of achieving such quality. Improving the cost accounting systems by incorporating tools such as Cost of Quality (COQ) can help companies to reduce costs and simultaneously increase the quality, thereby elevating satisfaction of their customers (e.g., Wilkes & Dale, 1998; Dreyfus et al., 1999; Mendes & Lourenço, 2014).

However, the concept of identifying COQ elements and implementing a COQ model is not very direct and the literature shows differences in the categorization of these costs (Machowski & Dale, 1998; Cheahet et al., 2011; Yang, 2008; Trehan et al., 2015). There are several techniques on how to assign expenses to COQ elements. In addition, there is no specific method to classify quality costs with their origins (Tsai, 1998). Organizations which decide to manage their quality costs have to select a model suitable for their accounting system, and match their cost structure with the cost elements of the COQ model (Ramdeen et al., 2007; Omachonu et al., 2004; Daunoriene & Katiliute, 2016; Akkoyun & Ankara, 2009). According to the British Standard (BS 6143 Part 2, 1990) and American Society for Quality Control (ASQC, 1971), Quality costs are those costs spent to satisfy the quality requirements and to cover the losses incurred due to the failure in fulfilling the quality requirements. Schiffauerova and Thomson (2006) and Sawan et al. (2018)Sa assert that the COQ is a tradeoff between the costs of conformance and costs of nonconformance

Companies have been interested in quantifying their COQ in order to increase their profits. Measuring COQ in industry has demonstrated various benefits, for example reduced total expenditure, improved quality, enhanced customer satisfaction, increased benefits and higher final profit (Iuliana et al., 2013). Schiffauerova & Thomson (2006) reported the savings achieved by implementing the COQ for several companies. As an example, ITT Europe headquartered in Belgium could save over $150 million after five years of controlling the quality cost.

Even though there are success stories of the companies implementing COQ methodology, the calculation of many of the COQ elements is not straightforward. Although there are many cost elements of the COQ that can be easily monitored and measured, some of them are difficult to trace and some are even hidden (Wood, 2007, Cheah et al., 2011 and Campanella, 1999). For example, opportunity costs (OC) are costs rarely considered in the COQ models. They are in fact benefits which could have been received but are given up in order to take a different course of action. There are different types of OC, Omar & Murgan (2014) measured the OC as a shortage of inventory material, machines setup costs, idle costs and processes waiting time. They estimated the OC, which the company incurred due to poor service delivery and process underutilization, and found them to be equal to around 60% and 40%, respectively. loss of customer goodwill is an important hidden OC which has a direct effect on whether the company will keep or lose their customers, and therefore this cost t needs to o be traced and managed properly (Liu et al., 2008). There have been some attempts to measure these costs. For example, Snieska et al. (2013) examined the customer satisfaction by measuring the external failure costs in a medical supply service company in Lithuania. They had developed a questionnaire to quantify the loss of customer's goodwill in a financial value. The significance of these costs is underlined by the fact that Snieska et al. (2013) find the hidden external failure quality costs equal to about 30% of sales. Measuring the customer's satisfaction is thus very important, as this OC can affect the reputation of the organizations and their future in the market. However, it is rarely addressed in the literature, and usually is skipped from the COQ models.

COQ models developed in the literature so far have focused only on an individual firm (*i.e.* on in-house COQ) and have not reflected cost elements related to the customers and suppliers. However, not all the quality costs are generated internally, and without considering all the quality aspects when assessing the COQ data, the accurate distinction between the high-quality and low-quality performing processes cannot be done and the quality improvement efforts hence cannot be focused upon appropriately. Srivastava (2008) was the first author who estimated the COQ in SC. He could measure the COQ and convert it into financial terms in a pharmaceutical manufacturing company situated in India. Castillo-Villar et al. (2012) used a Genetic Algorithm (GA) and Simulated Annealing (SA) to study the impact of COQ on Supply Chain Network Design (SCND). They proposed a model that could find the best combination of integer variables that maximizes the profit and minimizes the total COQ. Ramudhin et al. (2008) incorporated the COQ into their model to study a single product in a three-echelon SC. Their model minimized the quality costs, which were functions in the defective percentage at the supplier echelon. Ramudhin et al. claimed that adding quality costs to the suppliers in the objective function minimizes the defective percentage at the supplier, and the objective value increased by around 16%. Liu and Xie (2013) focused on the quality decision variables of the functional logistics service provider (FLSP) and the logistics service integrator. They suggested that it is important to improve the cooperation among the SC entities to improve QL and reduce quality risk. Despite these attempts COQ in the SC has not generated much interest in the literature so far.

Motivated by the case of integrating the COQ functions into the SC, e.g., different COQ functions, which characterize the QL at each echelon/facility, the focus of this thesis is on designing SC and SCND models, which can be applied in the manufacturing SCs sector. Designing SC and SCND based on COQ for such purpose for manufacturing is a complex problem, which is attributed mainly to the requirement that the various cost types have to be solved at the same time. According to the best of our knowledge, there is no study focused on the QL and COQ in a manufacturing SC and SCND, and this research intends to fulfill this gap. Our proposed models incorporate COQ, OC, and QL in the SC and SCND, allowing to analyze and observe the effects of centralized decision-making for QL in the SC. More precisely, we contribute to the existing literature in several ways. First, we address the problem of allocating the COQ in the SC through designing a comprehensive SCND for supplier/facility selection considering the QL of each facility. We further focus on integrating the OC (customer satisfaction costs) into the COQ model. Finally, we develop a hybrid Decision Support System (DSS) that further analyses the COQ in the SC with an aim to increase the number of new customers.

In the following section the studied problem is outlined, the scope is defined and objectives of this research are spelled out. We present the outline of this thesis at the end of this chapter.

1.2. Problem definition, scope, and framework

1.2.1. Supply Chain (SC)

Supply chain (SC) can be defined as integrated processes composed of organizations, people, products, activities and information, where various business entities from upstream to downstream interact with each other to add value to products or services to customers. Those business entities can be mostly classified in four main categories: suppliers, manufacturers, distributors and retailers (Beamon, 1998; Min & Zhou, 2002; Sezen, 2008; Garcia & You, 2015), who professionally interact to ensure business processes and the delivery of products and services.

These vital processes involve purchasing raw materials and parts, converting raw materials into finished products, adding value to the produced parts and products, distributing products to retailers and after that to customers/end-users, and facilitating and exchanging information among these entities (Min and Zhou, 2002). The SC thus not only includes the suppliers, manufacturers, and retailers, but also the transporters, inventory control, the warehouses, and the customers themselves. The ultimate objective of the SC is to optimize the overall activity that adds the value to the products (Chopra & Meindl, 2007).

From the customer's viewpoint, a better definition of SC can be expressed as a complete system involving several stages, directly or indirectly, to satisfy a customer request. The objective of SC network is to reduce and minimize the customer level of dissatisfaction, accumulation of price and lead delivery time (Cakravastia et al., 2002). Therefore, SC needs to be constructed in such a way as to minimize value-added costs while still maintaining a satisfactory QL.

1.2.2. Supply Chain Network Design (SCND)

The Supply Chain Network Design (SCND) aims at identifying and coordinating key facilities of the SC, i.e., suppliers, manufacturers, distributors, and retailers to minimize the expenditures and to maximize the profits. Among different suppliers, manufacturing plants, distributors, and retailers, the SC network aims to minimize spending on the product while SC entities are integrated to satisfy business requirements and constraints. Modeling SC network aims at optimizing organization resources, which is often carried out by minimizing the overall operational costs and involves evaluating different available scenarios among the SC entities (i.e., suppliers, manufacturers, distributors, and retailers), resources, and processes decisions within SC.

Why is it important to design the supply chain network? The recent pattern of manufacturing has shifted to an integrated SC rather than separate business. Hence, the ultimate success of an organization may be influenced by its ability to link to the SC members appropriately. It is worth mentioning that all the supply chain echelons from upstream (suppliers) to downstream (retailers) could severely affect the SC output. It is thus that the SC entities cooperate among themselves in order to reinforce the chain value closely.

1.2.3. Cost of Quality (COQ)

While the definition of quality costs is crucial for measuring the quality itself, there is no unique and accepted definition, as different authors define quality costs in different ways (Beecroft, 1999; Chiadamrong, 2003; Evans & Lindsay, 2014). According to (BS 4778: Part 2, 1991), quality costs can be defined as expenditures associated with a product or service quality that is paid by the producers, user, and by the community. A quality-related cost is defined as the sum of expenditures incurred to prevent defect, appraisal activities, and the losses as a result of internal and external failure (BS 4778: Part 2, 1991). According to the British Standard (BS 6143, 1990) and American Society for Quality Control (ASQC, 1971) quality costs are those costs that assure and ensure quality and the loss when quality is not fulfilled.

In the past, quality costs were mainly associated with inspection and testing. Accordingly, some of the total quality costs represented only a small portion of the total cost. In the literature, there are different estimations of total COQ, for example, Kent (2005) estimated them at 5-15% of turnover for companies in Great Britain, Crosby (1984) at 20-35% of sales for manufacturing and service companies in the USA, and estimated by Feigenbaum (2001) at around 10% of revenues. No matter the COQ estimation, these numbers are obviously high and suggest that significant portion of expenditures could be saved if these costs are managed properly. It is generally assumed that if organizations implement a strong quality cost system the total cost of quality will decrease, while the external failure costs will decrease as a percentage of total COQ (Sower et al., 2007).

COQ is an important factor in the SC because it reflects on the quality of the products in the SC. If the quality of the products does not match the standard of the required quality level, then more time and cost are required to restore it. Depending on this, quality influences the cost and responsiveness of the SC which strongly suggests that quality is a crucial factor in SC design.

1.2.4. Opportunity Cost

Opportunity cost (OC) is conventionally defined as the difference between an investment one makes and another one which he/she chose not to make, i.e. benefits that are not earned as a result of pursuing another alternative (Son, 1991). Most of traditional costing systems represent quality costs as those costs that are easily seen and monitored. Nevertheless, OC does not characterize true money, thus it is excluded from the company books. So far OC did not gain much interest in the COQ research literature, because most empirical studies have failed to find a way how to express them (Ittner, 1996; Castillo-Villar et al., 2012). Most quality costs are in fact hidden and not easy to measure (Krishnan, 2006; Wood, 2007). However, ignoring OC in COQ analysis leads to a value of zero in the cost accounting systems, which is definitely not an accurate estimate for these costs and can result in wrong conclusions and losses for the company (Chiadamrong, 2003).

In the literature, one can find various kinds of opportunity costs. However, their effects in the form of a loss of customer goodwill are rarely considered in the COQ models (Snieska et al. , 2013; Mäenpää, 2016). Chiadamrong (2003) claims that opportunity costs can be divided into four main categories, which are idle costs, batch waiting, process waiting and loss of goodwill. Sandoval-Chávez & Beruvides (1998) are the first scholars to integrate the OC into PAF COQ measurement. The OC represented the intangible costs of the model. The results of their model show that more than 83% of the total revenue was lost and also more than 56% of profit was not earned due to the loss of goodwill. Loss of goodwill can happen when a customer is not satisfied with a certain product, which may have serious consequences in terms of not only losing a specific customer and all his/her future sales, but also losing the reputation and with that more customers as well. Loss of organization's image is a serious issue, which may cost much more than expected. Ignoring these loss costs may lead various organization managers to make wrong decisions (Heagy, 1991; Trehan et al., 2015; Sansalvador & Brotons, 2017). Costs of losing goodwill are obviously difficult to calculate and not many researchers have attempted to evaluate

(Rashid et al., 2014; Elrod et al., 2013). Chiadamrong & Thaviwatanachaikul (2002) argued that by including opportunity costs and measuring the real performance, a company will get to the right path in the search for profitable strategies and towards increasing customer satisfaction as well. They developed a simulation model (SIMAN simulation language) which allowed to quantify the quality costs. Their study clearly demonstrated that the quality costs were higher when opportunity costs were included. Cheah et al. (2011) suggest that every company's competitive strategy should consider tracking and eliminating hidden poor quality costs. (Snieska et al., 2013) used a pilot study to investigate the external failure cots at a medical supply service company in Lithuania. They employed quality function deployment modified planning matrix (developed by Moen 1998) and loss calculation method due to unsatisfied customers lost (implemented by Jones & Williams, 1995) and found the hidden external failure quality costs to be quite elevated.

In this research we try to incorporate the OC in terms of customer satisfaction in the SC COQ analysis. We define OC as a monetary value and suggest a model, which integrates it with the total COQ under nonconformance costs category. Since we were able to incorporate the OC in our model, we could also perform experiments on the model to better understand the effects of QL on all the components of COQ.

1.3. Scope and objectives

Many industries today are in quest of improving their quality systems, finding ways to reduce failure and product nonconformities while increasing customer satisfaction. This thesis follows this motive and integrates opportunity cost (OC) with COQ into SC network design. The scope of this research involves an in-depth analysis of the COQ and QL in the SC and in the Supply

Chain Network Design (SCND). The research seeks to find an optimum QL that matches the minimum spending on the COQ. This work is expected to present a reliable SC COQ model, which can be used to measure COQ in SC. To achieve our research scope, four main objectives are identified:

1. Defining and integrating the OC into the SC COQ
   - ✓ Analyzing the COQ with and without OC
   - ✓ Finding the relationships among the COQ variables and OC
   - ✓ Finding the relationship between the OC and the number of new customers
2. Designing an uncapacitated SC based on COQ allocation
   - ✓ Analyzing the COQ among centralized SC echelons
   - ✓ Analyzing the COQ among decentralized SC echelons
   - ✓ Studying the effect of spending limitation of PA costs on the SC entities
3. Designing an SCND model which considers COQ in each facility
   - ✓ Analyzing the COQ with and without OC and studying the effect of the OC on facility selection
   - ✓ Increasing the overall SC QL by considering PA allocation in each SC echelon
   - ✓ Analyzing the effect of the transportation costs on COQ in SC
4. Designing a Decision Support System (DSS) to measure COQ in SC
   - ✓ Analyzing the COQ in a mathematical model
   - ✓ Analyzing the COQ in a simulation model
   - ✓ Increasing the number of the new customers in the SC

1.4. Outline of thesis

The manuscript has six chapters organized in the following sequence. In chapter 2, we study COQ within a supply chain using system dynamics approach. This chapter presents a methodology to build and examine a general behavior of the COQ factors, i.e., PA, F, OC, and QL within the supply chain. The chapter also examines the effect of integrating OC into the SC. Chapter 3 presents a mathematical model for designing SC network based on the impact of COQ allocation. It also offers a detailed discussion and sensitivity analysis of the QL and working below of the optimum QL. In addition, the chapter analyzes the behavior of the PA, F, OC costs and QL within centralized and decentralized SC. In chapter 4, SCND model based on COQ and QL analysis is presented. The chapter designs the network of facilities based on the COQ with and without the OC. In this chapter, the mathematical model is built based on the PAF model by using a mixed integer non-linear programming (MINLP) model. We also examine the allocation of PA investment at each SC echelon separately. In chapter 5, we propose hybrid decision support system (DSS) model, which is based on COQ and which has been developed by considering a mathematical and a simulation model. The hybrid model implements COQ based on PAF model, OC and QL. In this chapter, the optimization is used to solve the mathematical model and results are implemented in the System Dynamics simulation (SD) model. The developed SD model is useful in predicting the number of the customers at high PA values. Finally, section 6 presents the summary, conclusion and future research directions.

Chapter 2 - Analyzing the Cost of Quality within a Supply Chain Using System Dynamics Approach

Abstract

The objective of this paper is to examine the effects of incorporating the opportunity cost (O_C) into quality costing calculations in order to build a general framework for the behaviour of all quality cost factors within the supply chain (SC). The proposed cost of quality (COQ) model uses System Dynamics approach and is based on the traditional prevention-appraisal-failure (PAF) concept. The data were collected from real automobile manufacturing SC, and the O_C was captured by deriving the level and the dynamics of the customer satisfaction from a survey. Various simulation runs were implemented to develop general relationships between COQ factors and identify key relationships. The findings reveal that when O_C is considered in the COQ model the number of new customers and production units in SC decreases, which highlights the importance of the O_C analysis in making decisions for the quality management strategies. No work has been published regarding integrating PAF, the quality level (QL) and O_C into SC modelling; the findings will help better understanding the value of OC in SC.

Keywords: Opportunity Cost, Cost of Quality, PAF Model, Supply Chain, System Dynamics.

2.1. Introduction

Quality has been long recognized as an important aspect in the decision-making of the consumers when a variety of the products is available in the market. However, it is not only high quality which customers require; it is high quality with low price which attracts them and ultimately enable companies to outshine the competition (Chopra & Singh, 2015). In order to attract the customers, organizations must, therefore, consider not only the quality level (QL) of the products but also the cost for which such quality can be achieved. Integrating tools such as Cost of Quality (COQ) in their accounting systems can, therefore, help companies to minimize costs and at the same time increase the quality, thereby attaining better customer satisfaction (e.g., Dreyfus et al., 1999; Wilkes & Dale, 1998; Mendes & Lourenço, 2014). However, the concept of identifying COQ elements and implementing COQ model is not very straightforward, and there have been some differences about what each of these cost categories comprises (Yang, 2008; Cheahet et al., 2011; Trehan et al., 2015). Tsai (1998) states that there is no general technique on how to allocate expenses to COQ elements and no satisfactory method to trace quality costs to their sources. Organizations which decide to manage their COQ have to choose an appropriate model, which contains the elements and categories of their COQ (Omachonu et al., 2004; Ramdeen et al., 2007; Akkoyun & Ankara, 2009; Daunoriene & Katiliute, 2016).

Quality costs are defined by the British Standard (BS 6143 Part 2, 1990) and American Society for Quality Control (ASQC, 1971) as those costs that assure and ensure quality plus the loss incurred when quality is not achieved. In the past, quality costs were mainly connected with inspection and testing, and usually, these costs were considered as part of overhead costs. Accordingly, the sum of total quality costs represented only a small portion of the total cost (Chiadamrong, 2003). The purpose of considering COQ in the industry practices is to demonstrate and highlight the benefits of improving quality and to relate it to customer satisfaction, as well as to link these benefits with a matching cost in order to be able to reduce total costs and increase benefits (Iuliana et al., 2013). Therefore, the cost of quality can be considered as a tradeoff between the conformance costs and of nonconformance costs (Schiffauerova & Thomson, 2006; Sawan, 2014).

While there are numerous cases of COQ measurement and its implementation in organizations individually, there is so far only a few studies which attempt to measure COQ in the whole supply chain (SC) network (Srivastava, 2008; Castillo-Villar et al., 2012; Ayati, 2013; Gueir, 2016). Srivastava (2008) was the first author who combined COQ in SC performance measurement. According to Srivastava, COQ in SC is: "the sum of the costs incurred across a SC in preventing poor quality of the product and/or service to the final consumer, the costs incurred to evaluate and ensure that the quality requirements are being met, and any other costs incurred as a result of poor quality" (p. 194). Ramudhin et al. (2008) studied single product three echelon SC. Their model minimizes total operational and quality costs at the same time while it considers the percentage of defectives at the suppliers' echelon. They claim that adding supplier quality costs to the objective function minimizes the percentage of defectives at the supplier. The authors argue that adding COQ to the objective function increases the objective value by 16% and changes the solution considerably. Castillo-Villar et al. (2012) studied the impact of COQ on SC network design and used Genetic Algorithm (GA) and Simulated Annealing (SA) to solve their nonlinear model. Their proposed model was able to find the best combination of integer variables of a supplier, manufacturing plant, and retailer that maximizes the profit and minimizes the total COQ. Recently, Lim et al. (2015) proposed a mathematical programming model to optimize COQ. The model considered PAF framework and was recommended to be linearized in order to provide insights into the effects of changes in COQ parameters. Liu and Xie (2013) suggest that it is important to improve teamwork between the upstream and downstream SC to improve QL and reduce quality risk. Their research focuses on the quality decision variables of the functional logistics service provider (FLSP) and the logistics service integrator. They assume that the customer demand is affected by the quality defect guarantee. The research concludes that the customer punishment has a direct relationship with optimal quality defect guarantee of the FLSP. Omar and Murgan (2014), whose work was the main motivation for this research, find that production hidden quality costs equal to 66.7% of the overall total cost. In their case study the O_C, which was based on the operation's inefficiency, was found to be nearly 18.4%. They conducted their research on a semiconductor firm operating in South-East Asia and found that the nonconformance costs can be decreased at slight or no subsequent increase in the conformance costs.

However, Trehan et al. (2015) claim that not much research has been done to study the impact of prevention costs and appraisal costs on the failure cost, and also Omar and Murgan (2014) encourage conducting more research especially in more complex production lines. Some studies use QL in order measure quality. For example, Li et al. (2017) examine the reduction of the QL of a luxury product produced by a monopolist manufacturer. One finding of their research shows that the company can introduce a low-quality version of the product. Zhang et al. (2016) argue that the QL is considered as one index, which can be used to measure the performance of a whole enterprise. They claim that the QL is easy to measure and replicate different process management performance. However, to our knowledge, there is no study focusing on the QL in a manufacturing SC while analyzing COQ, and this paper intends to fill this gap. Our model incorporates QL analysis in the SC, allowing the COQ practitioners to observe the effects of centralized decision-making for QL in the SC. Therefore, the consideration of both O_C and the SC effects in the COQ model are the contribution highlights of this paper. The O_C represents the customer's satisfaction, and it will be represented as a monetary term in the model. The proposed model will be used to simulate various kinds of investments in the conformance costs, i.e., prevention and appraisal costs (PA_C), and to investigate the effect of this investment in the nonconformance costs, i.e., failure costs (F_C) and O_C. A case study for a manufacturing SC located in North Africa will be used to collect the data to illustrate the effect of incorporating O_C into COQ the relationships involved in the model and to help construct and to validate our model. The remainder of this paper is structured as follows: Section 2 provides a literature review on the COQ, section 3 explains the research methodology, and section 4 presents the results. In section 5, the relevant discussion is presented. In section 6, the conclusions are discussed, and finally, suggestions for future studies are outlined in section 7.

2.2. Background and literature review

The importance of quality derives from the fact that it greatly affects customers' decision about the purchase of any product. The differences among various products can thus be identified by the quality and its cost (Anshul, 2015). Over the past thirty years, there has been an aggressive battle among companies trying to provide quality for the lowest possible cost and, consequently, only those who succeeded survived (Bowbrick, 1992). In today's market, the quality differences became a critical element in competition (Chen & Hua, 2015; Nabin et al., 2016; Donauer et al., 2015). Therefore, a clear definition of the COQ for any product is necessary for effective operation and competition (Ben-Arieh & Qian, 2003). Even though the definition of quality costs is crucial for measuring the quality itself, there is no unique and accepted definition, as different authors define quality costs in different ways (Chiadamrong, 2003; Dennis, 1999; Evans & Lindsay, 1999). According to Srivastava (2008), COQ or quality costs can be defined as a measurement system that translates quality related activities into a monetary language for managers, i.e., it is the sum of costs incurred to ensure that the quality requirements are being met. Sum of the total quality costs, however, usually represent only a small portion of the total cost.

Tye et al. (2011) suggest that if the cost of quality is well implemented, it leads not only to the cost reductions, but it will also increase the reliability of product quality. More recently, Mahmood & Kureshi (2014) tested Cost of Poor Quality (COPQ) on a real-time public sector infrastructure project (a concrete bridge), their data was collected from machinery, labour, and material, which used in the project. The results presented a successful reduction in COPQ, which is from 36.41% to 15.07% in sixty days study period. Mahmood and Kureshi recommend the measuring of COPQ and the use of the system for future construction projects. Chopra and Garg (2012) built two models to measure the COQ and to develop the COQ system. They claim that their COQ program can be used to calculate the COQ in any industry. Chopra and Garg tested their model in a textile company located in Amritsar in India. In the first model, they constituted a COQ team to estimate the current level of COQ; the second model considered the recommendations of the necessary steps/investment to reduce the COQ level. Their result showed that the implementation of the COQ program is a very effective technique and that it helped the organization to reduce the COQ by 23%. By analyzing the COQ in manufacturing industries, Sailaja et al. (2014) were able to reduce the failure cost from 57% to 48%. The COQ was decreased from 8% to 5%. They analyzed the COQ using statistical tools, and they were able to identify the areas of improvements. In general, it is expected that the total cost of quality will decrease if the organizations implement a strong quality cost system, and the external failure costs will decrease too as a percentage of total COQ (Takala, 2015; Trehan et al., 2015).

2.2.1. PAF models

After Juran (1951) introducing the COQ, many researchers have proposed different approaches and models to measure COQ. Several authors, such as Plunkett and Dale (1988), Kumar et al. (1998), Schiffauerova and Thomson (2006), Omar and Murgan (2014) and Donauer et al. (2015), provided a review of various COQ models and approaches. They are all generally in agreement with classifying COQ models into the following generic groups which are: PAF (prevention-appraisal-failure) or Crosby's model, opportunity costs models, process cost models and ABC models. In literature, Juran's model is the most common model in the literature (Plewa et al., 2016), which is widely used in manufacturing industry due to its easy interpretation (Suthummanon & Sirivongpaisal, 2011). Juran claims that in order to obtain the lowest rate of COQ, failure costs should be equal to the sum of prevention and appraisal costs (Juran, 1951). This can be seen in the trend graph in Figure 2-1. PAF model has obtained general acceptance among various researchers and organizations, such as ASQ. COQ integrates the implications of poor quality, quality improvement efforts and hidden quality costs and translates them into understandable monetary terms for all stakeholders of an organization (Castillo-Villar et al., 2012). COQ measurement is mostly implemented for a specific organization or business.

Feigenbaum (1961) was instrumental in proposing quality terms; he also classified the quality costs into three widely accepted broad categories, which are prevention, appraisal, and failure (PAF). The PAF model involves the costs coming from three sources of activities, which are defined in the British Standard (BS 6143, 1990) as follows: Prevention costs (Pc) are the investment made to prevent and reduce the risk of nonconformity or defect, such as quality planning, process control costs, training, and general management costs. Appraisal costs (Ac) are the cost of efforts made to achieve conformance to requirements including, for example, test and inspection costs, and instrument maintenance costs. Failure costs (Fc) are the efforts exerted to correct a nonconformity that has occurred before or after delivery to the customer. Failure costs are thereby classified as internal failures and external failures, where internal failure costs are incurred within an organization due to nonconformity or defects at any stage of the quality loop, such as costs of the scrap, rework, retest, reinspection and redesign, whereas external failure costs represent costs which arise after delivering poor quality to a customer/user due to nonconformity or defects, such as the cost of repairs, returns, dealing with complaints and compensations.

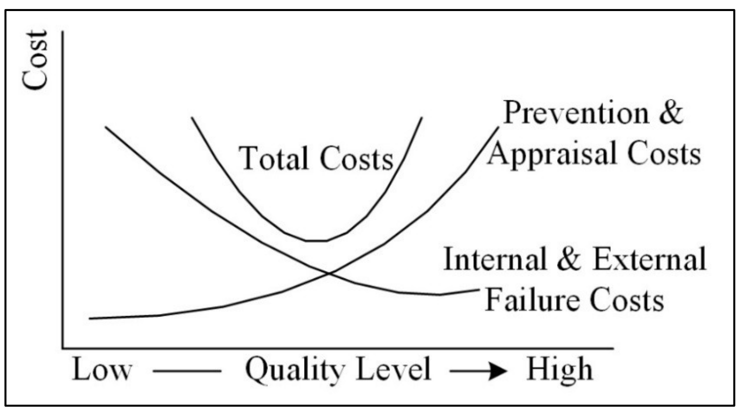


Figure 2-1 2: Juran's model for COQ (Source: Adapted from (Juran, 1951)

However with the increase in the organization complexity, these costs are increasing as well, and their cost elements may become unclear and more difficult to be captured (Bulgak et al., 2008; Trehan et al., 2015; Jennings et al., 2014). Cheah et al. (2011), Campanella (1999), Krishnan (2006) and Wood (2007) supported the view of most quality costs are in fact hidden and are not easy to be measured. This brings us to the concept of opportunity costs described in the next section.

2.3. Methods

The proposed COQ model in a manufacturing SC was established based on the PAF model. In order to analyze the components of quality costs, it is necessary to understand the correlation among each other. For example, when an investment is made in PA_C the F_C decreases. Organizations' quality control managers might want to know how much of an investment in conformance costs is necessary to reduce the costs of nonconformance. In addition, they may also be interested in finding out what is the optimum spending on PA_C in order to reduce spending on total COQ, because such information is significant when any investment in quality is required. However, the most important point of our analysis is to test the effect of incorporating O_C into the COQ in the SC and to examine the impact of including and excluding O_C from the calculations while considering the QL.

Our concept of adding O_C to the model is shown in Figure 2-2, where the COQ for these two cases is demonstrated. The full line (COQ_a) shows the case when O_C is not considered (i.e. $COQa = PA_C + F_C$). In this case, according to Juran's (1951) claims, the minimum spending on COQ would occur at the point (a), which is the intersection of PA_C and F_C. When the O_C is added to the graph, the intersection of PA_C and ($F_C + O_C$) will be shifted to the right side (b). This case is represented by the dotted line (COQ_b) and the total $COQ_b = PA_C + F_C + O_C$. According to the literature, Figure 2-2 shows that the COQ values in both cases are dissimilar (Sandoval-Chavez & Beruvides, 1998). Our visualization of the COQ at the point (a) is consistent with Douiri et al. (2016), in which he states that the trend of the O_C model is similar to the trend of the modern view of COQ model when O_C is considered.

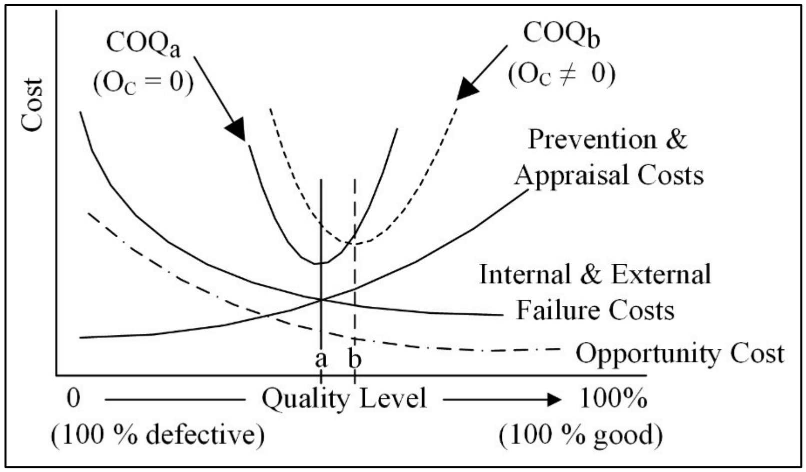


Figure 2-2: COQ before and after incorporating OC

2.3.1. Data collection

In order to build the model, we relied on various inputs mainly from existing literature, expert insights, and industry realities. We carried out a case study in a manufacturing SC in order to collect the most accurate data. The name of the company and the data provided remain confidential. The SC involved is an automobile manufacturing SC mainly consisting of metal casting, inspection, lubrication, machining and heat treatment. Examples of the company-produced parts are a heat sink, end bell, drum brakes, disc brakes, casting dies, and flywheels. Most of the data were obtained from main components of the SC general layout, i.e., one supplier, one manufacturer, customers and customers from the SC competitors. The SC provides different families of products in which both the supplier and manufacturer are involved. However, for simplicity, only one family of products was considered in our study, and one supplier can supply it. The products are manufactured by sand casting and die-casting in the supplier section. Machining processes are done at the manufacturer. The supplier works at a specific QL and uses various quality instruments. The inspection processes carried out through the selection of random samples at specific production times for each supplied lot. The supplied lots should maintain certain QL in order to be accepted and supplied to the manufacturer. There is a ratio of defects which can be accepted by the manufacturer for the supplied parts. The manufacturer returns products which fail to meet quality tests to the supplier, the rejected parts are then remanufactured at the supplier and resupplied again. The manufacturer implements the same procedures for the quality measures as the supplier does.

2.3.1.1. SC Data collection and PAF classification

The documented data were collected in collaboration with the SC entities. The data involves the records and comes mainly from the operation, quality, sales and customer service departments in the SC. The data were classified based on the literature classifications and is provided in Table 2-1 (Chiadamrong, 2003; Sharma et al., 2007; Zaklouta, 2011; Wudhikarn, 2012; Farooq et al., 2017).

Table 2-1: SC PAF cost component classification

Supplier Prevention Costs	**Supplier Appraisal Costs**	**Supplier Internal & External Failure Costs**
Recruiting Training Auditing Supplier certification Supplier assurance	Inspection of material Prototype inspection Quality auditing Outgoing inspection Equipment tests and calibration Production control	Downtime caused by defects Redesign Rework Re-inspection of reworking Retesting Scrap
Manufacturer Prevention Costs	**Manufacturer Appraisal Costs**	**Manufacturer Internal & External Failure Costs**
Quality planning and programs	In process testing	Downtime caused by defects

Quality planning training. Auditing Equipment maintenance Certifications	Field audit Process acceptance Product acceptance Equipment tests and calibration Outgoing inspection	Discounting sub optimal products Rework Re-inspection of reworking Sorting and screening of suboptimal products Scrap Customer service Product liability costs Lost sales Penalties Refund/compensation Warranty costs

2.3.1.2. Survey data

A case study for a manufacturing SC located in North Africa was selected for collecting the survey data to calculate and find out the value of the Oc to be incororporated into COQ. We conducted a survey to target the customers of SC of the case study company and customers of competitors' organizations. The total number of the SC customers and customers of competitive organizations who were contacted by email was 250. 116 customers of the SC and 76 customers of competitive organizations participated in the survey in 2013. The questions of the survey are provided in Appendix I (Dangayach & Deshmukh, 2001; Laosirihongthong & Dangayach, 2005). Opportunity cost related to customers' goodwill was calculated using the quality function deployment modified planning matrix method, which was used by Moen (1998) and Jones and Williams (1995) to determine the loss due to unsatisfied customers (see Appendix II). Calculation of the hidden external failure quality costs related to the loss of customers' goodwill is presented in Appendix III.

2.3.2. Casual loop diagram

System dynamics (SD) relies on causal loop diagram as a simple map to define the dynamic relationship among various factors, where it is capable of considering the effect of each variable on the other ones simultaneously. We established a causal loop diagram (CLD) to analyze the O_C of the SC. The relationships were based on the COQ relations taken from the literature and as input data we used the SC historical data and the results of the questionnaire. A correlation analysis was used to validate the relationship among the causal loop factors. Figure 2-3 illustrates the CLD of the SC from COQ viewpoint.

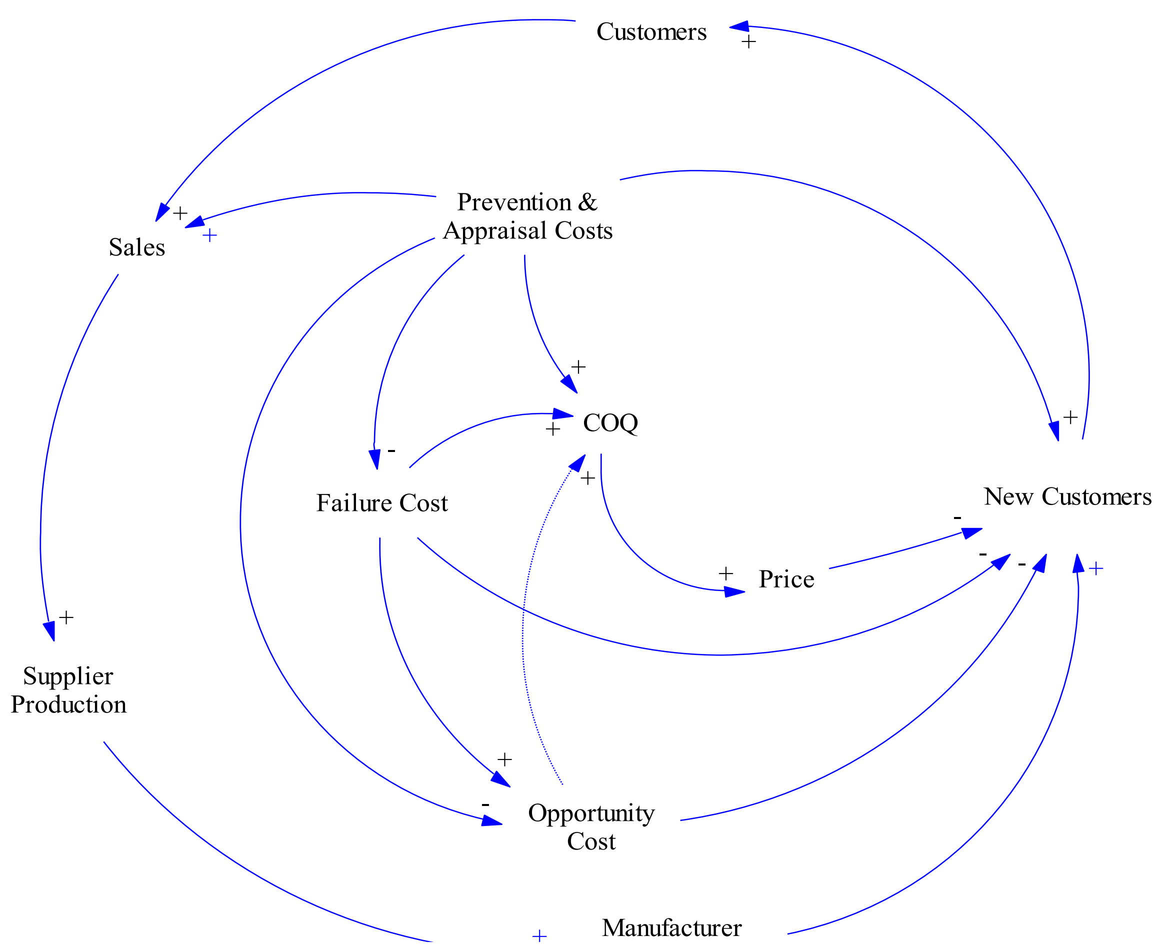


Figure 2-3: Causal loop diagram of the SC incorporating O_C

The CLD shows how various factors influence the number of new customers in the system. The main positive reinforcement loop shows the effects of the increase in the number of new customers on the number of the total customers, sales and on both supplier and manufacturer production. Three cost factors have a negative effect on the number of new customers, which are the price of the product, O_C, and F_C. The PA_C has a positive effect on the new customers and their value increase the number of new customers in the SC increases. The CLD implies that investment in prevention and appraisal would increase conformance, which will consequently minimize failure and opportunity costs. The causal loop of our study is also supported by Omar and Murgan (2014), Li et al. (2017), Omurgonulsen (2009) and Zhang et al. (2016).

2.3.3. SD model

Several tools, such as control charts, histograms and statistical process control (SPC) have been originally considered for the analysis of COQ and the assessment of their impact on quality measures. However, these tools do not consider the dynamics of the interaction among different cost factors. Since PA_C, F_C and O_C are interrelated and affect one another; they should not be treated independently. Investment in any of conformance costs can change the other nonconformance cost.

Thus, a dynamic approach was judged to be adequate to better analyze and comprehend the influence of cost factors and to highlight the most influential cost factors in achieving the expected QL and high customer satisfaction. Figure 2-4 shows the generated SD model. In order to build this model**,** an extensive interaction with the SC individuals was necessary, which helped us visualize our model. The SD model integrates the supplier, manufacturer, customers and COQ. In the model, if the number of new customers increases the sales increase and the corresponding supply increase at the manufacturer and supplier. A correlation analysis was employed to present the impact of the COQ on sales and the number of new customers.

Based on the correlation, we constructed the model, which implies that the investment in conformance costs (PA_C) will increase the number of new customers and consequently it will increase the number of total customers. On the other hand, any increase in nonconformance costs (F_C & O_C) reduces the number of new customers. The shape of the lookup function was structured based on the Juran's (1951) COQ model with different costs values for each COQ parameter. By changing the variables of the expected COQ factor, the model was simulated and run at different COQ scenarios in order to provide a general picture of the O_C and its effect on the number of new customers.

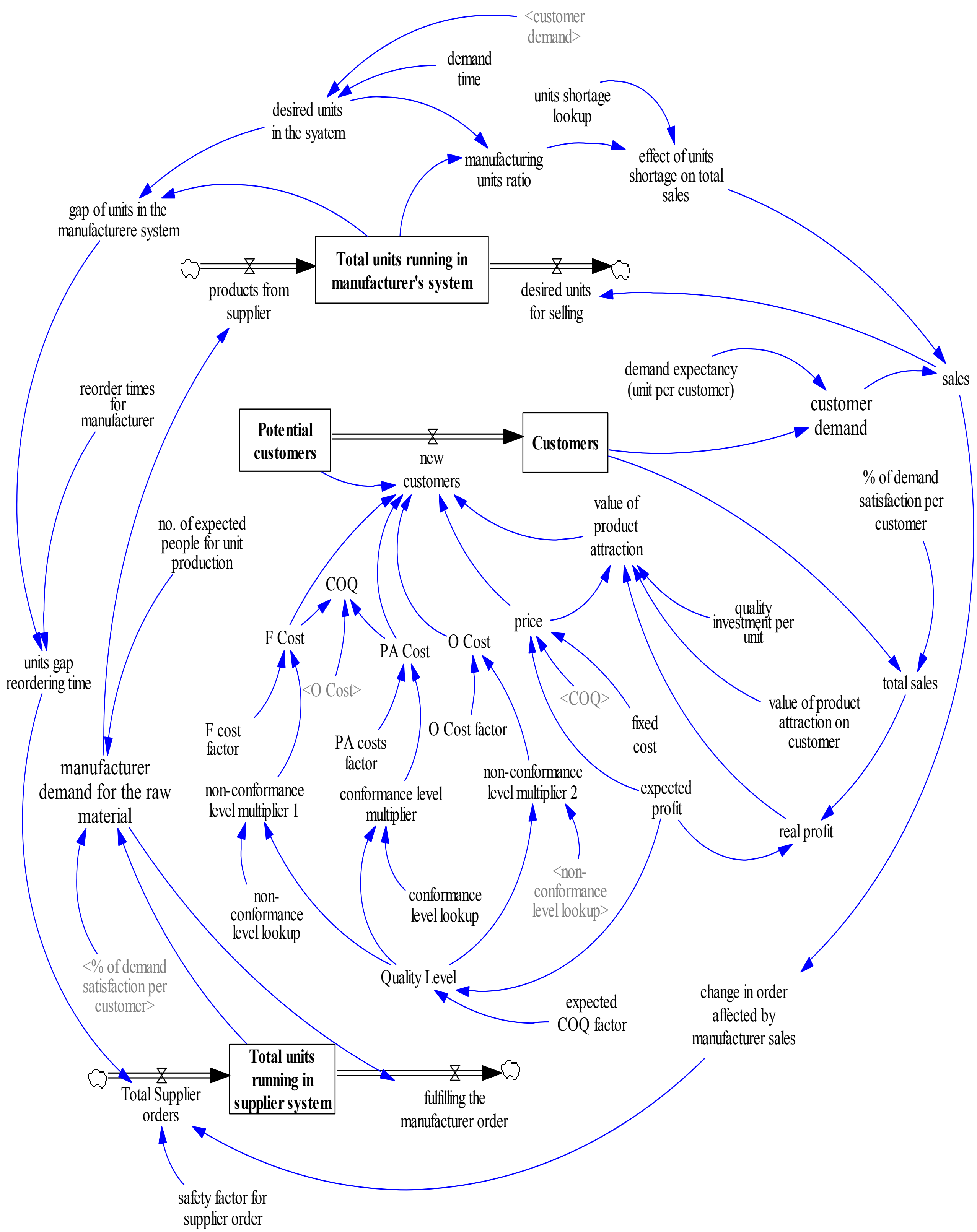


Figure 2-4: System Dynamics (SD) model

In order to obtain more accurate results, we have constrained our SD model. These constraints may, however, limit the external usability of the model. The model assumptions are as follows:

1 The customers' demand is satisfied by the manufacturer.
2 All supplied parts from the supplier are accepted at the manufacturer.
3 The manufacturer works at the same QL for the same types of products.
4 The SC products are 100% inspected before the products are delivered to the customers.
5 Nonconformance costs have the same trend at each echelon (lookup function) in the model.

2.3.4. Model validation

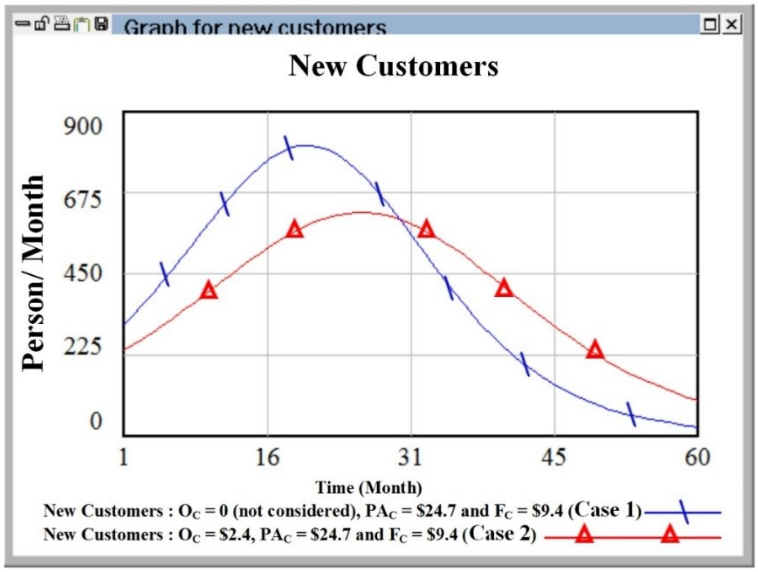
There is no single or general test which can be used to "validate" a system dynamics model (Robinson, 2014; Duggan, 2016). Confidence in system dynamics models gradually increases as the model passes more tests. Testing of a model can be obtained by comparing the model to the empirical reality, which means to test the model in various forms other than numerical statistics for the purpose of confirming or refuting the model (Forrester & Senge, 1996; Robinson, 2014; Duggan, 2016). The following sections describe the validation of our model.

2.3.4.1. Model structure and behaviour

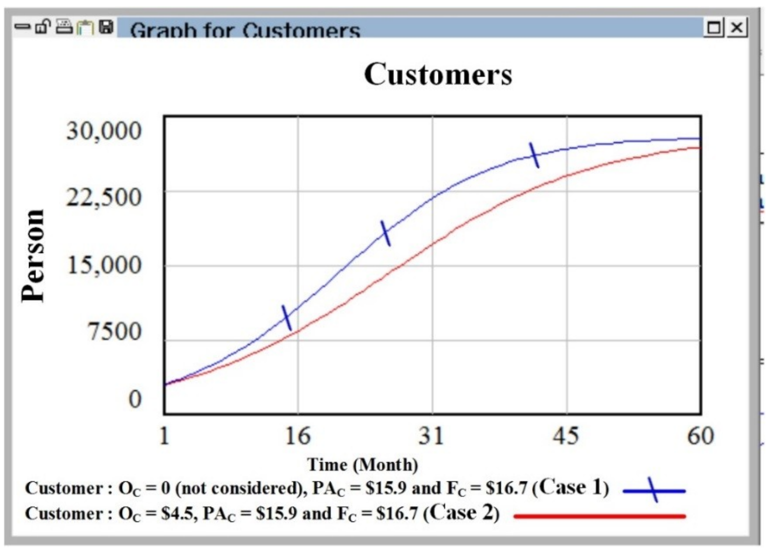
The validity of our model can be obtained by testing the model structure and its behaviour against the structure of the real system (Barlas, 1994; Robinson, 2014; Duggan, 2016). As the model structure must follow the structure of the real system and its functions, the structure of the model was discussed with the production and quality engineers of the SC for which we gathered our data. They agreed on the structure of the SD model and confirmed its suitability for the SC. Furthermore, since this research inspired by Juran's (1951) model, the results of the COQ model were compared with Juran's model in order to confirm that the behaviour of the COQ is compatible with his model (see Figure 2-9-a and 2-9-b, clearly corresponding to the relationships in Juran's model).

2.3.4.2. Parameter-verification test

This test is commonly used in the literature to check whether the parameters of the SD model correspond numerically and conceptually to real life (Marzouk & Azab, 2014; Mehrjoo & Pasek, 2016). The constant factor which we considered in our model as shown in Figure 2-4 is the QL factor. It affects the QL directly, and consequently, it influences COQ variables, PA_C, F_C, O_C and the price of products. Figure 2-5-a shows the observation for two cases, where Case 1 represents the number of new customers when O_C is not considered ($O_C = 0$) in the SC and Case 2 represents the expected number of new customers when O_C is integrated to the COQ. For the parameter-verification test, it was found that the average number of new customers in Case 1 is higher than in Case 2, which consequently affects the accumulative number of customers as shown in Figure 2-5-b. This corresponds to the situation observable in the real life, where the consideration of O_C reflects the lowest satisfaction of customers and hence their lower numbers in the SC.



a



b

Figure 2-5 (a & b): The observations for the number of new customers and the accumulative customers in the SD model (with & without O_C)

2.3.4.3. Extreme-conditions test

Forrester and Senge (1996) suggest that the structure in SD models should allow different combinations of levels in the represented system. Moreover, if knowledge about extreme conditions is integrated, the results will lead to an improved model in the normal operating region. Recent studies show that this test is commonly implemented by various authors to check if the equations of their models make sense when subjected to extreme conditions (e.g., Ahmad et al., 2015; Marzouk & Azab, 2014). Our model was tested against the extreme conditions (at the maximum and minimum points) for the model auxiliaries. For example, QL, which is the main auxiliary part for the new customers and the customer demand were tested at their extreme points. We found the outputs are equal to zero at the zero extreme point. In addition, the QL was tested at different high values as shown in Figures 2-9 and 2-10. Hence extreme-condition test was applicable and satisfactory for our model.

2.4. Results

2.4.1. Correlation analysis

In this research, correlation analysis, which was based on the data collected form the SC case study, was conducted to determine the statistical influence of the COQ components on the number of new customers, sales, and total produced units at both the manufacturer and supplier. The SC historical data, which collected over a period of four years (2010-2014) were used to determine the correlations. The results, which shown in Table 2-2, confirm that as conformance costs (PA_C) increase, quality improves and nonconformance costs (F_C) decreases, which corresponds to the basic assumptions of the PAF model. These results are also supported by Keogh et al. (2003) and Luther and Sartawi (2011). This table also shows a strong relationship among the PA_C, new customers, sales and number of units produced by the manufacturer and supplier. According to Table 2-2, the SC COQ data shows a strong inverse correlation between conformance costs and nonconformance costs, which implies that if the SC invests more in the PA_C, the FC decreases.

Table2-2: Correlation analysis among COQ elements, the number of new customers and sales

	PA_C	Internal F_C	External F_C	New customers	Sales	Manufacturer units	Supplier units
PA_C	1						
Internal F_C	-0.87	1					
External F_C	-0.90	0.67	1				
New customers	0.83	-0.52	-0.98	1			
Sales	0.96	-0.83	-0.97	0.91	1		
Manufacturer unit	0.96	-0.83	-0.97	0.91	1	1	
Supplier unit	0.96	-0.83	-0.97	0.91	1	1	1

2.4.2. SD Model

After we constructed the SD model, we run the model to determine the effect of adding O_C. The time frame which was used in the simulation is five years. To analyze the effect of O_C, we distinguished three Cases: in the Case 1, the model was run without O_C, in the Case 2, we added O_C to the model, in the Case 3 we adjust the QL of Case 2 to gain the same number of new customers as in Case 1. After establishing the cases, we run the SD model at different QL to construct a general relationship between COQ (PA_C, F_C, and O_C) and QL in the SC.

2.4.2.1. COQ without OC (Case 1) and with OC (Case 2 and Case 3)

Case 1 refers to the current situation of the SC, where the QL is 73%, PA_C = \$24.7/unit, F_C = \$9.4/unit, O_C = 0 and COQ = \$34.1/unit. With this QL the SC is expected to gain an average of 413 new customers per month as shown in Figure 2-6.

Case 2 is the situation when O_C is considered to be equal to \$2.4/unit in the model, which is the value obtained from the survey. In this case, the QL, PA_C and F_C are fixed at the same values as in Case 1 and the new COQ = \$34.1 + \$2.4 = \$36.5/unit. Here we observed a decline in the number of new customers, which is the result of the added O_C variable to the model. The SC should expect around 400 new customers per month, which is less than 4% compared to the previous expectation in Case 1.

In Case 3, we adjusted Case 2 to make the expected number of new customers the same as in Case 1. The purpose of presenting this case is to highlight the tradeoff among the COQ factors. We found that the QL should be increased to reach 77% to gain the same number of new customers which we had in Case 1. As a consequence of increasing QL, the model adjusts the conformance costs (PA_C) to be increased by around \$2 to reach \$27, whereas the nonconformance costs (F_C) on the other hand declined by around \$1.5 to become \$7.8 and the O_C cost has also decreased to approach \$2. The observations for these 3 cases are shown in Figure 2-6.

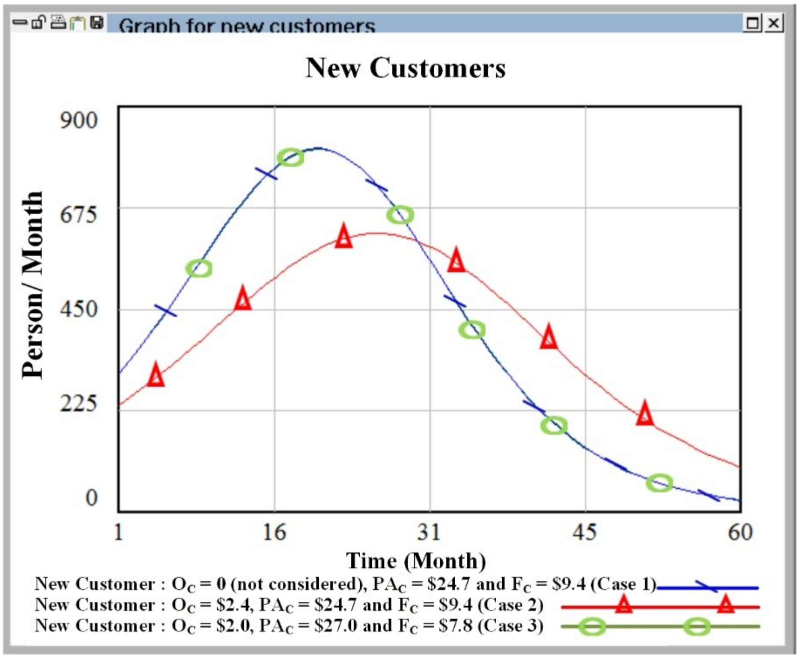


Figure 2-6: COQ observations for the number of new customers

The effect of Case 1, Case 2 and Case 3 on the total units, which are available at the supplier and manufacturer are shown in Figure 2-7 and Figure 2-8, respectively. The total decrease in the supplier and manufacturer units are 511806 and 158177 units, respectively (from Case 1 to Case 2), which represents 14.6% decrease at the supplier (see Figure 2-7) and 13.1% decrease at the manufacturer (see Figure 2-8). The effect of the O_C on the supplier is greater than its effect on the manufacturer because the manufacturer is working at around 1.5% QL higher than the supplier. In order to compensate for the decrease in the produced units at the supplier and manufacturer, an investment in PA_C of about $27/unit is required, which will represent the situation of Case 3. This will provide the same amount of products presented in Case 1 and would reduce the effect of the O_C on the model.

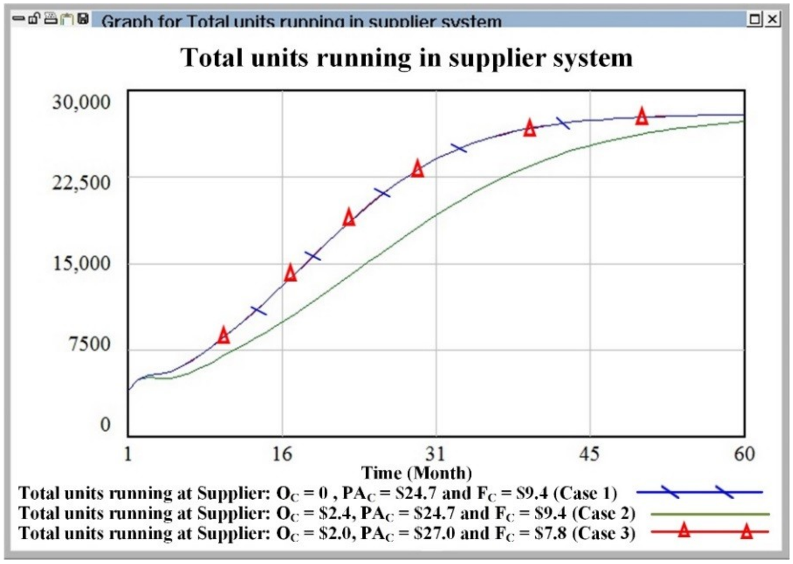


Figure 2-7: No. of units available at the supplier

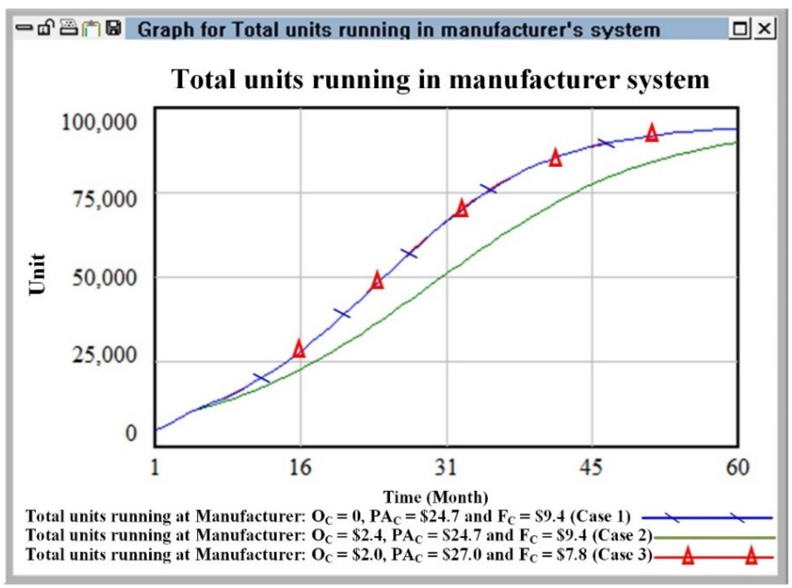
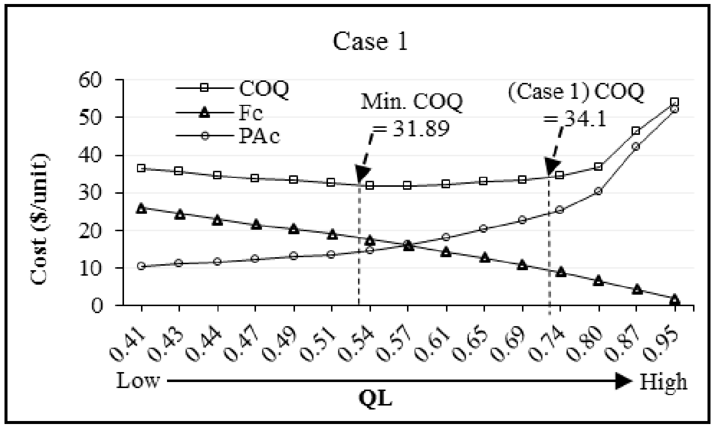


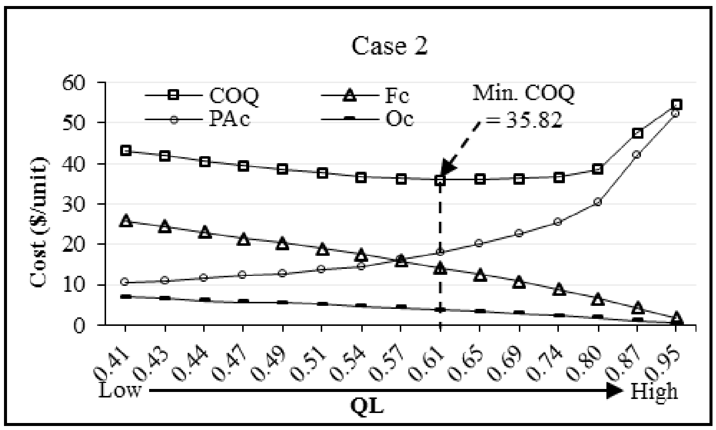
Figure 2-8: No. of units available at the manufacturer

2.4.2.2. The impact of QL on COQ

In this subsection, we present the results of running the SD model at different QL values. This is done to establish general relationships between COQ parameters and QL. The results can be used to find out the efficient QL for cost spending and the difference between Case 1 and Case 2. The Case 1 results are shown in Figure 2-9-a, which shows different simulation runs resulted from various QLs. We can notice that the minimum achieved COQ was \$31.89/unit at QL = 53%. Also, the Figure exhibits the current SC QL = 73%, at which COQ reaches \$34.1/unit. However, the minimum attained COQ in the Case 2, which is presented in Figure 2-9-b, was \$35.82/unit at QL = 61%. After adding the O_C to the model, the minimum COQ shifted to the right. These results validate our model since they comply with our concept, which is presented earlier in Figure 2-2, and with Sandoval-Chavez and Beruvides (1998) and Douiri et al. (2016) viewpoint. The O_C is a nonconformance cost and to compensate its effect on the model, the SC should invest in the PA_C. Furthermore, both Figures show that the total COQ increases rapidly after 80% QL. This is due to the shape of the PA_C function, which was used in the model as an exponential equation, which indicates that it is much more costly to improve QL beyond 80%. Therefore, the results are consistent with literature findings of Juran (1951) and Liu (2007), which states that after a certain QL COQ starts to increase exponentially. In general, the COQ is affected by the shape and curvature of PA_C, F_C and O_C cost function (lookup cost functions) in the SD model.



a

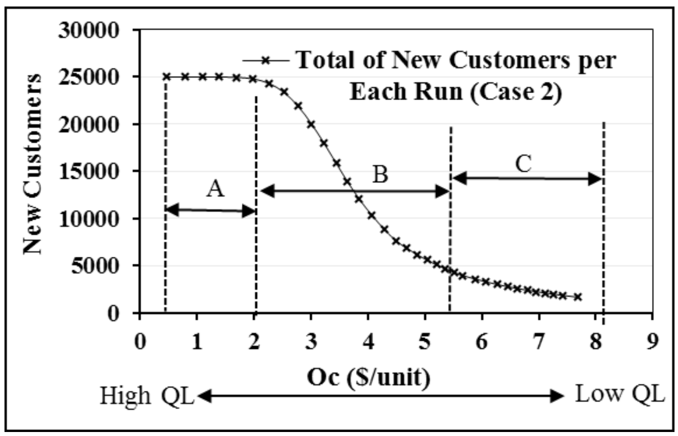


b

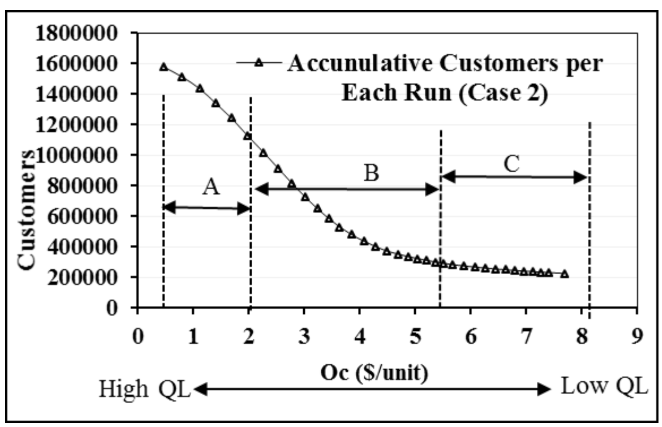
Figure 2-9 (a & b): Different simulation runs for COQ without and with OC

2.4.2.3. The relationship of OC and new customers in the SC

Different simulation runs at different QL values were carried out to find out the specific relationship between O_C and new customers and, consequently, on the total SC customers. Figure 2-10-a shows that if the QL declines, the O_C increases and the expected number of new customers decreases. In Figure 2-10-b, the number of the accumulative customers increases as the QL increases (O_C decreases). The customer accumulation function depends on the existing customers plus the new customers. Therefore it reaches its maximum number when QL is high (i.e., O_C approaches zero). In general, three distinct zones can be detected in Figure 2-10-a: In the first zone, A, when O_C is less than \$2.0/unit, the possible increase in the number of new customers is very small, and the investment in this area is therefore not profitable. In the second zone, B, when O_C is between \$2.0/unit and \$5.5/unit, we observe a large effect of O_C on the number of new customers, which means as the O_C decrease the number of new customer increases.



a



b

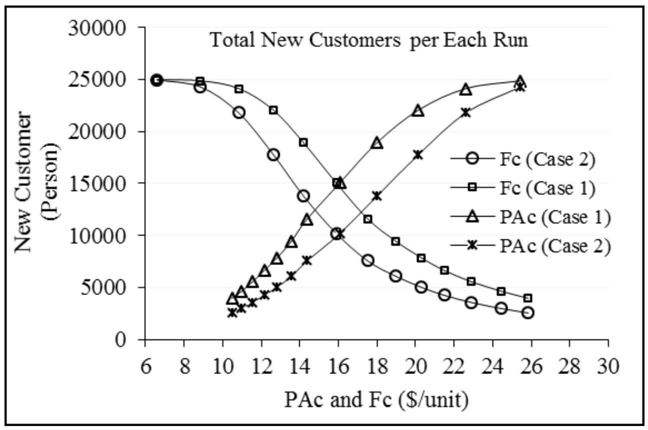
Figure 2-10 (a & b): The effect of O_C on the number of new customers and the accumulative number of customers

Therefore, if the SC makes any investment in zone B, (reduction in O_C/increasing in QL) there will be a significant increase in the number of new customers and, accordingly, it is an important zone to consider. Finally, in the third zone, C, which comes after \$5.5/unit, the amount of the possible increase in the number of new customers is smallest. However, here as observed in the proposed model we noticed a very small PA_C investment and F_C is at its highest level, which makes the investment in this zone critical and mandatory. The exact shape of the curve may vary from one organization to another, and in general, it depends on correlations between costs of conformance and costs of nonconformance.

2.4.2.4. The shape of PAc and F_C in Case 1 and Case 2

After running the SD model for Case 1 and Case 2 several times and at different QL values, we draw a general relationship among the total number of new customers, accumulative number of customers and both PA_C and F_C. Figure 2-11-a and 2-11-b, show that the PA_C has their noticeable effect on the number of new customers and, as a result, on the accumulative number of customers after they reach beyond \$14/unit and this effect can continue up to PA_C = \$26/unit in (Figure 2-11-a), after which any investment is not very effective because the increase in the number of new customers becomes insignificant. On the other hand, the accumulative number of customers always increase until it reaches the last simulation PA_C value, which is at \$51/unit (Figure 2-11-b). It worth noticing that the relationship between F_C and the number of new customers, in Figure 2-11-a, has the same tendency as in Figure 2-10-a, which is due to our assumption stating that the O_C and F_C have the same trend in the model with different costs values. F_C has a minor effect on the number of new customers if they remain below \$10/unit. However, their effect starts to intensify after this point and the increasing in F_C lead to a significant decline in the number of new customers until they reach around \$20/unit where this effect is already slowly losing its intensity, and where the number of total new customers becomes less than 5000 customers per each simulation run (Case 2).

The same effect of F_C can be seen in Figure 2-11-b, i.e., as F_C diminish, the number of the accumulative customers increases. Therefore, to maintain the number of new customers at high levels, the SC should control the F_C and keep them below \$10/unit, which is, in fact, what the model presented in Case 1 (F_C = \$9.4/unit), even though the SC is not considering the O_C in the COQ analysis.



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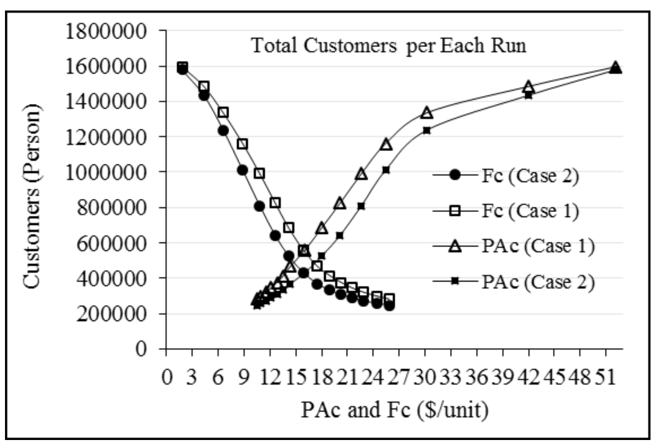


b

Figure 2-11 (a & b): The effect of PA_C and F_C on the total number of new customers and accumulative number of customers

2.5. Discussion

The model investigated the efficacy of spending on the conformance costs (PA_C) regarding its effect on the number of new customers. Based on the relationships between COQ parameters and their relations with other variables three distinct zones of investment were identified. In the first zone, OC is very low, but the QL is high as is the level of current spending on the cost of conformance (PA_C). Also, the F_C is not significant. In this zone, the product is already enjoying high quality and popularity with its customers, and the further investment in the conformance cost will most likely not be very effective as it is not expected that it will have a significant effect on the number of new customers. In the opposite zone, where the O_C is quite high, the QL is low, it is very critical to invest further in the conformance cost (PA_C) because at the current state PA_C is too low and the failure cost has reached an alarming level.

The quality of the product offered to the customers is not sufficient and it is, therefore, essential to increase the quality and invest in PA_C, even though is not assumed that this investment will have a major direct effect on the number of new customers. Finally, the most effective investment falls to the middle zone of the OC where the level of quality is neither too low nor too high. In this zone, it is suggested that the spending on the conformance costs is going to be most efficient and they are going to lead to the substantial increase of the new customer numbers. In order to conclude our experiments, we compare Case 2 and Case 3 as presented in Table 2-3. The findings show that the SC has good control on the QL, which causes the O_C to be in the region of improvement. For Case 1, we find that the value of O_C = \$2.4/unit falls inside the second zone, B, as seen in Figure 2-11.

Table 2-3: Difference between the current situation and the improved situation (O_C is considered in both)

Case	QL (%)	COQ ($/unit)	PA_C ($/unit)	F_C ($/unit)	O_C ($/unit)	Total New Customers / QL	Total Customers / QL
Case 2	73	36.5	24.7	9.4	2.4	23926	965747
Case 3	77	36.7	26.9	7.8	2.0	24798	1120072
Difference	5%	1%	9%	-17%	-17%	4%	16%

Accordingly, it is advisable to spend more on conformance costs, PA_C, and increase them by 9% in order to increase the number of new customers as presented in Case 3. This will also improve the QL to the level of 77% and increase the total COQ by 1.0%. Most importantly, it will consequently decrease the nonconformance costs, F_C and O_C, by 17% each. Furthermore, the expected number of new customers and a total number of customers in the model will increase by 4% and 16% respectively.

According to these findings, the authors are in favor of the fact that most of the COQ in the real-life industry are hidden as also stated by Cheah et al. (2010) and Omar and Murgan (2014). Specialists in the industry may be uncertain about the nature of the relationship between PA_C, F_C, and O_C, even though they realize that the increase of the QL is bound to reduce the F_C, O_C and increases the customer satisfaction. Modelling COQ is a precise approach to measure the COQ; nevertheless, organizations' management must be able to distinguish between operational and quality costs to understand the relationship between visible and hidden quality costs.

The proposed SD model can generate COQ curves, which resemble both the original Juran's model and the work by Sandoval-Chavez and Beruvides (1998). The behaviour of Juran's original model is observed with and without O_C both with high and low QL. On the other hand, the behaviour of Sandoval-Chavez and Beruvides's model is observed when O_C was added to PA_C and F_C, in which the QL and minimum COQ have increased to the level above Juran's model.

Therefore, the COQ practitioner and decision makers may use the findings/results of this research to assist and provide more reliable decisions when testing and improving their COQ plans, which intended to reduce opportunity loss costs and increase customer satisfaction. Although our findings are constructed based on an illustrative SC case, these findings are pertinent to the current SC and may not be applicable to another manufacturing SC because of the SC structure and investment in the COQ are dissimilar from one organization to another.

2.6. Conclusion

This paper had two main objectives. The first objective was to investigate the effects of the inclusion of the O_C into the COQ model with consideration of QL in the SC. The second objective was to examine the efficacy of the investment in the conformance costs in terms of its effect on the number of new customers and total customers in the SC. The model was built using System Dynamics approach and it was based on the traditional PAF approach, but its unique feature was the consideration of O_C and its integration into the model. A simultaneous analysis of all the COQ factors, i.e., PA_C, F_C and O_C with QL enabled us to build a more general framework for the behaviour of all the quality cost factors within SC models.

In order to gain the best practical insights, a real manufacturer SC was considered. A case study within an automobile manufacturing SC was carried out and the data collected within several entities of the SC. The level and the dynamics of the customer satisfaction in the SC was derived from a survey. The historical data, survey results, and the literature were used to build the System Dynamics model. Various simulation runs were implemented in the model in order to derive a general relationship between COQ factors and QL. The model enabled us to find out the minimum COQ and to evaluate the effect of various spending strategies.

First, the relationships between COQ parameters and their correlations with several variables were examined. The results suggest that PA_C are strongly positively correlated with the number of new customers and a total number of customers in the whole SC and with the number of units produced by the supplier and by the manufacturer, while the F_C shows strong negative correlations.

In order to highlight the importance of the O_C in the COQ analysis, we investigated two separate cases, one which did not consider O_C and one which incorporated it into the COQ calculations. We found that the introduction of the O_C to the COQ model would lead to the decline in the number of new customers and to the decrease in the number of production units running in both supplier and manufacturer systems. In order to reach the original number of customers and produced units the quality level (QL) needs to be increased, for which an investment in the PA_C costs is needed. This will lead to the decline in the F_C and, finally, to the decrease in the O_C. The model was able to demonstrate different COQ scenarios at different QLs. In general, it has been proved that increasing conformance (PA_C) in the supply chain can directly decrease nonconformance costs (F_C and O_C), which makes, therefore, the outcomes of this research correspond to the definitions of Juran (1951).

We recognize the limitations of this work in that it may not perfectly capture the integration of O_C in the model. However, we concluded that it was the most realistic approach to allow us to incorporate the O_C in the model. The study considered the customer satisfaction from a survey and may thus suffer from some inaccuracies. Moreover, the collected data considered four years, which may not reflect the entire COQ spending. Therefore, we expect the model will be improved if it considers a longer period.

By considering the O_C along with QL in the COQ model, the quality practitioners in the SC are expected to introduce a broader image of the SC COQ to the top quality managers. After integrating the O_C into the SC accounting system, the supply chain is expected to increase its QL and customer satisfaction level, which will allow the SC to compete efficiently in the market.

2.7. Suggestion for future studies

Just like COQ was modelled in the SC as one representation, it can also be modelled at the manufacturer and supplier separately, and the total effect of O_C on the whole model can be studied. Also, further research could address a multi-product COQ, i.e., different lookup functions can be assigned for different products, at the supplier's and manufacturer's sites. The complexity of such a combination model would be high but will perhaps be possible to be dealt with again through System Dynamics, which will consider different functions simultaneously and provide a variety of COQ parameters over a time period. The research can be expanded to study the relationship of the O_C and QL while considering budget limitations in a capacitated/uncapacitated SC, in such study a mathematical model might be suitable to address this problem.

Acknowledgements

The authors would like to thank all the engineers of the quality department and finance department of the SC for their co-operation, support and data provision.

2.8. Appendices

Appendix I

Questions for targeted SC customers and for customers of competitive organization

1. Please rate your overall satisfaction with [Product x].
2. Please rate [Product x] on:
   - Quality of Product
   - Length of life of Product
   - Design of the product
   - Consistency of quality
3. Please rate the staff for:
   - Courtesy from staff
   - Representativeness
   - Reliability of the product
   - Availability
   - Knowledge
   - Complaint resolution
   - After sales service
   - Technical service
4. I will recommend [Product x] to others
5. Short-term warranty of the product has a positive influence on purchase decision of the consumer.
6. Long-term warranty of the product has a positive influence on purchase decision of the consumer.
7. Is there anything that product X could have done to improve your satisfaction?

Appendix II

Calculation of raw weight (adapted by Moen, 1998)

Customers' requirement to a product	Weight importance to customers (I_i)	Organization & competitive organization performance conformity to requirement evaluated by customers 0 1 2 ---- m	Difference between organization & competitive organization conformity to requirements ($R_i = P_i - P_{ic}$)	Raw weight related to the loss of customers' goodwill ($RW_i = I_i$ X R_i)
Req # 1	X	-- -- -- ---	X	X
Req # 2	X	-- -- -- ---	X	X
Req # 3	X	-- -- -- ---	X	X
----	-	-- -- -- ---	-	-
----	-	-- -- -- ---	-	-
Req #k	X	-- -- -- ---	X	X
Sum	$\sum_{i=1}^{n} I_i$			$\sum RW_i$

Where:

I_i: Weight importance of requirement i;

R_i: Difference between organization and competitive organization conformity to requirement;

i: customer requirement, i=1,...k.

Raw weigh is calculated by:

$R_i = P_i - P_{ic}$ .... (1)

Where:

P_i: Organization conformity to requirement i according to the voice of the customer;

P_{ic}: Competitive organization conformity to requirement i.

$$r_{loss} = \frac{T_{loss}}{RW_{i,\max}} = \frac{T_{loss}}{R_{i,\max} \times \sum_{i=1}^{n} I_i} \qquad (2)$$

Appendix III

Loss occurred by unsatisfied customers (adapted by Jones & Williams, 1995)

	Description	Value
1	Average value of each sale of good (service)	X
2	Average retain profit	X
3	Sales during the period selected for analysis	X
4	How many customers the organization has	X
5	Average periodicity of purchases	X
6	Number of satisfied customers	X
7	Number of unsatisfied customers (U)	X
7A	Number of unsatisfied customers who are not intended to buy repeatedly	X
7B	Number of unsatisfied customers who are intended to buy repeatedly	X
8	Number of purchases of product of satisfied and unsatisfied with intentions to buy customers during analyzed period (line 6 x line 5 + line 7B x line 5)	X
9	Loss of customers' purchases due to unsatisfying (line 7A x line 5)	X
10	Loss of income due to unsatisfied customers (line 9 x line 2)	X
11	Average costs of attraction of new customer	X
12	Costs of replacing of unsatisfied customers by others (line 9 x line 11)	X
13	Total loss (line 12 + line 10) (T_{loss})	X

Chapter 3 - Managing Quality Decisions in Supply Chain

Abstract

Purpose – The purpose of this paper is to develop an optimization model to better allocate Cost of Quality (COQ) in the supply chain (SC). In addition, the paper provides a roadmap based on COQ that allocates limited given budget (GB) among the SC entities.

Design/methodology/approach – This paper presents a comprehensive SC model while introducing six different scenarios, where each scenario minimizes fixed costs and COQ of the SC.

Findings – The results showed that the highest portion of the COQ should be allocated at the retailer echelon while the lowest portion should be kept at the manufacturer echelon. The findings also presented that the retailer should always maintain the highest quality level (QL) compared to the manufacturer and supplier.

Practical implications – Considering COQ in SC network design can be used to improve QL of goods for an organization, which helps to attain the lowest possible quality-related costs. In a centralized SC network, it is crucial to determine the optimal quality costs.

Originality/value – Considering prevention appraisal and failure (PAF) cost model, this research defines the tradeoff among PA, F costs, QL and material flow in the SC network, no work has been published regarding integrating PAF, QL, and material flow into SC modeling.

Keywords Supply Chain, PAF Model, Cost of Quality, Quality Level, Given Budget Limitations.

Paper type Research paper

3.1. Introduction

Quality is important because it greatly influences customers' decision when purchasing any product. The quality and its cost can thus recognize the differences among several products. Over the past years, there has been a hostile battle among companies trying to provide products for the lowest possible costs, and, consequently, the only those who succeeded survived. Recently, quality differences became a significant element in the market competition (Bowbrick, 1992). Therefore, a proper definition of the quality costs for any product is necessary for efficient operation and competency (Ben-Arieh & Qian, 2003). COQ or quality costs can be defined as a measurement system that translates quality-related activities into a financial language for managers. It is the sum of total costs that spent to ensure the required quality is met (Srivastava, 2008). The purpose of measuring COQ in the manufacturing industry is to reveal and demonstrate the benefits of increasing quality to improve and gain more customer satisfaction, as well as to link them with the appropriate cost to minimize total costs and increase profits. According to Chopra and Garg (2011), average industries do not implement COQ systems in their industries because they lack resources that allow them to hire the tools of implementing COQ in their industries. Therefore they proposed simple models to be implemented by average industries. Chopra and Garg argue that the total quality costs are reduced by implementing a robust quality cost system. COQ can be considered as a trade-off between the costs of conformance and the costs of nonconformance (Schiffauerova & Thomson, 2006). These costs constitute the widely used traditional prevention, appraisal, and failure (PAF) model, which was proposed by Feigenbaum (1956). PAF model has acquired broad acceptance from different researchers, companies, and organizations, such as American Society for Quality (ASQ). Prevention and appraisal costs are expenditures to ensure conformance to the specifications. Failure costs are costs resulting from nonconformance to the specifications. Campanella (1990) states that quality costs are categorized and defined as follows:

- Prevention costs. The costs of all activities that occurred to reduce or prevent poor quality in products or services, such as quality planning, process monitoring and control costs, and training and general administration costs.
- Appraisal costs. The costs related to measuring, evaluating, and auditing products or services to ensure that the standards, performance, and the quality requirements are met, for example, test, audit, and inspection costs.
- Failure costs. The cost occurred due to products or services not conforming to requirements of customers' needs. Failure costs are subdivided into internal and external failure cost categories:
    - Internal failure costs. Failure costs arise before finalizing and delivering of the product, or providing a service, to the customer/user, such as costs of scraps, rework, retest, re-inspection, and redesign.
    - External failure costs. Failure costs occur after the product and during or after a service reaches to the customer, such as the repairing and returning of defect products' costs, dealing with complaints, and compensations.

Juran (1951) provides a graphical representation of how costs of nonconformance and conformance affect the overall QL of a given system Figure 3-1. Juran (1951) states that the lowest level of COQ can be obtained when failure costs intersect with prevention and appraisal costs. Juran's model is considered as the most commonly used model in the literature, which is widely used in manufacturing industry because it is easy to understand (Jaju & Lakhe, 2009). In their research, Chopra and Garg (2011) present a strong negative correlation between prevention costs and internal failure costs. They suggest improving prevention activities in order to reduce internal failure costs.

Few researchers incorporated the COQ in the SC cost analysis. Ramudhin et al. (2008) claim that they are the first authors who integrate COQ in the SC. They present the COQ at suppliers, manufacturing plants, and customers. Their model seeks to minimize the total operational and quality costs. Ramudhin et al. considered the COQ as a function in the percentage of defectives. They could minimize the overall operational and COQ in the SC. Alglawe et al. (2017) considered the opportunity cost (OC) with COQ (i.e., COQ = PA + F + OC), in which the OC represented the monetary value of unsatisfied customers. They investigated the importance of incorporating the OC in the SC and could provide the difference between the SC with and without OC. The idea of designing the SC based on the COQ allocation has not been presented yet. Hence, this work aims at integrating the COQ (PA + F + OC) into the modeling of SC. This paper is organized as follows: Section 2 gives a literature review on COQ and OC; the model and methodology are presented in Section 3; Section 4 provided the results; Section 5 contains the Discussion: and finally, Section 6 contains the concluding remarks and future works.

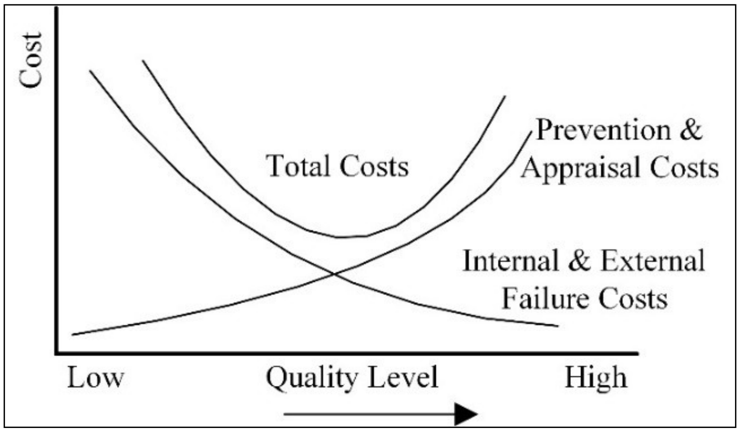


Figure 3-1: Juran’s model for COQ (Juran, 1951)

3.2. Literature review

Measuring quality costs represents a good indicator of the quality which shows the overall performance of an organization. It is hard for the food manufacturing industry to effectively compete in the market without managing their overall costs (Omurgonulsen, 2009). In a Turkish food manufacturing industry, Omurgonulsen finds that spending 1% on the conformance costs reduces the cost of nonconformance by 0.83%. In order to precisely measure the COQ a strong accounting system that provides accurate cost information should be established by the firms (Özkan & Karaibrahimoğlu, 2013). However, identifying COQ elements to measure the COQ is not very straightforward. There have been some differences about what these costs comprise (Machowski & Dale, 1998). Omar and Murgan (2014) develop a simulation model to quantify the COQ. In their study, they considered real-life industrial data from a semiconductor firm. The results of their study showed that the reduction of failure costs could be reached at almost without investment in the conformance costs. Guinot et al. (2016) examine the impact of COQ on the present worth (PW) of a new product launch in North American. They used a Monte Carlo simulation in their research, which targeted an automobile manufacturer, by considering various cash flows for a new product launch. They conclude that COQ should be measured in a product launch PW analysis before any commitment to invest. Plewa et al. (2016) find that there is a significant lower relationship between the total COQ and its F cost component at higher levels of quality, in addition, the PA cost components are not detected to be considerably higher at higher quality levels (lower F costs).

In the literature, there are different types of hidden costs in which these costs do not characterize true money during manufacturing processes. The majority of traditional costing systems characterize quality costs as those costs which can be easily seen and monitored. Thus many organizations excluded hidden costs from their accounting books. Opportunity Cost (OC) is one of these costs which does not have a tangible value. It is conventionally defined as the difference between an investment one makes and another which chose not to make, i.e., benefits that are not obtained because of pursuing a different alternative (Son, 1991). Although it is difficult to measure hidden quality costs, we still need to be aware of their existence and their importance as well. These costs are the causal factor in the termination and closure of many companies because they represent an important portion of the money and they remain hidden (Sansalvador & Brotons, 2017). Liu et al. (2008) argue that intangible costs such as the loss of customer goodwill are in fact the most important costs that need to be managed properly. Loss of goodwill in the form of OC can occur when a customer is not happy with a certain product/service, which may lead to serious consequences that an organization not only loses a specific customer and all his future sales but more seriously losing the reputation. Therefore the organization may lose more customers as well. Loss of organization's image is a critical issue that may cost much more than the expectations. Furthermore, not considering the OC in the COQ analysis may lead many organization managers to make unsuitable decisions (Heagy, 1991).

Snieska et al. (2013) use a pilot study to analyze the external failure costs at a medical supply service company in Lithuania. They conducted a questionnaire to measure and analyze the customer satisfaction. Snieska et al. used quality function deployment modified planning matrix, which developed by Moen 1998, and loss calculation technique due to unsatisfied customers lost, which was implemented by Jones and Williams (1995). They were able to convert the customer dissatisfaction (loss of customers' goodwill) into a monetary value. The hidden external failure quality costs may reach up to 30% of the analyzed period sales (Snieska et al., 2013). Since Snieska et al. (2013) could successfully convert the loss of customers' goodwill to a monetary value, therefore, in our model, we suggest the same criteria to be implemented to obtain the OC.

After many individual companies considered the COQ in their cost accounting systems, it is necessary for the companies to coordinate and integrate the COQ into SC entities, which will assist addressing the COQ elements allover Supply Chain Network Design (SCND) (Douiri et al., 2016). Srivastava (2008) is the first author who combined, measured, and estimated COQ in SC performance measurement. He estimated COQ in SC as financial terms at selected third-party contract manufacturing sites of a pharmaceutical company located in India. He defines COQ in SC as: "the sum of the costs incurred across a SC in preventing poor quality of the product and/or service to the final consumer, the costs incurred to evaluate and ensure that the quality requirements are being met, and any other costs incurred as a result of poor quality" (p. 139).

COQ studies have so far focused on internal quality costs of individual firms but not on the costs of an entire SC (Srivastava, 2008). There are not enough references which analyze and develop of SCND incorporating the COQ, the majority of contributions are directed towards assisting companies to improve their quality and profitability at the same time (Douiri et al., 2016). COQ combines poor quality, quality enhancement efforts and hidden quality costs, and translates them into understandable monetary terms for all stakeholders of the organization Castillo-Villar et al. (2012). Thus, it is important to extend COQ to the SC measures and to integrate the inclusive costs into SC modelling.

In general, the idea of integrating the COQ into the supply chain network design (SCND) problems is fairly new. Nevertheless, it has been considered by a reasonable number of researchers. Ramudhin et al. (2008) were the first authors to integrate COQ in the SC. In their proposed model, they presented a three-echelon system (suppliers, manufacturing plants, and customer groups). They incorporated COQ into the SC modelling network to minimize the overall operational and quality costs. Ramudhin et al. (2008) find that the solution changes completely by adding a COQ function only to suppliers into the objective function. When COQ is considered in their model, the solution increases approximately by 16% in costs. Another work directed towards integrating COQ in the SC was introduced by Alzaman et al. (2009). They establish a mathematical model to incorporate a known quadratic COQ function integrating a defect ratio at all SC nodes. Their COQ function is based on Juran's original model (Juran, 1951). They argue that, although the COQ functions are quadratic, they can be incorporated in SC network design and can be solved successfully by different developed heuristics. Castillo-Villar et al. (2012) develop a formal framework for computing the quality cost across a single-product three-echelon serial SC model, which can be used to design the SC logistic route. The model presented a minimum total cost while it maintains an overall QL. Their model intended to evaluate the impact of investment in quality and showed how it could be used to increase overall profits. More recently, Castillo-Villar et al. (2014) develop a strategic level model to computing the COQ in a multistage, capacitated SCND. Their SC network consists of three suppliers, one manufacturing plant, and two retailers. The COQ is computed as the sum of the P, A, and internal and external F costs (Castillo-Villar et al., 2014). By adding capacity constraints to their problem and the combinatorial nature of a MINLP made Castillo-Villar et al.'s problem difficult to solve. In their research, Ridwan and Noche (2014) focused on analyzing Process Capability Indices (PCI) and Cost of Poor Quality (COPQ) to improve the performance of SC in CDG Port, Indonesia. The case study, reveals that the COPQ in cargos handling is about 39.02 % of the average sale. They measure the COPQ based on PAF cost model classification. The concept of COQ can be used to measure the performance of the SC as suggested by Gueir (2016) who integrated the COQ into the SCND, in which his model is multi-products and multi-component SC. According to Gueir, the results showed that integrating the COQ into his model changed the resulting routes and provided influence on the designing of the process.

No work has addressed how to design the SC based on COQ allocation by using PAF and OC model. Alglawe et al. (2017) incorporated the opportunity cost (OC) into COQ, which was based on PAF cost model. They simulated the COQ in a System Dynamics approach and found that when OC is considered in their model, the expected number of new customers in SC decreases to become less than the SC expectation. Alglawe et al.'s model highlights the importance of the OC analysis in decision making for the SC quality management strategies. Therefore, this paper develops a PAF COQ model by considering it in each SC entity. The proposed model considers PA, F, and OC in the form of functions in the Quality Level (QL) for each SC facility. This work provides the best allocation of the COQ in the SC and the relationship among the PA, F, and OC for each facility and among the SC entities. It also measures the COQ in centralized and decentralized SC based on the COQ. Moreover, the proposed model investigates how COQ components and QL interact among each other in case of budget spending limitations. No previous work has addressed the allocation of COQ based on PA, F and OC cost functions in SC nor how the three COQ components interact in centralized and decentralized SC.

3.3. Methods

In this research, we incorporate the OC into PAF COQ, i.e., our proposed model will be PA + F + OC. Where OC is a financial value of the unsatisfied customers (i.e., loss of customers' goodwill) at the time of investing in PA costs to achieve a certain quality level in the model. The model represents a four-echelon SC system consisting of suppliers, manufacturers, retailers, and customers. The objective of the proposed model is to find out the best solution for the COQ, QL, and their associated material flow in the SC. It minimizes the produced fixed cost, COQ at the suppliers' echelon. Moreover, the produced fixed costs, facilities fixed costs, total COQ at both of the manufacturers and the retailers' echelons and total transportation costs between SC echelons. The input parameters, decision variables, and constraint parameters are explained in Table 3-1.

Table 3-1: Model notations for SC COQ

I: Set of suppliers, *J*: Set of manufacturers, *K*: Set of retailers, and *C*: Set of customers	
Decision variables	
Z_i, Z_j, and Z_k	Supplied components to a supplier (i), manufacturer (j), and retailer (k), respectively; $i \in I, j \in J, k \in K$
$O_{i,j}$, $P_{j,k}$ and $Q_{k,c}$	Number of good components to exit from a supplier (i), manufacturer (j), and retailer (k), respectively; $i \in I, j \in J, k \in K, c \in C$

x_i, y_j, and u_k	Quality level (QL) at a supplier (i), manufacturer (j) & retailer (k), respectively; $i \in I, j \in J, k \in K$
b_{2j}	Binary variable; 1 if manufacturer (j) is open; 0 otherwise; $j \in J$
b_{3k}	Binary variable; 1 if retailer (k) is open; 0 otherwise; $k \in K$
Parameters (input data)	
α_i, α_j and α_k	Fixed costs per unit product at a supplier (i), manufacturer (j) and retailer (k), respectively; $i \in I, j \in J, k \in K$
λ_j and λ_k	Facilities fixed costs at a manufacturer (j), and retailer (k), respectively; $j \in J, k \in K$
$f_{PA}(x_i)$, $f_{PA}(y_j)$, and $f_{PA}(u_k)$	Prevention and appraisal cost functions at a supplier (i), manufacturer (j) & retailer (k), respectively; $i \in I, j \in J, k \in K$
$f_F(x_i)$, $f_F(y_j)$, and $f_F(u_k)$	Failure cost functions at a supplier (i), manufacturer (j) and retailer (k), respectively; $i \in I, j \in J, k \in K$
$f_{OC}(x_i)$, $f_{OC}(y_j)$, and $f_{OC}(u_k)$	Opportunity cost functions at a supplier (i), manufacturer (j) and retailer (k), respectively; $i \in I, j \in J, k \in K$
$T_{i,j}$	Transportation costs of products from a supplier (i) to a manufacturer (j); $i \in I, j \in J$
$T_{j,k}$	Transportation costs of the products from a manufacturer (j) to a retailer (k); $j \in J, k \in K$
$T_{k,c}$	Transportation cost of the products from a retailer (k) to a customer (c); $k \in K$, $c \in C$
Input parameters	
D_c	The production demand for a customer (c); $c \in C$
φ_i, φ_j and φ_k	The production capacity of a supplier (i), manufacturer (j) and retailer (k), respectively; $i \in I, j \in J, k \in K$

The objective function for a centralized SC COQ cost model, which minimizes the facility fixed costs, and COQ in the SC and its constraints are presented as follows:

$$\text{Min} \sum_{i\in I}\alpha_i Z_i + \sum_{i\in I}\begin{pmatrix} f_{\mathrm{PA}}(x_i) \\ + f_{\mathrm{F}}(x_i) \\ + f_{\mathrm{OC}}(x_i)\end{pmatrix} * Z_i + \sum_{i\in I}\sum_{j\in J} O_{i,j}T_{i,j} + \sum_{j\in J}\alpha_j Z_j$$

$$+ \sum_{j\in J}\lambda_j b_{2j} + \sum_{j\in J}\begin{pmatrix} f_{\mathrm{PA}}(y_j) \\ + f_{\mathrm{F}}(y_j) \\ + f_{\mathrm{OC}}(y_j)\end{pmatrix} * Z_j + \sum_{j\in J}\sum_{k\in K} P_{j,k}T_{j,k}$$

$$+ \sum_{k\in K}\alpha_k Z_k + \sum_{k\in K}\lambda_k b_{3k} + \sum_{k\in K}\begin{pmatrix} f_{\mathrm{PA}}(u_k) \\ + f_{\mathrm{F}}(u_k) \\ + f_{\mathrm{OC}}(u_k)\end{pmatrix} * Z_k \tag{1}$$

$$+ \sum_{k\in K}\sum_{c\in C} Q_{k,c}T_{k,c}$$

Subject to:

$$\sum_{k\in K} Q_{k,c} = D_c \quad \forall c \tag{2}$$

$$Z_k \le \varphi_k\, b_{3k} \quad \forall k \tag{3}$$

$$Z_k u_k = \sum_{c\in C} Q_{k,c} \quad \forall k \tag{4}$$

$$\sum_{j\in J} P_{j,k} = Z_k \quad \forall k \tag{5}$$

$$Z_j \le \varphi_j \, b_{2j} \; \forall j \tag{6}$$

$$Z_j y_j = \sum_{k \in K} P_{j,k} \;\; \forall j \tag{7}$$

$$\sum_{i \in I} O_{i,j} = Z_j \;\; \forall j \tag{8}$$

$$Z_i \le \varphi_i \;\; \forall i \tag{9}$$

$$Z_i x_i = \sum_{j \in J} O_{i,j} \;\; \forall i \tag{10}$$

$$0 < x_i \le 1, 0 < y_j \le 1, \text{and } 0 < u_k \le 1 \tag{11}$$

$$b_{2j}, b_{3k} \in \{0,1\} \tag{12}$$

$$Z_i \ge 0, \;\; Z_j \ge 0, \; Z_k \ge 0, O_{i,j} \ge 0, \; P_{j,k} \ge 0, \; Q_{k,c} \ge 0 \tag{13}$$

The constraints from (2) to (13) perform the following: Constraint (2) ensures that the customers' demand is satisfied by the retailers. Constraint (3) puts an upper bound for the retailer's capacity (if the facility is open). Constraint (4) ensures that the retailer's good products are equal to the customer's demand. Constraint (5) guarantees that the manufacturer's good products satisfy the retailer's demand. Constraint (6) puts an upper bound to a manufacturer's capacity (if the facility is open). Constraint (7) is the equality constraint for the manufacturer to supply good products to the retailers. Constraint (8) is the equality constraint for the good products from the supplier to satisfy a manufacturer's demand. Constraint (9) ensures that no supplier produces more than his capacity. Constraint (10) is the constraint for the good products from the supplier to satisfy the manufacturers' demand. Constraint (11) is the QL constraint for suppliers, manufacturers, and retailers, respectively. Constraint (12) is the binary constraint for the manufacturers and retailers, in which b_{2j} equals 1 if the manufacturing facility is open. Otherwise, it is 0, b_{3k} equals 1 if a retailer facility is open or otherwise it is 0. Constraint (13) imposes the non-negativity restriction on the decision variables.

To conduct our experiment, we provide an illustrative example, in which we simplify the model to find the effect of the QL, PA, F, and OC at the SC echelons. Furthermore, having one facility at each echelon facilitates the sensitivity analysis and makes it less complicated compared to having more than one facility at each echelon. This is done by eliminating the capacity and integrality constraints (3) (6) and (9) to make one uncapacitated facility at the supplier, manufacturer, and retailer echelon. Furthermore we substitute i =1, j =1, and k =1. The terms 5 and 9 in the objective function become constant and therefore will be eliminated. The SC becomes as shown in Figure 3-2. The transportation costs are disregarded in the model as they will not affect the QL decision due to having only one facility assigned at each echelon. If there were more than one facility at each echelon, the model might select a low-cost combination among different transportation and COQ options.

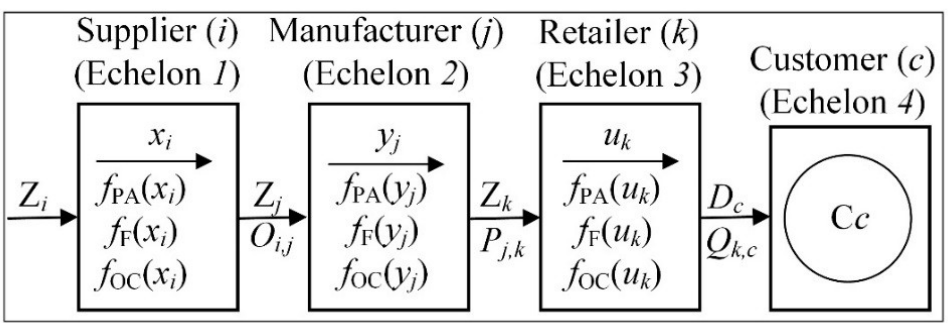


Figure 3-2: Uncapacitated SC model which considers COQ and material flow

3.3.1. Model inputs and assumptions

In our model, we come up with nine cost functions and three QLs in the whole SC model. The COQ equations, which are used in the model are presented in Table 3-2. Different COQ functions are used at the SC facilities as shown in Figure 3-3. The Prevention and Appraisal cost functions, i.e., $f_{PA}(x_i)$, $f_{PA}(y_j)$, and $f_{PA}(u_k)$ are represented by exponential equations. On the other hand, the Failure cost functions, i.e. $f_F(x_i)$, $f_F(y_j)$, $f_F(u_k)$, $f_{OC}(x_i)$, $f_{OC}(y_j)$ and $f_{OC}(u_k)$ are symbolized by polynomial equations. In our model, we assume the OC has a separate cost function at each SC echelon to present a solution that integrates different COQ functions at each SC echelon. The shapes of the total COQ functions at each echelon are shown in Figure 3-4, which provides three designed COQ levels. Low spending on COQ, which is denoted by a dollar sign ($). The medium COQ, which was symbolized by a two-dollar sign ($$). The highest amount of the COQ was characterized by a three-dollar sign ($$$). In this model, COQ is highly affected by the QL at each echelon. In addition, the QL directly affects the number of components that are supplied to each echelon (i.e., Z_i, Z_j & Z_k) and the output components from each echelon ($O_{i,j}$, $P_{j,k}$, & $Q_{k,c}$).

Table 3-2: PA, F, and OC cost functions

Supplier	**Manufacturer**	**Retailer**
$f_{PA}(x_i) = 0.085e^{6.41x}$	$f_{PA}(y_j) = 0.27e^{5.69y}$	$f_{PA}(u_k) = 0.18e^{6.01u}$
$f_F(x_i) = 8x^{-2} - 5x - 2$	$f_F(y_j) = 21y^{-2} - 7y - 14$	$f_F(u_k) = 11u^{-2} - 8u - 3$
$f_{OC}(x_i) = 5x^{-2} - 5x$	$f_{OC}(y_j) = 5y^{-2} - 5y$	$f_{OC}(u_k) = 5u^{-2} - 5u$
$f_{COQ}(x_i) = f_{PA}(x_i) + f_F(x_i) + f_{OC}(x_i)$	$f_{COQ}(y_j) = f_{PA}(y_j) + f_F(y_j) + f_{OC}(y_j)$	$f_{COQ}(u_k) = f_{PA}(u_k) + f_F(u_k) + f_{OC}(u_k)$

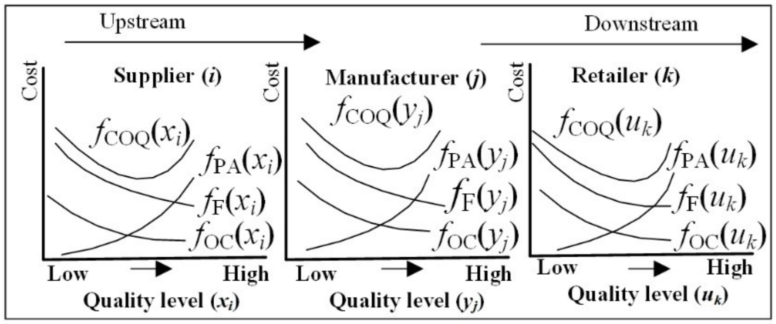


Figure 3-3: Shape of the COQ functions in the SC

The retailer is considered as an entity of the production system and it has its production and quality costs. We set the fixed costs per unit (α_i, α_j, & α_k) at the supplier, manufacturer and retailer to be equal to \$10/unit. The total customer demand D_c = 4500 units. We assume that the $f_{OC}(x_i)$, $f_{OC}(y_j)$ and $f_{OC}(u_k)$ are identical functions. However, after the optimization, the OC will be different according to the optimum QL at each echelon.

Six different (possible) scenarios were designed to find out the best scenario which allocates the COQ among the SC entities. All scenarios are expected to satisfy the model constraints. The best scenario should provide the minimum objective value. The six scenarios are provided in Table 3-3, which the first scenario is shown in Figure 3-4.

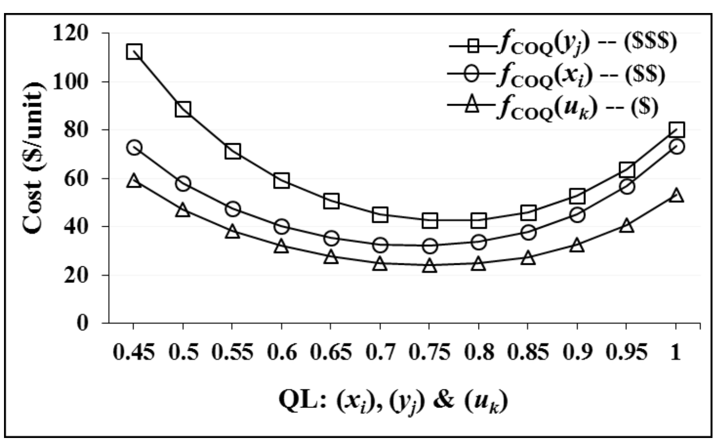


Figure 3-4: Demonstration of the 1st scenario

Table 3-3: COQ scenarios among SC entities

Scenario no.	Supplier	Manufacturer	Retailer
1	$f_{COQ}(x_i)$ = **$$**	$f_{COQ}(y_j)$ = **$$$**	$f_{COQ}(u_k)$ = **$**
2	$f_{COQ}(x_i)$ = **$**	$f_{COQ}(y_j)$ = **$$$**	$f_{COQ}(u_k)$ = **$$**
3	$f_{COQ}(x_i)$ = **$$**	$f_{COQ}(y_j)$ = **$**	$f_{COQ}(u_k)$ = **$$$**
4	$f_{COQ}(x_i)$ = **$**	$f_{COQ}(y_j)$ = **$$**	$f_{COQ}(u_k)$ = **$$$**
5	$f_{COQ}(x_i)$ = **$$$**	$f_{COQ}(y_j)$ = **$$**	$f_{COQ}(u_k)$ = **$**
6	$f_{COQ}(x_i)$ = **$$$**	$f_{COQ}(y_j)$ = **$**	$f_{COQ}(u_k)$ = **$$**

In this table, the (**$**) symbol refers to the smallest portion of COQ, ($$) symbol presents the medium portionof the COQ, while the (**$$$**) symbol refers to the biggest portion of COQ. We implemented each scenario separately in the objective function. In each scenario, we determined the best obtained objective value, QL (x_i, y_j & u_k) and the COQ.

3.4. Results

In the following three subsections we analyze our SC model presented in Figure 3-2. In the first subsection, we analyze the SC echelons as a centralized SC, i.e., all echelons work together to satisfy the customers' demand. We aim to investigate the best COQ and its QL arrangement among the SC entities. In the second subsection, we decompose our objective function to constitute decentralized SC entities. In this section, while each SC entity works at its minimum COQ, each entity satisfies the demand from the next immediate downstream entity. For example, the retailer needs to satisfy the customer's demand, and the retailer demand is satisfied by the manufacturer. In the last subsection, we investigate the effect of limitations in spending on PA costs in the centralized SC. Here we examine the effect of PA costs on the objective value, COQ, and QL in order to find the range of different spending on PA costs and what is their impact on the objective value.

The proposed model is nonlinear because it has two decision variables multiplied by each other in the objective function and the constraints 4, 7 and 10. Excel Solver (GRG Nonlinear) program is used to solve the model. In addition, as our model uses Juran's COQ principles, we confirmed that the behaviour of the model presented a similar tendency. Juran (1951) claims that when if an investment made in the costs of conformance, costs of nonconformance decrease. This behaviour is clearly observed in our model.

3.4.1. Analyzing the COQ among centralized SC echelons

In this subsection, we consider a centralized SC to solve the six scenarios which are presented in Table 3-3. Table 3-4 presents the results of COQ parameters: (i) the total PA costs of the SC and PA costs at the supplier, manufacturer, and retailer's echelon, (ii) the total SC F costs, the F costs at the supplier, manufacturer, and retailer's echelon, and (iii) the total SC OC as the aggregate of OC at the supplier, manufacturer, and retailer. This table also provides the total SC COQ per unit and the equivalent objective values for each scenario. According to the Table 3-4, the best scenario among the six scenarios is the scenario no. 4. It presents the minimum SC objective value, and the COQ, which is allocated as follows: the supplier spends the smallest portion of COQ (**$**). The manufacturer is assigned with the medium portion (**$$**) of the COQ. The most significant portion of COQ (**$$$**) is allocated at the retailer (see Table 3-3 the scenario no. 4). For this scenario, the minimum obtained objective value is $850,264.8. The highest obtained objective value which is $875,472.4 presented in the scenario no. 6. It is higher than the objective value of the scenario no. 4 by around 3%. It is worth noticing that, while scenario no. 4 results in the lowest COQ/unit, it does present the lowest COQ value. However, the scenario no. 6 does not result in the highest COQ/unit and among the six scenarios, the highest COQ/unit is presented in the scenario no. 5. These results suggest that, if the COQ is allocated according to the scenario no. 4 the total COQ/unit and objective value reach the minimum. On the other hand, if the COQ is allocated according to the scenario no. 5 the total COQ/unit will reach a maximum value. As a result, it is recommended allocating the COQ as demonstrated in the scenario no. 4, and it is not recommended allocating the COQ according to the scenario no. 6.

Table 3-4: Optimum results for each scenario in the centralized SC

Scenario No.	**SC PA** ($)/unit	**SC F** ($)/unit	**SC OC** ($)/unit	**SC COQ** ($)/unit	**Objective Value** ($)
1	96.4	17.8	7.0	121.2	854,236.9
2	93.8	17.4	7.5	118.7	860,045.2
3	93.5	17.0	7.4	117.9	851,689.6
4	92.2	16.8	7.8	116.8	850,264.8
5	98.9	18.1	6.4	123.4	870,687.0
6	97.5	17.8	6.6	121.9	875,472.4

Table 3-5 presents the decision variables of the QL (x_i, y_j & u_k) at each echelon and the supplied materials (Z_i, Z_j & Z_k) to each echelon for the six scenarios. Based on this table, for all scenarios the QL at the supplier is between $0.80 \leq x_i \leq 0.83$, the QL at the manufacturer is between $0.84 \leq y_j \leq 0.89$, and the QL is between $0.90 \leq u_k \leq 0.94$ at the retailer. Therefore, the most interesting finding in these scenarios is that the highest QL value is always assigned to the retailer and then to the manufacturer and it is constantly the lowest value assigned to the supplier. According to Table 3-5, one can justify why the highest COQ/unit scenario does not necessarily lead to the highest objective values. The reason is that the QL also affects the supplied components (Z_i, Z_j, and Z_k) to each SC echelon. This means in case of high QL, the COQ/unit is high, which results in the decrease of the rejected components, and therefore the number of good components increases at the SC echelon. Consequently, the overall objective value decreases i.e., it is a mutual effect among both QL, COQ and components which enter each echelon.

Table 3-5: Decision variables for the six scenarios

Scenario no.	x_i	y_j	u_k	Z_i (Unit)	Z_j (Unit)	Z_k (Unit)	D_c (Unit)
1	0.80	0.87	0.94	6870	5480	4775	4500
2	0.81	0.86	0.90	7086	5770	4978	4500
3	0.80	0.88	0.91	7056	5628	4958	4500
4	0.81	0.84	0.91	7209	5870	4959	4500
5	0.83	0.86	0.94	6670	5508	4763	4500
6	0.83	0.89	0.91	6747	5571	54967	4500

The results of our proposed model and its constraints are shown in Figure 3-5, which is the best solution obtained among the six scenarios (scenario no. 4). The figure shows the SC solution for QL, PA, F, OC, total COQ and material flow (Z_i, Z_j, and Z_k) at each echelon in addition to the objective value. According to the figure, in order to satisfy the customers' demand of 4,500 units, the supplier has to start with Z_i = 7,209 units, and he has to work at x_i = 0.81 to provide Z_j = 5,870 units.

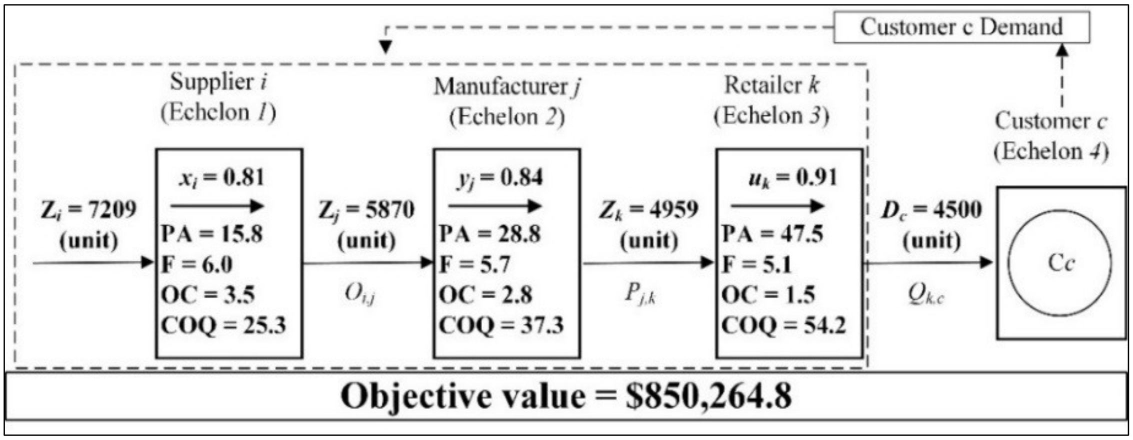


Figure 3-5: Decision variables for the scenario no. 4 (PA, F, OC, and COQ = $/unit)

The manufacturer should work at a higher y_j = 0.84 in order to provide Z_k = 4,959 units, and finally, the retailer should work at the highest (QL) u_k = 0.92 to satisfy the customers' demand of 4,500 units. The retailer should also spend on conformance costs, PA costs, more than what the supplier and manufacturer spend together, which equals to $47.5/unit at the retailer, around $28.8/unit at the manufacturer and $15.8/unit at the supplier. However, with the QL for this scenario the retailer spends the least OC, and then the manufacturer and the supplier result in the highest OC. Moreover, the manufacturer and retailer will result in fewer F costs, while the supplier will end up with the highest F costs. The distributing (percentage) of the COQ/unit at each echelon for the scenario no. 4 is shown in Figure 3-6.

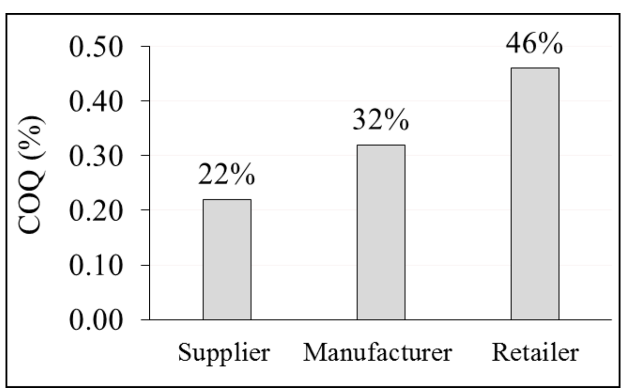


Figure 3-6: Distribution of COQ in the SC for the scenario no. 4

3.4.2. Analyzing the COQ among decentralized SC echelons

The implications of each echelon working at its lower COQ in the SC explored in order to compare it with centralized SC echelons. This subsection assumes that each SC echelon works at its minimum COQ/unit to satisfy the demand. As shown in Figure 3-7, the demand goes from downstream echelon to the next immediate upstream echelon, i.e., the customers' demand is satisfied from the retailer, the retailer's demand is satisfied from the manufacturer and the supplier fulfills the manufacturer's demand. In this case, the objective function becomes three consecutive minimizations as follows:

$$\text{Min } \Big(\sum_{i\in I}\alpha_i Z_i + \sum_{i\in I}\begin{pmatrix} f_{\text{PA}}(x_i) \\ + f_{\text{F}}(x_i) \\ + f_{\text{OC}}(x_i)\end{pmatrix} * Z_i\Big) + \text{Min } \Big(\sum_{j\in J}\alpha_j Z_j + \sum_{j\in J}\begin{pmatrix} f_{\text{PA}}(y_j) \\ + f_{\text{F}}(y_j) \\ + f_{\text{OC}}(y_j)\end{pmatrix} * Z_j\Big)$$

$$+ \text{Min } \Big(\sum_{k\in K}\alpha_k Z_k + \sum_{k\in K}\begin{pmatrix} f_{\text{PA}}(u_k) \\ + f_{\text{F}}(u_k) \\ + f_{\text{OC}}(u_k)\end{pmatrix} * Z_k\Big) \qquad (14)$$

The objective function (14) is subjected to the same constraints as in the previous section (3.1), in which the constraints satisfy the customers' demand (4,500 units). In Table 3-6, we notice that in all the scenarios the PA, F, OC, and COQ are always the same. However, the best obtained objective values are different. We can notice that scenario no. 4 still results in the minimum (best) objective function. This means scenario no. 4 is the best scenario that allocates in the COQ in the SC. We provide the results of the scenario no. 4 in Figure 3-7 showing the minimum COQ at each echelon. The COQ at the supplier remains at the same value as in Figure 3-5, which means the supplier in both cases remains working at the minimum COQ. Also one can observe the reduction in the COQ which occurred at the manufacturer from \$37.3/unit to \$33.5/unit by around 5%/unit and at the retailer from \$54.2/unit to \$44.0/unit by around 19%/unit. The reduction in COQ is mainly affected by y_j at the manufacturer from 0.84 to 0.80 and the retailer (u_k) from 0.91 to 0.83.

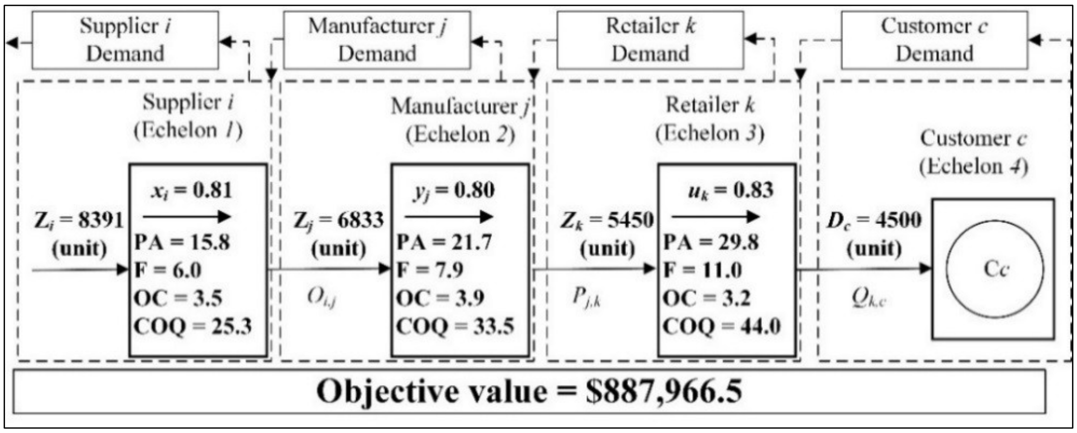


Figure 3-7: Decision variables for the scenario no. 4 (PA, F, OC, and COQ = \$/unit)

However, to compensate the reduction in QL at the supplier and retailer, the input components (Z_k) in this case increased by around 10% to satisfy 4,500 units of the demand (*Dc*). The input components Z_j, have also increased by around 16.4% to (6,833 units) to satisfy the retailer's demand. The input components Z_i, have increased by around 16.4% (8,391 units) to satisfy the retailer's demand. The Z_i is increased as well by around 16.4% (8,391 units) to satisfy the manufacture's demand. As a result, the objective value increased by around 4.4% to become \$887,966.5. This implies that if the SC echelons are not centralized, each echelon will work at its minimum COQ and the input components to each echelon increase, which consequently leads to increase in the objective value. As the total COQ functions at each echelon are quadratic functions, the minimum COQ results of the optimization at each echelon tend to be less than the best-obtained results in Figure 3-5. The minimum COQ (without optimization) is after the intersection of PA and F costs which is due to the effect of added OC as shown in Figure 3-8.

Table 3-6: Optimum results for the decentralized SC (Six scenarios)

Scenario No.	SC PA ($)/unit	SC F ($)/unit	SC OC ($)/unit	SC COQ ($)/unit	Obj. Val. ($)
1	67.4	24.9	10.5	102.8	921,743.6
2	67.4	24.9	10.5	102.8	910,868.6
3	67.4	24.9	10.5	102.8	895,835.2
4	67.4	24.9	10.5	102.8	887,966.5
5	67.4	24.9	10.5	102.8	949,875.6
6	67.4	24.9	10.5	102.8	943,465.2

The optimized COQ for the manufacturer and retailer falls between the minimum COQ (for the quadratic functions) and the best results obtained in the centralized SC. In the decentralized SC, the tradeoff among QL, COQ, and flow of components (Z_i, Z_j, and Z_k) reduced the COQ, increased the material flow, and subsequently increased objective function.

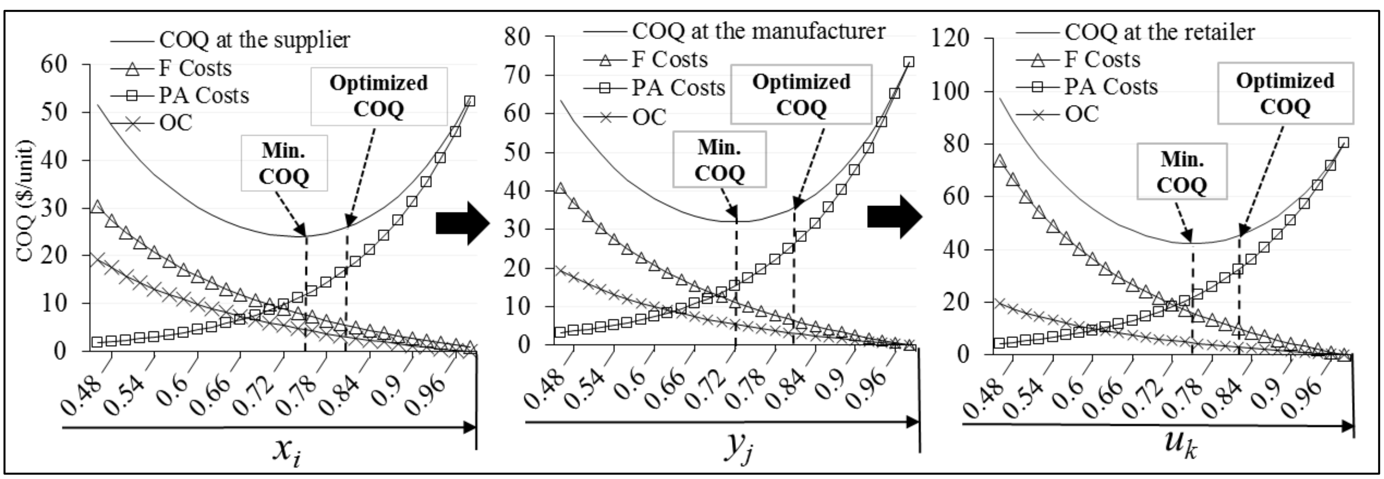


Figure 3-8: Decentralized SC with minimum and optimized COQ and QL

3.4.3. Analyzing the effect of spending limitations on PA costs among the SC echelons

In this experiment, we consider the centralized SC which analyzed in subsection 3.1. We aim to describe how the spending limitation (i.e., spending less than the optimal value of PA costs) can affect the QL and the total objective value. We test the six scenarios presented in Table 3-4 by adding a constraint which controls $f_{\mathrm{PA}}(x_i)$, $f_{\mathrm{PA}}(y_j)$, and $f_{\mathrm{PA}}(u_k)$ cost functions as follows:

$$f_{\mathrm{PA}}(x_i) + f_{\mathrm{PA}}(y_j) + f_{\mathrm{PA}}(u_k) = \mathrm{GB} \tag{15}$$

This to draw a general relationship among the COQ parameter, which is done by applying a constraint on the PA costs to a given budget (GB). After we optimized the models, we observe how the PA costs change among the SC entities according to a limited given budget (GB). Figure 3-9 shows the shape of the objective values for the six scenarios, in which the objective values increase as spending on PA costs decreases. This is because of the effect of the nonconformance costs, F and OC, increases, they result in more components to satisfy the SC demand (*Dc*) as described in subsection 3.2, which consequently drives the objective value in each scenario up. Figure 3-10 shows the effect of spending limitations on PA costs for the scenario no. 4 and how it reduces the QL of the supplier, manufacturer, and the retailer. The lowest SC PA costs per unit, which equal the summation of PA at the supplier, PA at the manufacturer and PA at the retailer, can be obtained at \$92.2/unit (at best obtained objective value = \$850,264.8).

In Figure 3-10, we can distinguish three different zones: in the zone (a), which is between \$92.2/unit ≥ GB ≥ \$80/unit, the changes in the objective values are minimal. The objective value increases by around 0.7% when GB = \$80/unit, in the zone (b), which is between \$80/unit ≥ GB ≥ \$60/unit. We observe a noticeable increase in this range, the objective value increased by around 6.8% to be \$908,429.6 at GB = \$60/unit. The objective value increased dramatically in the zone (c), which is between \$60/unit ≥ GB ≥ \$40/unit, it becomes \$109,128.2 at GB = \$40/unit, which is equivalent to about 28.3%. Therefore, apart from the best obtained objective value at GB = \$92.2/unit and according to our model, we can assert that zone (a) can be considered as the safest zone for investment. In this zone, the maximum increase in the objective value is around 0.7%, which is by far the lowest increase in the objective value compared to the other two zones, b, and c. Figure 3-11, Figure 3-12 and Figure 3-13 show the effect of spending limitations on PA costs at the supplier, the manufacturer, and the retailer (from GB = \$92.2/unit to GB = \$40.0/unit at each echelon) for the scenario no. 4. In Figure 3-11, the best x_i value that results in the minimum objective value at the supplier is 0.81. In this case, the supplier needs to spend \$15.8/unit on PA costs to reduce F costs to \$6.0/unit and OC to \$3.5/unit.

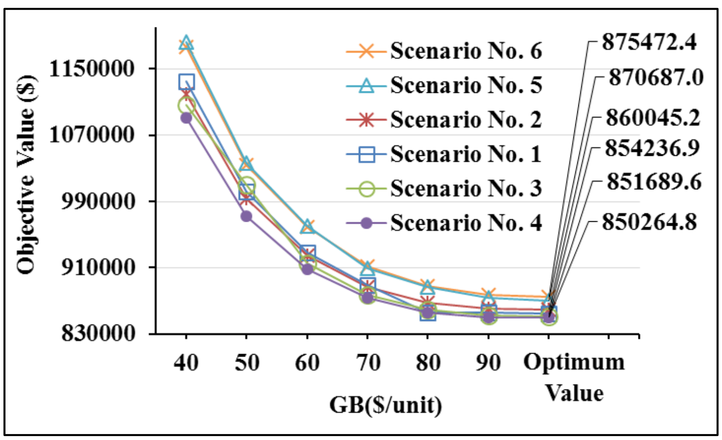


Figure 3-9: The effect of GB on the obj. values (All scenarios)

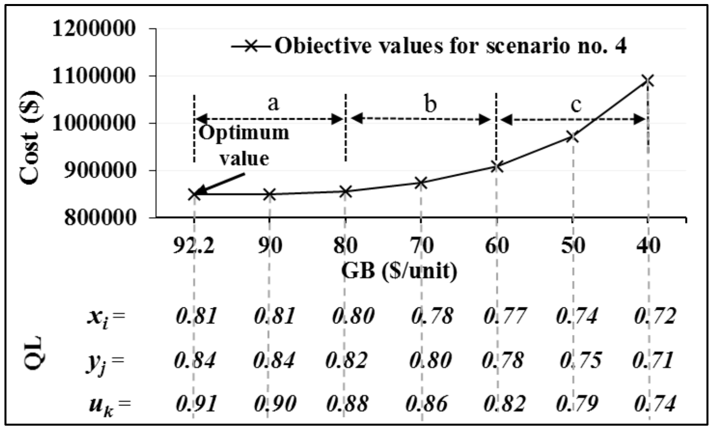


Figure 3-10: The effect of GB on the obj. value (Scenario no. 4)

As the GB decreases, the PA costs at the supplier decrease and consequently both F costs and OC increase. PA costs become equal to F costs when GB is around $45/unit at x_i = 0.73. Below this x_i, the F costs become higher than PA costs. Figure 3-12 shows PA, F, and OC relationship at the manufacturer for different GB. The best y_j value is obtained when y_j = 0.84 in which the manufacturer has to spend around $28.8/unit on PA costs, and the resulted F and OC are $5.7/unit and $2.8/unit, respectively. While GB decreases, the PA costs decrease, and consequently both F costs and OC increase. At the manufacturer, PA costs intersect with F costs when y_j = 0.72 and GB is around $40/unit. Below this y_j, the F costs become higher than PA costs.

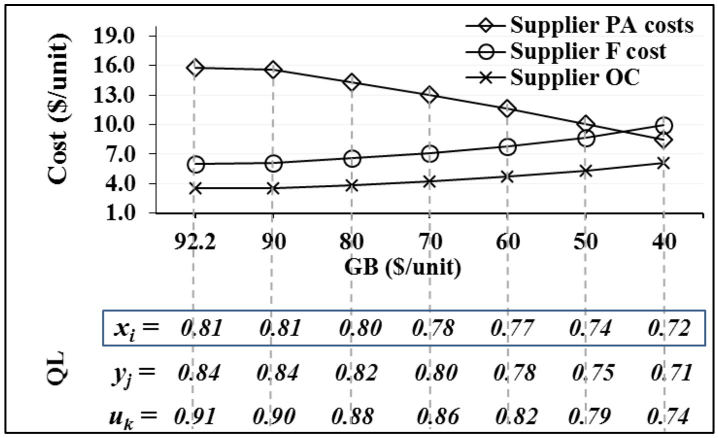


Figure 3-11: The effect of GB on the COQ at the supplier

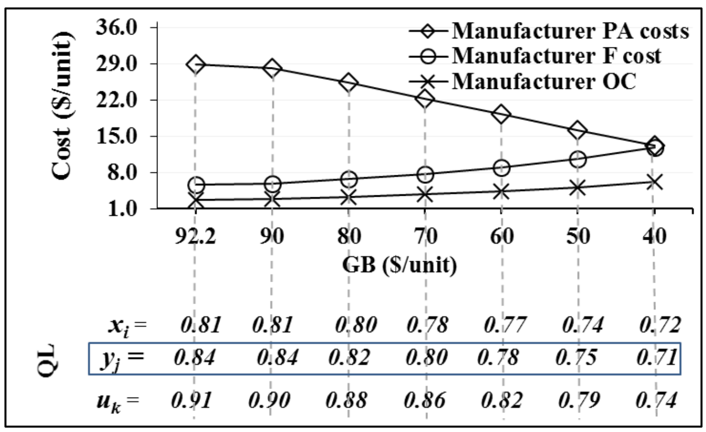


Figure 3-12: The effect of GB on COQ at the manufacturer

Figure 3-13 shows PA, F, and OC at the retailer for the limited GB. At the minimum solution, the retailer has to spend around $47.5/unit to achieve the u_k = 0.91 and at this QL, the F cost = $5.1/unit and the OC = $1.5/unit. When the GB decreases gradually, PA costs at the retailer decrease and both F and OC increase. The relationships among x_i, y_j, u_k and GB are shown in Figure 3-14. It is clear that the x_i, y_j and u_k tend to decrease as the GB decreases. The gaps (values) among x_i, y_j and u_k decrease until they reach GB = $50/unit, and at around GB = $35/unit x_i exceeds y_j.

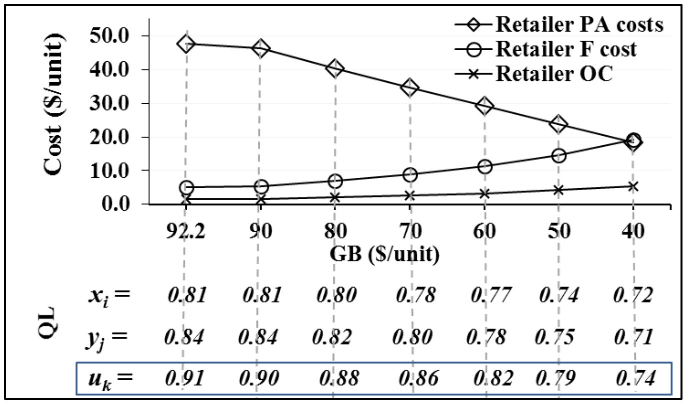


Figure 3-13: The effect of GB on the COQ at the retailer

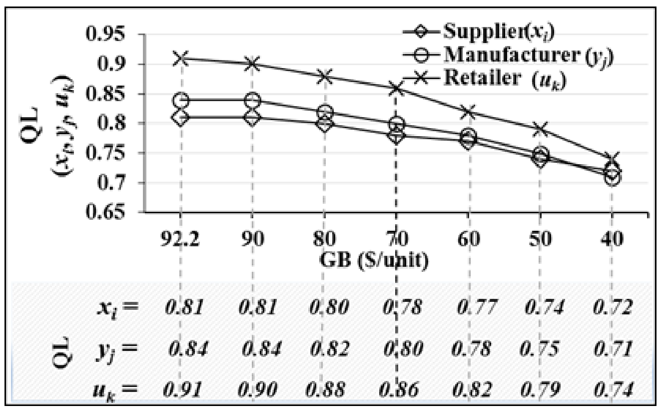


Figure 3-14: The effect of GB on QL at each echelon

In general, the effect of GB is not very high when it is near the optimality, and the solution does not change significantly. However, as the GB becomes less, the effect of F costs become high until they intersect with PA costs at around $40/unit (almost at each echelon). After which the F costs in the SC become higher than the PA costs. Table 3-7 summarizes the effect of GB reduction from the best obtained value (PA = $92.2/unit) and when GB = $40/unit. For the QL, the decrease in the GB affects the retailer much more than the manufacturer, and the weakest effect occurs at the supplier by about around 19%, 15%, and 11% respectively. The same trend can be noticed for the PA costs i.e., the highest reduction in the PA appeared at the retailer echelon and then at the manufacturer, while the lower reduction occurred at the supplier by approximately 61%, 54%, and 46% respectively. PA costs intersect with F costs at QL = 0.74 and GB = $40/unit, below which F costs become higher than PA costs. The previous results were the best-obtained results from the optimization. Our model can be solved as a linear model especially after we find the best solution. We recommend creating three loops (one loop for each QL) and solve the model as a linear model. The proposed algorithm for the linearized model is provided in Figure 3-15.

Table 3-7: Optimum results (Scenario no. 4) for the centralized SC

QL	**PA = $92.2/unit**	**PA = $40/unit**	**Reduction in QL (%)**
$x_i =$	0.81	0.72	11%
$y_j =$	0.84	0.71	15%
$u_k =$	0.91	0.74	19%
PA	**PA = $92.2/unit**	**PA = $40/unit**	**Reduction in PA (%)**
Supplier PA	15.8	8.5	46%
Manufacturer PA	28.8	13.2	54%
Retailer PA	47.5	18.4	61%

Set SC QL = [x_i, y_j, u_k]

Generate x_i = [0.77, 0.78 ……,1]

y_j = [0.77, 0.78 ……,1]

u_k = [0.77, 0.78 ……,1]

Find ∀ SC QL between 0.77 and 1.0.

Calculate the objective function (Eq. 1) for the linear model for each SC QL.

Choose the minimum objective value.

Figure 3-15: Solution methodology for the linearized model

3.5. Discussion and managerial suggestions

The proposed model is constructed based on PAF and OC approach, and it provides the minimum best solution for PAF and OC cost combinations. The proposed PAF cost parameters resemble Juran's model entirely. The behavior of Juran's model is observed when the SC entities work at different QLs, i.e., when the PA costs and QL are low, the F costs are high. As the QLs increase, F costs decrease. The F costs present a negative relation with conformance costs, which complies with (Castillo-Villar et al., 2012) findings. The PAF and OC model is used to design and allocate the COQ in the SC at the minimum costs for the centralized and decentralized SC.

The results of the proposed model agree with (Zhang & Hong, 2017) and (Ma, Wang & Shang, 2013) findings, in which the centralized SC functions better than the decentralized one. Our model could also study the effect of budget limitations and spending on COQ, which recommended in the literature, i.e. (Eftekhar et al., 2014). For this purpose, our optimization model presented that spending on PA costs slightly less than the best obtained PA costs (from the optimization) slightly increase the objective value. In this case, the increase in the objective value was around 0.7%, which will have a minimal effect on the investment.

3.6. Conclusions and future work

Minimizing cost of quality (COQ) is an important subject which attracts the attention of many researchers. However, while few researchers implement COQ in the supply chain (SC), no research has been done so far to analyze the concept of allocating COQ and QL in centralized and decentralized SC. Furthermore, in the proposed model, we investigate the consequences of working below the optimum QL. We were able to provide how the PA, F, OC costs behave within the SC and QL. We also provided how the COQ changes with QL at each echelon. Therefore, the novelty of this work that it attempts to analyzing COQ and its QL in SC. We have modelled COQ in the SC by using a nonlinear mathematical programming model. The non-linearity is presented in our objective function through the convex quality functions, in which different equations were used at each echelon of the SC to symbolize PA, F, and OC costs. The non-linearity is also presented in the model constraints. By implementing the model and solving it as a non-linear model, we were able to conduct different experiments and run the sensitivity analysis. The COQ functions were used in our model were inspired from Juran's COQ model (Juran, 1951). Therefore, our model and the COQ equations can be modified to mathematically represent the COQ system of a given SC, which consists of one supplier, one manufacturer, and one retailer. In addition, we can increase the number of cost functions at each echelon to represent different costs attributes and obtain an optimized solution that denoted by QL.

Just like COQ and QL were modelled in uncapacitated SC, further research could focus on modelling COQ and QL in a capacitated SC, i.e., the number of capacitated suppliers, manufacturers, and retailers. Moreover, further research could address multiple products with different COQ in SC. In addition, this will expand the model to have more decision variables and extra constraints and will add more complexity to the SC model, which is a consequence of the interrelations between parameters and decision variables in the model. The complexity of such a problem would, therefore, require the formulation of a solution methodology that uses metaheuristics such as genetic algorithms.

Chapter 4 - Supply Chain Network Design Based on Cost of Quality and Quality Level Analysis

Abstract

Recent studies have shown that the cost of quality (COQ) is a critical factor for organizations than previously perceived. Suppliers tend to work at different COQ and Quality Levels (QL), in which they are crucial elements for satisfying more customers and for competition in the market. Selecting appropriate suppliers is a significant factor in strategic and tactical decisions. The purpose of this article is to explore the impact of COQ expenditure allocations on supply chain design decisions within a capacitated SC network. We propose a nonlinear optimization model which integrates the opportunity cost (OC) into the COQ with consideration of the QL in the supply chain network design (SCND) decisions. In addition, it examines the effect of investment decisions at each SC echelon to ensure the best overall QL. A numerical example is presented to illustrate the behavior of the model. The results show how the QL, COQ and location decisions change when incorporating the OC, investments, and transportation costs into the model.

Keywords— Supply Chain Network Design, Cost of Quality, Investment Allocation, Quality Level.

4.1. Introduction

Supply chain network design is considered one of the most critical strategic level decisions in determining the success of commercial goods in today's competitive markets. The SCND problem involves the sum of different activities exerted by different facilities, which are organized to better transfer raw materials to finished products from one echelon to another (Ramezani et al., 2013). The SCND problem determines the number, capacity, location of the facilities and the technology of each facility need to be considered. It also regulates the transportation network among the SC entities and specifies the number of items, which are needed to be purchased, produced, consumed, distributed and shipped. Since it is cost prohibitive to open and close the facilities, the change of the network arrangement is not straightforward. Hence, the SCND configuration should be robust to changes in demand and supply needs for a long period. The optimization, therefore, is necessary for the long-term and efficient operation of entire SC (Ramezani et al., 2013; Perez Loaiza et al., 2017).

Even though the quality is an ambiguous term to define, as it is understood from a different perspective by manufacturers and end-users, delivering a satisfactory quality product is an ultimate goal of all SC entities. COQ is used as a measuring tool to evaluate any production system performance. In the SC perspective, COQ could be utilized as a key performance measure and evaluation tool. Measuring the quality level in monetary terms facilitates understanding of the SC performance to the SC shareholders (Srivastava, 2008; Prakash & Mohanty, 2017). Even though, COQ has been considered by several authors within the manufacturing SC, such as Ramudhin et al. (2008), Castillo-Villar et al. (2012 a), Alzaman et al. (2010) and Castillo-Villar et al. (2014), there is no a comprehensive COQ model for designing a capacitated SC in literature. Therefore, this research aims at modelling COQ in the form of PA, F, and OC in a four-echelon SC with consideration of the QL in all SC facilities. In addition, the model is used as an evaluation tool to examine the impact of COQ investment at each SC echelon. The model also provides the impact of COQ, material flow on transportation costs among the SC echelons. The rest of the paper organized as follows: In section 2 we present a literature review about COQ, OC, and SC. In the third section, our proposed model is represented for a capacitated SCND problem, which consists of the four-echelon system (i.e., suppliers, manufacturers, retailers, and customers), aiming at minimizing the overall facility fixed costs, production costs, and COQ. Next, the results are presented. The final section presents the conclusions and the future work.

4.2. Literature review on the COQ

The importance of quality arises from the fact that it dramatically affects customers' decision about the purchase of any product. The quality and the cost can thus identify the differences among various products. Over the past thirty years there has been a fierce battle among businesses trying to improve quality while maintaining it at lowest possible cost, and, consequently, only those who succeeded it survived. In today's market, the quality preferences became a crucial element in competition (Bowbrick, 1992). Therefore, efficiently defining the COQ is necessary for effective competition and to remain in the market (Ben-Arieh & Qian, 2003). Even though the measuring the quality itself necessitates a good definition of quality costs, there is no accepted definition of the quality.

Various works in literature attempt to define quality costs in different ways (Chiadamrong, 2003). Plunkett and Dale, 1988; Kumar et al., 1998; Schiffauerova and Thomson, 2006 provided a review of generic models and approaches to measuring COQ. These models include

Prevention, Appraisal and Failure (PAF) models, Crosby's model, opportunity or intangible cost models, process cost models, and activity-based costing (ABC) models. According to the quality management literature, quality costs occur in four categories of the process of quality management. These costs are identified by British Standard (BS 6143, 1990) as follows:

- **Prevention cost**s: The investment which is made to ensure that the required quality level in the process of production is achieved to reduce the risk of nonconformity or defect, such as quality planning, quality training, process control costs, and general management costs.
- **Appraisal cost**s: The cost of efforts made to identifying poor quality before shipment to achieve conformance to requirements including, for example, test and inspection costs, in-process inspection and testing cost, and instrument maintenance costs.
- **Internal failure cost**: The cost incurred when defects are discovered before shipment within an organization due to nonconformities or defects, such as scrap costs, rework cost, retest and re-inspection costs and redesign costs.
- **External failure cost**: The cost associated with delivery of defective goods or services to a customer due to nonconformities, the cost of claims against warranty, complaint adjustment costs, and returned material costs.

The aforementioned COQ categories have been developed and commonly accepted in organizations (Crosby & Free, 1979; Harrington, 1987; Juran & Gryna, 1988; Schiffauerova & Thomson, 2006). Juran(1951) model is the most common model used in the literature, and it is also widely used in manufacturing industry due to its natural understanding (Jajuet al., 2009). Juran claims that obtaining the lowest rate of COQ occurs when prevention and appraisal costs are equal to failure costs (Juran, 1951). This can be observed in the trend graph in Figure 4-1. Quality cost is generally understood as the sum of the PAF cost categories of quality-associated costs. It is widely agreed that the total cost functions of the four COQ are convex functions. Hence, the COQ is also convex (Feigenbaum, 1983; Juran & Gryna, 1993; Campanella, 1990; Shank & Govindarajan, 1994; Alzaman et al., 2010).

According to Srivastava, COQ or quality costs can be defined as the aggregate of costs occurred to make sure that the quality requirements are being met and it is also defined as a measurement system that translates quality related activities in monetary language for managers (Srivastava, 2008). In general, the total costs of quality are expected to decrease when implementing a robust quality cost system. Schiffauerova and Thomson (2006) have highlighted the savings achieved through the COQ employment in various companies. As examples of published success stories, ITT Europe headquartered in Belgium has saved over $150 million for five years of coping with quality cost control. Based on a correlation analysis in a manufacturing unit, Plewa et al. (2016) find that total COQ and its failure cost are noticeably lower at higher QL, while the PA costs observed to be increased insignificantly at a higher QL.

Although a high portion of the COQ elements can be seen and measured easily, there some cost elements have proven difficult to measure and track hence remained hidden (Sörqvist, 1997). Hidden costs do not characterize true money throughout manufacturing processes thus many organizations ignored them from their accounting files. OC is one of many hidden costs, which does not signify a tangible value. It usually defined as an alteration in investment one makes instead of making another one, i.e., benefits which are not earned due to pursuing different alternatives (Son, 1991). Even though it is challenging to track and measure hidden quality costs, still it is crucial to be aware of their existence and their significance.

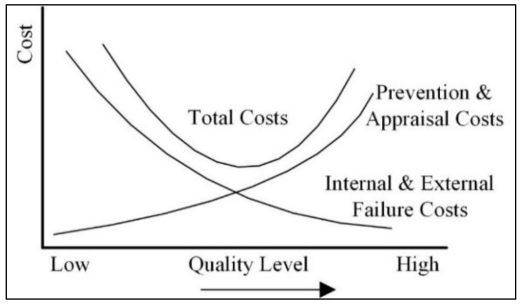


Figure 4-1: Juran's model for COQ (Juran, 1951)

Cheah et al. (2011), Campanella (1999), and Wood (2007) support the view that most quality costs are in fact hidden and are not easy to measure. Hidden costs such as the loss of customer goodwill represent the essential cost component, which has to be managed appropriately (Liu et al., 2008). Omar and Murgan (2014) report that the opportunity loss cost occurred by inefficient processes and poor delivery of services are equal to around 40% and 60%, respectively. In their model, Omar and Murgan measured the OC as a deficiency of inventory material, idle costs, machines setup costs and processes waiting time. Snieska et al. (2013) analyze the external failure costs in a pilot study at a medical supply service company in Lithuania. They develop a questionnaire to measure and inspect the customer satisfaction. They use quality function deployment planning matrix, which is developed by Moen (1998) and loss calculation method due to dissatisfied customers lost, which is developed by Jones and Williams (1995). They could measure the customer satisfaction in the form of a loss of customers' goodwill and transform it into financial value. Alglawe et al. (2017) integrates the OC into their model and represents it as monetary value. They integrated OC into SC PAF cost model by using System Dynamics, and the value of OC was found to be \$2.4/unit. They recommend investing more in PA costs to reduce the OC in order to gain newer customers.

4.2.1. COQ in SC

Srivastava (2008) was the first author measure the COQ and combine it with the SC performance. He defined COQ in the supply chain "the sum of the costs incurred across a supply chain in preventing poor quality of the 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" (p. 139). There are different approaches and methodologies in the literature, which incorporate COQ into SC. Srivastava measured COQ at selected third-party manufacturing sites for a pharmaceutical company. He suggests that mapping COQ can reveal where quality improvement efforts are needed most and where to exert more effort in order to reduce the COQ. Although numerous cases measure COQ and its implementations in organizations individually, only a few studies attempt to measure COQ in the whole supply chain networks. Ramudhin et al. (2008) argue that incorporating COQ in the SC results in a minimum overall cost. Conversely, there is a high risk of selecting low-quality suppliers when supply chain network does not consider COQ. Ramudhin et al. study single product three-echelon SC. Their model minimizes total operational and quality costs at the same time. They claim that adding supplier quality costs to the objective function minimizes the percentage of defects at the supplier, while this also minimizes the overall objective function. They argue that adding COQ to the objective function increases the objective value by around 16% and the solution changed considerably due to the influence of COQ (Ramudhin et al., 2008).

Later, Alzaman et al. (2009) proposed a heuristic approach to solve a mathematical model containing a quadratic COQ function. They state that a quadratic COQ function can be incorporated in the SCND with binary variables and solved efficiently. Castillo-Villar et al. (2012 a) studied the impact of COQ on SCND and used Genetic Algorithm (GA) and Simulated

Annealing (SA) to solve their proposed nonlinear model. Their proposed model could find the best integer variables that minimize the total COQ and maximize the profit and. Castillo-Villar et al. (2014) considered a capacitated SCND model that considers the manufacturing, distribution, and COQ. Their model, which can be used for a strategic planning level, maximizes the profit and minimizes the total costs. Castillo-Villar et al. recommend studying multi-products in a capacitated SCND including COQ. Castillo-Villar et al. (2014) and Herbert-Acero (2013) argued that further research is needed to include the COQ for the whole SC. Recently, Alglawe et al. (2017) incorporated the OC into a COQ simulation model in the whole SC. They find that after adding the OC to the model, the QL needs to be increased in the proposed model to achieve the same expected number of new customers compared to the case without incorporating the OC to the model. According to the previous literature, one can conclude that still there is a need for more work on OC in the SCND (Alglawe et al., 2017). Alglawe et al. suggest studying the effect of the OC and QL in an uncapacitated SC. The idea of modeling and designing a capacitated SC based on the COQ as (PA + F + OC) has not been addressed in the literature. Studying the QL in the SCND while analyzing the COQ have not been proposed yet in literature. Moreover, no previous work has considered the effect of OC and PAF on the SCND modeling. Further, addressing the relationships among PA, F, and OC, the effect of investing at each SC echelon, and the effect of transportation costs on the COQ for a capacitated SCND model were not explored in the literature while they are usefully presented in this paper.

4.3. Methods

The proposed model represents a capacitated SC network design problem, which consists of four-echelon SC system as shown in Figure 4-2. The proposed model aims at minimizing the overall operation and quality costs to provide the SCND that works at the minimum COQ.

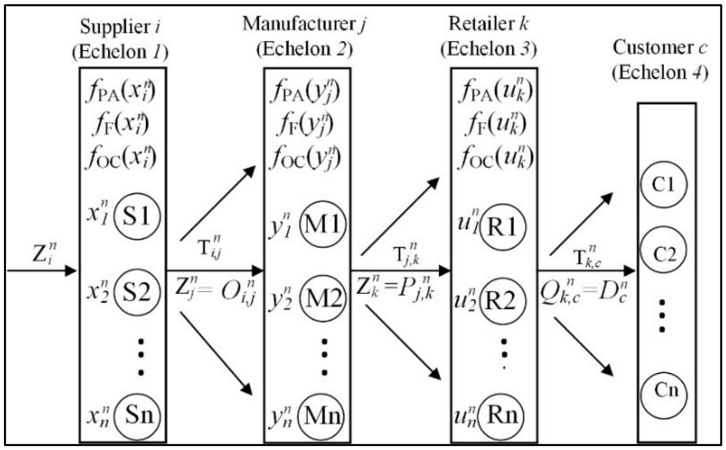


Figure 4-2: Capacitated supply chain

The resulting formulation is a MINLP model in which the SC decisions are centralized. This means the suppliers, manufacturers and retailers are subsidiaries of the SC and they are managed by a central decision-making entity. For example COQ at the supplier's echelon would also be cost attributes for the SC and would be accounted for in the model. The costs are calculated in the same manner at the suppliers, manufacturers and retailers echelons with the consideration of the facility opening costs.

4.3.1. Assumptions for constructing the model

When formulating the proposed MINLP mathematical model, certain assumptions have been taken into consideration as follows:

- The SC consists of a number of suppliers, manufacturers, and retailers.
- The quality measures are implemented by suppliers, manufacturers, and retailers to assure the quality of the products to be at a certain QL.
- The demand is deterministic.

- There is a production capacity constraint for each supplier, manufacturer and retailer.
- The demand for the component type is satisfied from new material and the remanufactured products, which meet the QL at each facility.
- The OCs represent the costs of the unsatisfied customers.
- Unlimited source of the raw material at suppliers' echelon and limited source of the raw material at manufacturers and retailers' echelon.

4.3.2. Model notations

The model represents the COQ as input parameters that comprise different costs functions for each SC facility. The COQ functions in our optimization model inspired by Juran's (1951) COQ model. Figure 4-3 shows the approximate shapes of the conformance and nonconformance COQ functions at each echelon (*i*), (*j*) and (*k*). Costs of conformance functions, PA, were represented by exponential equations and costs of nonconformance functions, F and OC, were represented by polynomial equations. The notations of the COQ function and the other notations are presented in Table 4-1.

Table 4-1: Model notations for SC COQ

I: Set of suppliers, *J*: Set of manufacturers, *K*: Set of retailers, *C*: Set of customers, A: Different types of products at the suppliers: *N*: Different types of products at the SC
Decision variables

Z_i^n , Z_j^n and Z_k^n	A number of different (*n*) components (*Z*) at a supplier (*i*), at a manufacturer (*j*) & at a retailer (*k*), respectively; $n \in N, i \in I, j \in J, k \in K$
$O_{i,j}^n, P_{j,k}^n$ and $Q_{k,c}^n$	A number of different (*n*) good quality components (*O*) to exit from a supplier (*i*), different (*n*) good components (*P*) to exit from a manufacturer (*j*), and different (*n*) good components (*Q*) to exit from retailers (*k*), respectively; $n \in N, i \in I, j \in J, k \in K, c \in C$
x_i^n, y_j^n and u_k^n	Quality level (QL) components at a supplier (*i*) for different products (*n*), at a manufacturer (*j*) for different products (*n*) & at a retailer (*k*) for different products (*n*); $n \in N, i \in I, j \in J, k \in K$
b_{2j}	Binary variable; 1 if manufacturer (*j*) is open; 0 otherwise; $j \in J$
b_{3k}	Binary variable; 1 if retailer (*k*) is open; 0 otherwise; $k \in K$
Parameters (Input Data)	
α_i^n	Production costs per unit at a supplier (*i*) for different products (*n*); $i \in I, n \in N$
λ_j and λ_k	Facilities fixed costs at a manufacturer (*j*) & a retailer (*k*), respectively; $j \in J, k \in K$
$f_{\text{PA}}(x_i^n)$, $f_{\text{PA}}(y_j^n)$ and $f_{\text{PA}}(u_k^n)$	Prevention and appraisal cost functions at a supplier (*i*) for a product (*n*), a manufacturer (*j*) for a product (*n*) & a retailer (*k*) for a product (*n*), respectively; $n \in N, i \in I, j \in J, k \in K$

$f_{\mathrm{F}}(x_i^n)$, $f_{\mathrm{F}}(y_j^n)$ and $f_{\mathrm{F}}(u_k^n)$	Failure cost functions at a supplier (i) for a product (n), manufacturer (j) for a product (n) & retailer (k) for a product (n), respectively; $n \in N, i \in I, j \in J, k \in K$
$f_{\mathrm{OC}}(x_i^n)$, $f_{\mathrm{OC}}(y_j^n)$ and $f_{\mathrm{OC}}(u_k^n)$	Opportunity cost functions at a supplier (i) for a product (n), manufacturer (j) for a product (n) & retailer (k) for a product (n), respectively; $n \in N, i \in I, j \in J, k \in K$
$f_{\mathrm{Pen}}(x_i^n)$, $f_{\mathrm{Pen}}(y_j^n)$ and $f_{\mathrm{Pen}}(u_k^n)$	Penalty cost functions at a supplier (i) for a product (a), manufacturer (j) for a product (r) & retailer (k) for a product (g), respectively; $n \in N, i \in I, j \in J, k \in K$
$\mathrm{T}_{i,j}^n$	Transportation costs of the good products (v) from a supplier (i) to a manufacturer (j); $n \in N, i \in I, j \in J$
$\mathrm{T}_{j,k}^n$	Transportation costs of the good products (e) from a manufacturer (j) to a retailer (k); $n \in N, j \in J, k \in K$
$\mathrm{T}_{k,c}^n$	Transportation costs of the good products (h) from a retailer (k) to a customer (c); $n \in N, k \in K$, $\mathrm{c} \in C$
D_c^n	The production demand from a customer (c) for a product (n); $n \in N, c \in C$
φ_i^n, φ_j^n and φ_k^n	the production capacity of a supplier (i) for a product (n), a manufacturer (j) for a product (n) and retailer (k) for a product (n), respectively; $n \in N, i \in I, j \in J, k \in K$

The COQ functions are created in an attempt to introduce a wide range of applicable situations. Our models examine different practical scenarios in respect to the COQ and QL when all SC entities are centralized to satisfy customers' demand.

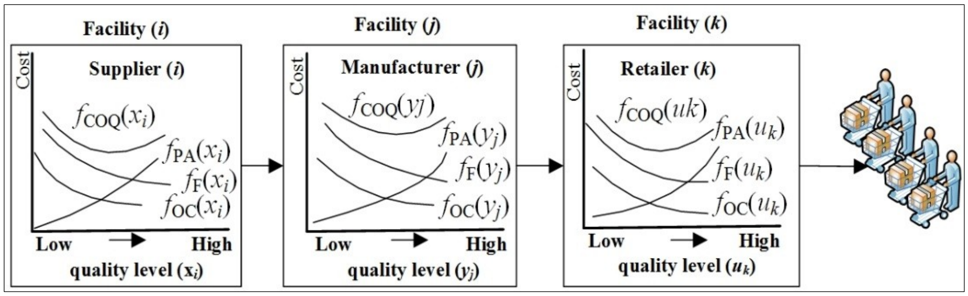


Figure 4-3: SC COQ functions

The objective function for the centralized SC model minimizes facility fixed costs and COQ in the SC opened facilities and its constraints are presented as:

$$\text{Min} \ \sum_{n\in N}\sum_{i\in I}\alpha_i^n Z_i^n + \sum_{n\in N}\sum_{i\in I}\begin{pmatrix} f_{PA}(x_i^n) \\ + f_F(x_i^n) \\ + f_{OC}(x_i^n) \end{pmatrix} * Z_i^n + \sum_{n\in N}\sum_{i\in I}\sum_{j\in J} O_{i,j}^n \mathrm{T}_{i,j}^n$$

$$+ \sum_{j\in J}\lambda_j b_{2j} + \sum_{n\in N}\sum_{j\in J}\begin{pmatrix} f_{PA}(y_j^n) \\ + f_F(y_j^n) \\ + f_{OC}(y_j^n) \end{pmatrix} * Z_j^n + \sum_{n\in N}\sum_{j\in J}\sum_{k\in K} P_{j,k}^n \mathrm{T}_{j,k}^{\mathrm{n}}$$

$$+ \sum_{k\in K}\lambda_k b_{3k} + \sum_{n\in N}\sum_{k\in K}\begin{pmatrix} f_{PA}(u_k^n) \\ + f_F(u_k^n) \\ + f_{OC}(u_k^n) \end{pmatrix} * Z_k^n + \sum_{n\in N}\sum_{k\in K}\sum_{c\in C} Q_{k,c}^n \mathrm{T}_{k,c}^{\mathrm{n}}$$

(1)

Subject to:

$$\sum_{\mathrm{k}\in \mathrm{K}} Q_{kc}^n = D_c^n \quad \forall c, \forall n \tag{2}$$

$$Z_k^n \le \varphi_k^n \, b_{3k} \quad \forall k, \forall n \tag{3}$$

$$Z_k^n u_k^n = \sum_{c \in C} Q_{k,c}^n \quad \forall k, \forall n \tag{4}$$

$$\sum_{j \in J} P_{j,k}^n = Z_k^n \quad \forall k, \forall n \tag{5}$$

$$Z_j^n \le \varphi_j^n \, b_{2j} \; \forall j, \forall n \tag{6}$$

$$Z_j^n y_j^n = \sum_{k \in K} P_{j,k}^n \quad \forall j, \forall n \tag{7}$$

$$\sum_{i \in I} O_{i,j}^n = Z_j^n \quad \forall j, \forall n \tag{8}$$

$$Z_i^n \le \varphi_i^n \quad \forall i, \forall n \tag{9}$$

$$Z_i^n x_i^n = \sum_{j \in J} O_{ij}^n \quad \forall i, \forall n \tag{10}$$

$$0 < x_i^n \le 1, 0 < y_j^n \le 1, \text{and } 0 < u_k^n \le 1 \tag{11}$$

$$b_{2j}, b_{3k} \in \{0,1\} \tag{12}$$

$$Z_i^n \ge 0, \;\; Z_j^n \ge 0, \;\; Z_k^n \ge 0, O_{ij}^n \ge 0, \;\; P_{j,k}^n \ge 0, \;\; Q_{k,c}^n \ge 0 \tag{13}$$

The objective function (1) minimizes the total quality costs at the suppliers', manufacturers', and retailer echelon, and total transportation costs between SC echelons. The constraints from (2) to (13) perform the following: Constraint (2) ensures that the customers' demand is satisfied by the retailers. Constraint (3) puts an upper bound on the retailer's capacity if the facility is open. Constraint (4) ensures that the retailer's available products to sell are equal to the customer's demand. Constraint (5) is the manufacturer's good products, which satisfies the retailer's demand. Constraint (6) puts an upper bound to the manufacturer's capacity if the facility is open. Constraint (7) is the equality constraint for the manufacturers' product outflows to the retailers' inflow. Constraint (8) is the equality constraint for the good products from the supplier to satisfy a manufacturer's demand. Constraint (9) ensures that no supplier produces more than his capacity. Constraint (10) is the constraint for the good products from the supplier to satisfy the manufacturers' demand. Constraint (11) is the QL constraint for suppliers, manufacturers, and retailers, respectively. Constraint (12) is the binary constraint for the manufacturers and retailers, in which b_{2j} equals 1 if a manufacturing facility is open. Otherwise, it is 0, b_{3k} equals 1 if a retailer facility is open otherwise it is 0. Constraint (13) imposes the non-negativity restriction on the decision variables.

The constraints force the proposed model to work as a centralized SC, which means that the suppliers satisfy the manufacturers' demand, the manufacturers supply the retailers with the needed products, and finally, the retailers fulfill the customer demand. COQ is highly affected by products' QL at each SC echelon. The behavior of the COQ functions is validated based on Juran's (1951) COQ model, i.e., when the QL approaches zero we can see that COQ is high, then the COQ decreases as PA increase till it reaches a certain point after which it starts to increase again. At high QL values, the costs of nonconformance approaching their lowest values and costs of conformance increase exponentially.

4.3.3. Model input parameters

According to the objective function and the constraints, our proposed model is mixed-integer nonlinear programming (MINLP) model. It is a centralized capacitated SC which means that the model minimizes the overall, production costs for the products at the suppliers, facilities fixed costs at the manufacturers' and retailers' echelons, facility fixed costs, COQ and transportation costs among the echelons. In order to solve the proposed models for an illustrative example, we assume that the proposed model consists of six-suppliers, six-manufacturers, and six-retailers. We also assume that the SC produces are only one type of products (N) to draw a general conclusion based on the relationship between COQ and QL. The proposed models optimize the COQ at each open facility. The models were designed to address the effect of OC ON the SCND. Model A, which does not consider the OC, consists of two COQ functions at each facility to represent PA and F costs. For this model, a total of thirty-six COQ functions used in the whole SC. The total COQ in each facility is the sum of PA and F costs. Model B, which considers the OC, consists of three COQ functions and the total COQ is the sum of PA, F, and OC costs at each SC facility. In this Model, there are a total of fifty-four COQ functions. The COQ function for the Model A and Model B are presented in Appendix I.

Our assumption for the input parameters are as follows: the customers' demand D_c is 4,500 units. Production costs (α_i) for each component produced at the facility (i) is \$10/unit. Facility fixed costs λ_j and λ_k for each open facility are \$1000. The capacity of a supplier (i) and a manufacturer (j) (φ_i and φ_j) if they are open equal to 2,000 units and the capacity of each open retailer facility (φ_k) is 1,500 units. The solutions and insights of the illustrative example are presented in next section.

4.4. Results

In this section, we present the best-obtained solutions (minimum objective values) of our input data set. The solution was obtained based on the previous assumptions, the model is mixed integer non-linear programming (MINLP) model. It was optimized as a nonlinear to reach the best minimum solutions for the proposed models by using Excel Solver (GRG nonlinear). The model is expected to freely fetch the best QL values: x_i, $y_{j,}$ and u_k.For all the instances, the solutions are obtained in less than 5 minutes after we provided the models with initial values. In section 4.1, we present the results of Model A, in which the objective function does not include the opportunity cost functions: $f_{\mathrm{OC}}(x_i)$, $f_{\mathrm{OC}}(y_j)$ and $f_{\mathrm{OC}}(u_k)$. We also present the results of the Model B to find out the effect of OC on decisions. For both models (A &B) we present the difference between the optimization solution and individual facilities at the minimum COQ (e.g., at the bottom of the quadratic COQ functions). In section 4.2, we aim to investigate the value of investment in each echelon separately.

In the first two subsections, the transportation costs are eliminated from the proposed SC model because we expect the transportation will effect on facility selection and SCND, in which the model may select a lower transportation cost as a preference in opening any facility. Therefore, in section 4.3 we present the effect of the transportation costs on the total COQ, the material flow among the SC echelons, and QL in each echelon.

4.4.1. COQ model with/without OC

The results of the optimized Model A are presented in Figure 4-4, which are based on (i) $f_{\mathrm{PA}}(x_i)$ and $f_{\mathrm{F}}(x_i)$ for the suppliers, (ii) $f_{\mathrm{PA}}(y_j)$ and $f_{\mathrm{F}}(y_j)$ for the manufacturers, and (iii) $f_{\mathrm{PA}}(u_k)$ and $f_{\mathrm{F}}(u_k)$ for the retailers in the objective function, The Figure shows the SCND and open facilities for this model as suppliers 2-5, manufacturers 2-4 and retailers 1, 2, 5 and 6. The resulting objective value for this model is \$719,199.7. After adding the OC to the objective function: $f_{\mathrm{OC}}(x_i)$, $f_{\mathrm{OC}}(y_j)$ and $f_{\mathrm{OC}}(u_k)$ to each SC facility, the results of SCND for the Model B are shown in Figure 4-5. The results show that suppliers 1-6, manufacturers 2-4 and retailers 1, 2, 5 and 6 are selected. In the Model B, the minimum objective value obtained from the optimization has increased by

9.1% to reach $784,439.0.

It is important to notice in Figure 4-5 that the QL has increased in each selected facility in Model B compared to Model A. The overall average of QL has increased in each echelon by approximately 5.3%, 2.3% and 2.3% at the suppliers, manufacturers, and retailers, respectively. In order to overcome the effect of incorporating the OC (i.e., $f_{OC}(x_i)$, $f_{OC}(y_j)$ and $f_{OC}(u_k)$) into the objective function, the values of PA and QL in of each facility increased as shown in Figure 4-5 and Table 4-2. This is due to the inverse proportion between material and QL in the model. As a result of the increased QL, the supplied input materials to the suppliers, manufacturers, and retailers, i.e. $\sum_{i=1}^{6} Z_i$, $\sum_{j=1}^{6} Z_j$, and $\sum_{k=1}^{6} Z_k$ have decreased in the Model B. This implies that if the QL increases at any facility, the number of supplied good products increases, on the other hand, the defective rate in each facility decreases. In general, the Model B leaned towards increasing the QL and reducing the flow of the input materials in the selected facilities. It is important to notice that the relationships among PA and F costs are different from one facility to another. Therefore, any increase in PA costs in one facility affects the F costs of the same facility and consequently the average F costs and COQ of the entire SC. Table 4-2 summarizes the obtained solutions for the Models A and B. It presents the average of PA, F, OC and COQ per unit produced in both models.

Table 4-2: Average SC COQ for Model A and Model B

COQ	Model A	Model B	Increase (%)
A_{ver}. PA ($/unit)	79.9	92.8	16.1%
A_{ver}. F ($/unit)	24.6	20.6	-16.3%
A_{ver}. OC ($/unit)	-	8.4	-
A_{ver}. COQ ($/unit)	104.5	121.8	16.6%

The results show that when the OC is measured in the Model B, the average PA costs is increased by around 16% (from $79.9/unit to $92.8/unit). The average F costs of the SC is decreased by approximately 16% (from $24.6/unit to $20.6/unit). The average COQ in the SC increased by nearly 17% (from $104.5/unit to $121.8/unit). As a result, the objective value has increased by 9.1%.

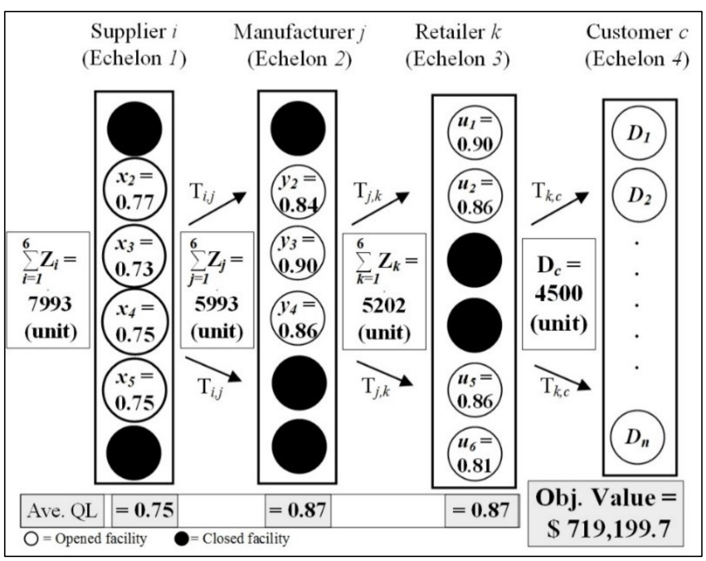


Figure 4-4: SCND considers COQ for Model A

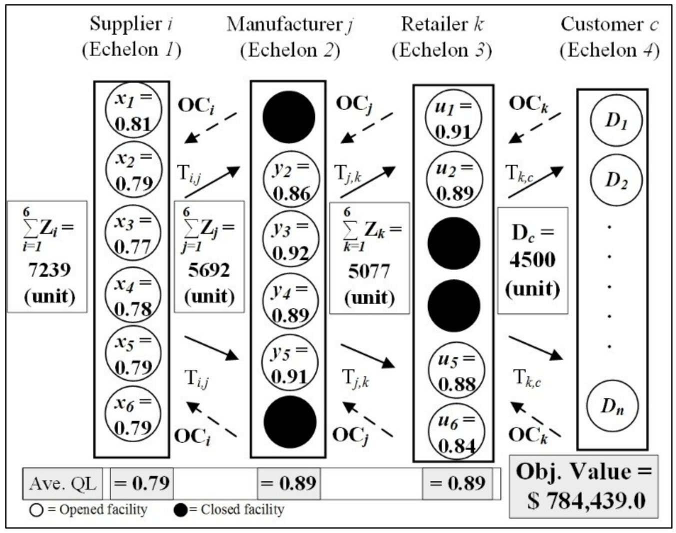


Figure 4-5: SCND considers COQ for Model B

Based on the optimization, the SCND solution results in COQ values and QL higher than the values of the individual (un-optimized) SC facilities. The minimum COQ values and their QL before and after the optimization are presented in Table 4-3 and Table 4-4. For both models (Model A and Model B) the optimized QL and COQ that assigned to the selected facilities are higher than the minimum values of the individual facilities (the minimum values of the quadratic functions). According to the results in Table 4-3, the highest average increase from the minimum QL to the optimized QL values has occurred at the manufacturer.

Table 4-4 presents the results of the Model B. For this Model, the average spending on the COQ is increased by around 5%, 33%, and 26% at suppliers, manufacturers, and retailers echelons, respectively higher than the minimum values of each facility (minimum values of the quadratic functions). Table 4-4 also presents the QL values for the opened facilities, in which the average increase in the QL values (with optimization and minimum values of the quadratic functions) are 6%, 19% and 15% at the suppliers, manufacturers and retailers' echelon, respectively. In both Tables, 4-3 and 4-4, the highest average increase in the QL is assigned to the manufacturers' echelon followed by the retailers' echelon and the suppliers' echelon with the least average increase in the QL.

Table 4-3: SCND for Model A

Facility no.	Supplier (i)				Manufacturer (j)				Retailer (k)			
	Minimum		Optimized		Minimum		Optimized		Minimum		Optimized	
	QL (x_i)	COQ ($/unit)	QL (x_i)	COQ ($/unit)	QL (y_j)	COQ ($/unit)	QL (y_j)	COQ ($/unit)	QL (u_k)	COQ ($/unit)	QL (u_k)	COQ ($/unit)
1	0.73	29.7	N/A	N/A	0.71	24.2	N/A	N/A	0.77	46.8	0.90	58.6
2	0.73	20.6	0.77	21.7	0.73	21.0	0.84	26.3	0.73	34.0	0.86	45.5
3	0.67	24.9	0.73	26.4	0.75	23.0	0.90	30.2	0.69	64.6	N/A	N/A
4	0.71	26.0	0.75	27.1	0.67	20.6	0.86	29.3	0.63	54.9	N/A	N/A
5	0.71	18.4	0.75	19.6	0.69	23.1	N/A	N/A	0.75	36.7	0.86	46.6
6	0.71	28.8	N/A	N/A	0.75	30.6	N/A	N/A	0.69	53.0	0.81	64.9

(N/A = Facility is closed)

For the average increase in the COQ values represented in Table 4-4, the suppliers, manufacturers, and retailers' echelons need to spend an average of 4%, 6%, and 23% higher than the minimum values. The optimization forced the Model A and Model B to increase spending on the COQ and to improve the QL (compared to the individual facilities cases). However, for the spending on the COQ in Model A should be higher at the manufacturers' echelon. On the other hand, the retailers' echelon spends an average of COQ higher than the other echelons in Model B. For Model A and Model B, the best QL is obtained when the retailers' echelon spends the highest average portion of the SC COQ on PA, followed by the manufacturers' echelon and when the least spending on COQ is allocated at suppliers' echelon. The plots for the obtained COQ and QL results for the Model A and Model B are shown in Appendix II, Appendix III, and Appendix IV.

Table 4-4: SCND for Model B

Facility no.	Supplier (*i*)				Manufacturer (*j*)				Retailer (*k*)			
	Minimum		Optimized		Minimum		Optimized		Minimum		Optimized	
	QL (x_i)	COQ ($/unit)	QL (x_i)	COQ ($/unit)	QL (y_j)	COQ ($/unit)	QL (y_j)	COQ ($/unit)	QL (u_k)	COQ ($/unit)	QL (u_k)	COQ ($/unit)
1	0.77	36.5	0.81	37.6	0.75	29.8	N/A	N/A	0.79	52.5	0.91	64.7
2	0.75	24.3	0.79	25.6	0.75	24.6	0.86	30.0	0.77	42.1	0.89	53.3
3	0.73	34.3	0.77	35.6	0.77	25.2	0.92	32.9	0.71	75.4	N/A	N/A
4	0.73	33.0	0.78	34.2	0.71	24.4	0.89	33.2	0.67	66.1	N/A	N/A
5	0.75	26.3	0.79	27.4	0.77	29.5	0.91	37.0	0.77	43.2	0.88	53.4
6	0.75	35.5	0.79	36.8	0.79	34.8	N/A	N/A	0.73	63.9	0.84	75.8

(N/A = Facility is closed)

Table 4-5 summarizes the results of COQ for Model A and B. It presents the average of spending on the PA costs in Model A, which is $80/unit. This is equivalent to about 77% of the COQ in this Model. An average of $93/unit spent on PA costs in Model B, which it is around 82% of the COQ. At the retailer echelon, the average spending on PA costs is $42.6/unit in Model A (about 53% of the total PA costs in Model A). In Model B, the average spending on PA costs is $48.5/unit for the retailer echelon (52% of the total PA costs in Model B). In general, to consider the burden of incorporating the OC to the models, Model B increased the spending on PA costs at the suppliers, manufacturers, and retailers' echelons by around: 27%, 14%, and 14%

respectively.

Table 4-5: COQ decision variables for Model A and Model B

	Model A			Model B		
	S	M	R	S	M	R
Aver. PA ($/unit)	13.1	24.3	42.6	16.7	27.7	48.5
Aver. F ($/unit)	10.6	4.3	9.6	9.2	3.5	7.9
Aver. OC ($/unit)	-	-	-	4.5	1.1	2.8
Aver. COQ ($/unit)	23.7	28.6	52.2	30.4	32.3	59.2
Obj. Val. ($)	719199.7			784439.0		

(S = Supplier, M = Manufacturer and R = Retailer)

The results for PA, F, and OC for each facility are presented in detail in Appendix V. The percentage increase in COQ and QL for Model B (for the same opened facilities in Model A and Model), are represented in Table 4-6. The QL and COQ are increased in the Model B. The highest percentage increase occurs at the suppliers' facilities.

Table 4-6: Difference in the QL and COQ between Model A and Model B

Facility no.	Supplier (i)		Manufacturer (j)		Retailer (k)	
	QL (%)	COQ (%)	QL (%)	COQ (%)	QL (%)	COQ (%)
1	-	-	-	-	1%	10%
2	5%	35%	2%	14%	3%	17%
3	4%	26%	2%	9%	-	-
4	5%	40%	3%	13%	-	-
5	-	-	-	-	2%	15%
6	-	-	-	-	4%	17%

4.4.2. The effect of investing in each SC echelon

In this subsection, we have considered three different scenarios, which subjected to the same constraints of the previous objective function (1). In the 1st scenario, penalty cost function $f_{\text{Pen}}(x_i)$ is considered at each supplier as presented in the following objective function:

$$\text{Min} \sum_{i\in I}\alpha_i Z_i + \sum_{i\in I}\begin{pmatrix} f_{\text{PA}}(x_i) \\ + f_{\text{F}}(x_i) \\ + f_{\text{OC}}(x_i) \\ + f_{\text{Pen}}(x_i) \end{pmatrix} * Z_i + \sum_{i\in I}\sum_{j\in J} O_{i,j}\mathrm{T}_{i,j}$$

$$+ \sum_{j\in J}\lambda_j b_{2j} + \sum_{j\in J}\begin{pmatrix} f_{\text{PA}}(y_j) \\ + f_{\text{F}}(y_j) \\ + f_{\text{OC}}(y_j) \end{pmatrix} * Z_j + \sum_{j\in J}\sum_{k\in K} P_{j,k}\mathrm{T}_{j,k} \qquad (14)$$

$$+ \sum_{k\in K}\lambda_k b_{3k} + \sum_{k\in K}\begin{pmatrix} f_{\text{PA}}(u_k) \\ + f_{\text{F}}(u_k) \\ + f_{\text{OC}}(u_k) \end{pmatrix} * Z_k + \sum_{k\in K}\sum_{c\in C} Q_{k,c}\mathrm{T}_{k,c}$$

In the 2nd scenario, the penalty cost function $f_{\text{Pen}}(y_j)$ is considered at each manufacturer (i.e., in the fifth term of the objective function (14)). In the 3rd scenario, the penalty $f_{\text{Pen}}(u_k)$ is allocated at each retailer (i.e., in the eighth term of the objective function (14)). The penalty cost functions: $f_{\text{Pen}}(x_i)$, $f_{\text{Pen}}(y_j)$ and $f_{\text{Pen}}(u_k)$ are polynomial nonconformance cost functions. These functions have the same constants with different variables as follows:

$f_{\text{Pen}}(x_i) = 22x_i^{-2} - 15x_i - 7$, $f_{\text{Pen}}(y_j) = 22y_j^{-2} - 15y_j - 7$ and $f_{\text{Pen}}(u_k) = 22u_k^{-2} - 15u_k - 7$.

This section aims to find the best echelon to allocate the investment at in order to increase the QL at minimum COQ spending. By optimizing 1st, 2nd, and 3rd scenarios, we could observe the changes in COQ and QL. In each scenario, the model increases the PA values and consequently improves the QL. The proposed model presented different results for each scenario. In the 1st scenario, which is shown in Figure 4-6, the model selected the following facilities (SCND): suppliers 1, 2, 4-6, manufacturers 2, 3, 6, and retailers 1, 2, 5 and 6. The obtained results for the average QL at each echelon are as follows: 0.85, 0.93 and 0.90 for the suppliers, manufacturers and retailers' echelons, respectively.

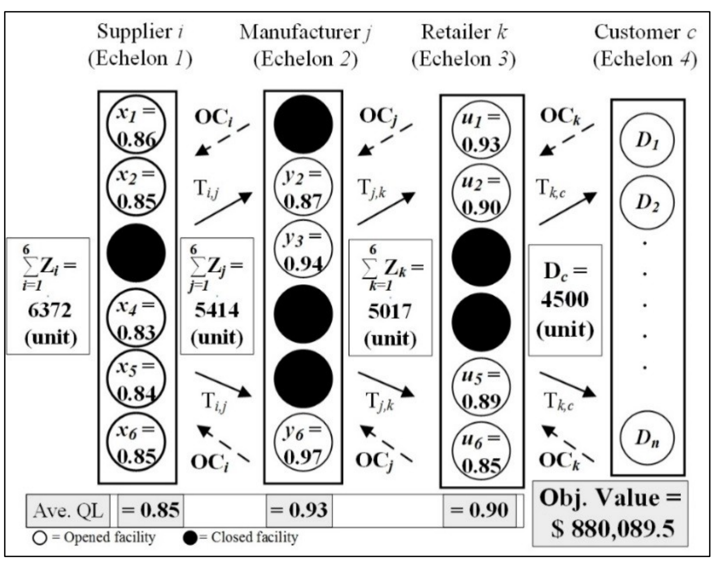


Figure 4-6: 1st scenario, $f_{\text{Pen}}(xi)$ allocated at the suppliers

The minimum obtained objective value is $880,089.5. The results of the 2nd scenario are shown in Figure 4-7, the proposed model selected the following facilities (SCND): suppliers: 1-5, manufacturers: 1, 2, 6, and retailers: 1, 2, 5 and 6. The average QL, which obtained at each echelon, are 0.79, 0.95 and 0.91 for the suppliers, manufacturers, and retailers respectively. For this scenario, the best (minimum) obtained objective value is $830,010.5. In the 3rd scenario, as shown in Figure 4-8, the selected facilities (SCND) are suppliers: 1-6, manufacturers: 3, 5, 6, and retailers: 1, 2 and 5, 6. The average QL values which are obtained at each echelon: 0.79, 0.93 and 0.92 for the suppliers, manufacturers, and retailers, respectively.

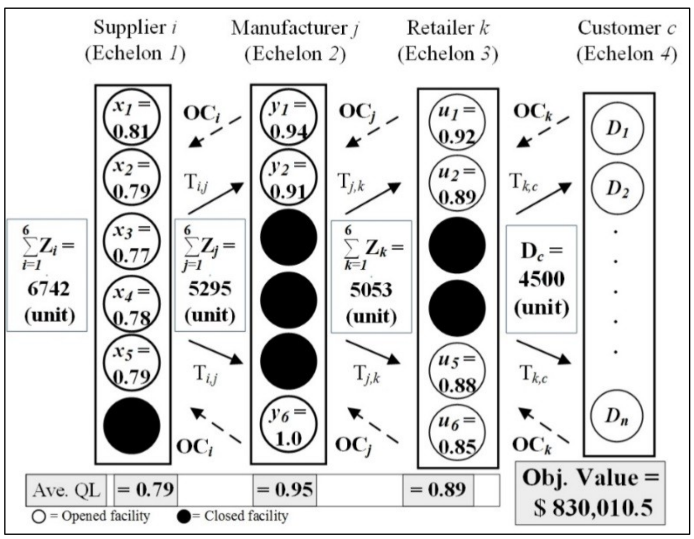


Figure 4-7: 2nd scenario, $f_{\text{Pen}}(yj)$ allocated at the manufacturers

The best (minimum) objective value for the third scenario is obtained at $825,316.2. The decision variable results for the three scenarios are presented in Appendix V (1st, 2nd, and 3rd scenario). Further analysis of the three scenarios is presented in Table 4-7, in which it presents the increase in the objective value in each scenario and the average PA, F, and OC for the SC. The average increase in the QL of each scenario (after implementing the penalty cost functions) compared to the average QL obtained in Model B are 4.2%, 2.3% and 2.7% for the 1st, 2nd, and

3rd scenarios, respectively. The results imply that by allocating the investment at the retailers' echelon, it improves the SC average QL at the minimum spending on PA costs. Overall, the three scenarios have presented nearly the same QL increase as shown in Figure 4-9, which is due to the small value of the $f_{\text{Pen}}(x_i)$, $f_{\text{Pen}}(y_j)$ and $f_{\text{Pen}}(u_k)$ investment.

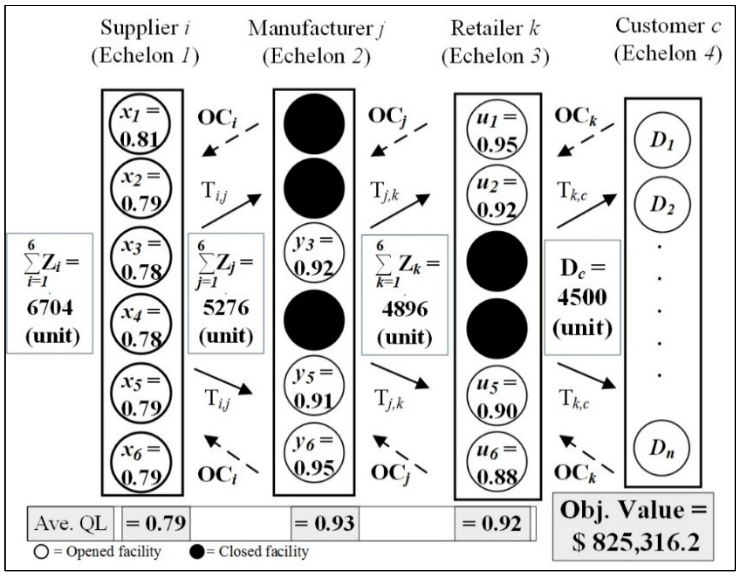


Figure 4-8: 3rd scenario, $f_{\text{Pen}}(uk)$ allocated at the retailers

Table 4-7: Average SC COQ for Model B and the three scenarios

	Model B			1st Scenario "Model B"			2nd Scenario "Model B"			3rd Scenario "Model B"		
	S	M	R	S	M	R	S	M	R	S	M	R
Aver. PA ($/unit)	16.7	27.7	48.5	39.8	35.1	53.6	17.9	44.5	51.5	18.8	34.5	67.8
Aver. F ($/unit)	9.2	3.5	7.9	6.8	2.0	7.7	9.3	2.5	8.2	9.5	2.4	6.1
Aver. OC ($/unit)	4.5	1.1	2.8	2.9	0.7	2.9	4.8	0.6	3.0	4.7	0.9	2.2
Aver. COQ ($/unit)	30.4	32.3	59.2	49.5	37.8	64.2	32.0	47.6	62.7	33.0	37.8	76.1
Obj. Val. ($)	784439.0			880089.5			830010.5			825316.2		

(S = Supplier, M = Manufacturer and R = Retailer)

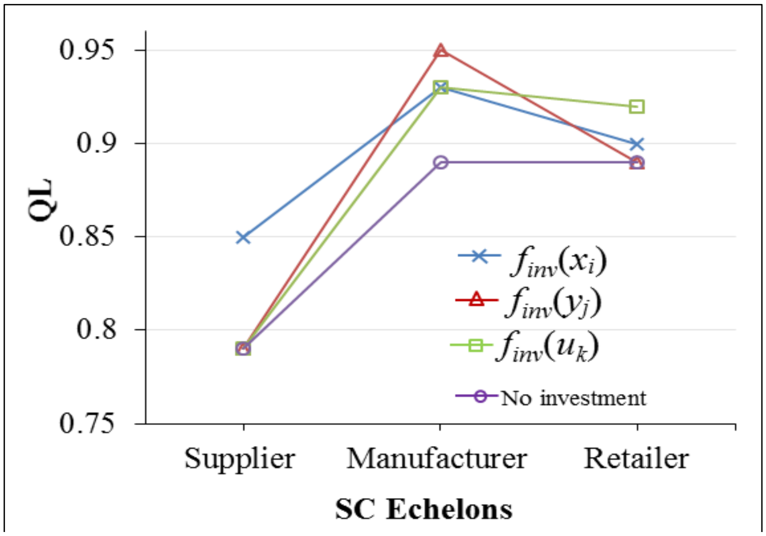


Figure 4-9: The effect of the investment on the SC QL

4.4.3. Analyzing the effect of the transportation costs on COQ in the SC

In this subsection, we try to find out the relationship among different transportation costs and COQ in the SC. We assume that the transportation costs from any facility to other facilities downstream are the same (i.e. $T_{i,j} = T_{j,k} = T_{k,c}$). This is to facilitate drawing a general relationship among the transportation costs and COQ. Afterward, we test the proposed model at different transportation costs for $T_{i,j} = T_{j,k} = T_{k,c} = 0$, 1, 2, 3, 4, and 5 ($/unit). The results are presented in Table 4-8, in which we came up with seven transportation costs scenarios (TRCSs). In the TRCS A(0), we present the QL and the material flow for the Model A (presented in section 4.1) when the transportation cost equal to zero $/unit. For the Model B, we presented six TRCSs at six different transportation costs (i.e. B(0) = 0 $/unit, B(1) = 1 $/unit, B(2) = 2 $/unit, B(3) = 3 $/unit, B(4) = 4 $/unit and B(5) = 5 $/unit).

The results of the table present that as the transportation costs increase, the average QL and COQ in the SC increases. The model reduces the number of defect units by increasing the PA cost and reducing the F costs and OC. High transportation costs force the SC to increase the QL and to transport less number of defective products among the SC facilities and to the customers. In Table 4-8, the QL values are rounded up to two digits after the point. Therefore, the increase in the average QL is not noticeable in the TRCSs. As a consequence of the inverse proportion between the number of the total components and QL in each echelon, the transported components noticeably decrease. Although there is no direct relationship among Z_i, Z_j and Z_k and transportation costs in the objective function, we observe that the number of products in the SC is reduced as the transportation costs increase. As a summary, after adding the transportation costs to the model, the results show an increase in the average QL and its associated COQ. As a result of QL increase, the number of products that flow in the SC decreases. By increasing the QL, the model reduces the cost of defective components so the model transports less (good quality) products among the SC echelons.

Table 4-8: Decision variables for the six scenarios

TRCS	Cost ($/unit)	Average			$\sum_{i=1}^{6} Z_i$ (Unit)	$\sum_{i=1}^{6}\sum_{j=1}^{6} O_{i,j} = \sum_{j=1}^{6} Z_j$ (Unit)	$\sum_{j=1}^{6}\sum_{k=1}^{6} P_{j,k} = \sum_{k=1}^{6} Z_k$ (Unit)	$\sum_{k=1}^{6}\sum_{c=1}^{6} Q_{k,} = \sum_{c=1}^{6} D_c$ (Unit)	SC	
		x_i	y_j	u_k					Aver. COQ ($/unit)	Objective function ($)
A(0)	0	0.75	0.87	0.87	7993	5993	5202	4500	104.5	719,199.7
B(0)	0	0.79	0.89	0.89	7239	5692	5077	4500	121.8	784,439.0
B(1)	1	0.79	0.89	0.89	7232	5692	5072	4500	121.9	801,443.3
B(2)	2	0.79	0.90	0.89	7145	5642	5059	4500	123.0	819,363.0
B(3)	3	0.79	0.90	0.89	7109	5614	5050	4500	123.7	837,310.7
B(4)	4	0.79	0.90	0.89	7086	5602	5045	4500	124.0	855085.1
B(5)	5	0.79	0.91	0.90	7011	5547	5029	4500	125.3	873,909.1

4.5. Discussion of findings

Our proposed SCND problem incorporates the COQ in designing the SC. We implement the COQ in the form of the PAF model. We characterized the SC costs of conformance by PA costs as one cost attribute. The SC costs of nonconformance by F costs. The proposed model addresses three different SC issues: the effect of adding the OC cost to the PAF model in the SCND problem, the value of investing in each SC echelon, and the effect of transportation costs on the COQ and QL. The proposed model can be implemented by the top managements to design and control their COQ and QL in the SCND as stated by Castillo-Villar et al. (2012b) and Noday (2014). In the literature, there is a wide implementation of SCND approach, which can be used to solve different problems (Noday, 2014; Gueir, 2016).

The findings distinguished between the two cases (i.e., PA + F and PA + F + OC). By incorporating the OC into the COQ model, the QL increases and thus the number of products and the number of defect products decrease in the SC network. The results are in line with Alglawe et al. (2017) who claimed that adding the OC to the COQ model increases the necessary minimum QL in their proposed model. Incorporating the OC into the COQ SC model affects the decision of the facility selection in the SC network and it changes the objective function as well. The proposed model explored the efficiency of the investment in the SC echelons which is a crucial issue (Farahani et al., 2014). The results showed that allocating the investment downstream is better than allocating it upstream. Increasing the investment in the QL is a significant issue for companies, which can increase the customer satisfaction and market demand. Therefore the SC benefits the profit (Qiang et al., 2013). The third objective of our experiment focused on the relationship between COQ and transportation costs. It is found that controlling the transportation costs in the SC is crucial because it affects the COQ and the price of the product. Accordingly, the results of our proposed model presented a direct proportion between the transportation costs increase and the COQ.

4.6. Conclusions and Future Work

In this paper, the cost of quality is incorporated within a nonlinear capacitated SCND problem. Our proposed mathematical model is built based on the PAF model approach using a mixed-integer nonlinear programming model, where individual COQ parameters, PA costs, F costs and OC costs are represented as polynomial cost functions. We have modelled PA, F in each SC facility with and without OC costs. The proposed model has been illustrated with an example of six capacitated facilities in a four-echelon SC network. While our proposed model considered the COQ and its associated QL in each facility, the unique feature of our model is the consideration of QL and OC and their integration into the SCND problem. In general, the model has generated solutions which take into consideration fundamental COQ tradeoffs in SCND problems. The results show that in order to accommodate the effect of considering the OC in the model, the objective value increase by around 9.1%. In addition, since QL is directly proportional to PA costs the increase in the PA costs caused the QL to rise as well.

Our model had not only sought to examine the effect of integrating the OC into PAF model but also considered the allocation of investment at each SC echelon. We were able to demonstrate the differences among considering the investment at each SC echelon and how it can affect the QL. Our solution presented that the cost of increasing the SC QL necessitates the lest investment when it is allocated at the retailers' echelon. However, it will be the most expensive if the investment is allocated at the suppliers' echelon. Another finding of this research shows that as the transportation costs increase among the SC echelons, the model puts more importance on transporting good parts among the SC echelons resulting in improved prevention efforts. As a result, the COQ and QL in the model increase. The proposed model tends to reduce the number of defective material to compensate the increase in the transportation costs among the SC echelons.

In this paper, excel solver has been used to solve the proposed nonlinear mathematical models, which presented the (best) minimum solution for our models. However, it is advisable for future work to propose some solution approaches to find an exact solution within a reasonable computational such as linearizing the model. In addition, the excel solver will not be suitable to solve larger size (facilities) problem. To this purpose, the use of metaheuristic methods is recommended.

4.7. Appendices

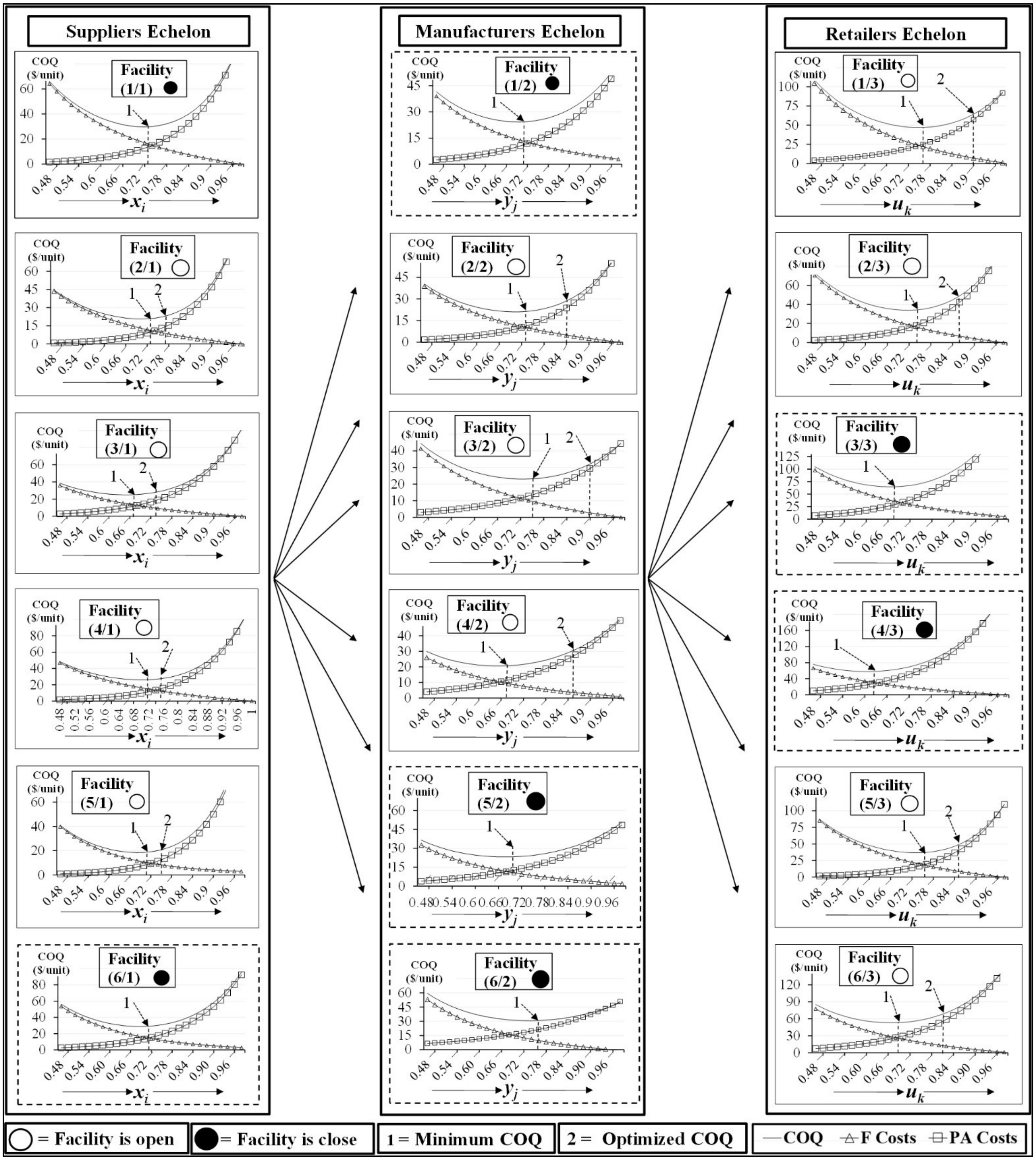
Appendix I

COQ input functions to the model

	PA, F, and OC Function		
Cost Type	**Suppliers**	**Manufacturers**	**Retailers**
PA(facility 1) =	$= 0.0395e^{7.807x_1}$	$= 0.15e^{5.907y_1}$	$= 0.25e^{5.907u_1}$
F(facility 1) =	$= 18x_1^{-2} - 8x_1 - 10$	$= 10y_1^{-2} - 5y_1 - 2$	$= 30u_1^{-2} - 7u_1 - 22$
OC(facility 1) =	$= 8x_1^{-2} - 3x_1 - 5$	$= 5y_1^{-2} - 5y_1$	$= 10u_1^{-2} +3u_1 - 13$
PA(facility 2) =	$= 0.00985e^{9.207x_2}$	$= 0.059e^{6.97y_2}$	$= 0.077e^{7.17u_2}$
F(facility 2) =	$= 12x_2^{-2} - 7x_2 - 5$	$= 10y_2^{-2} - 10y_2$	$= 20u_2^{-2} - 7u_2 - 13$
OC(facility 2) =	$= 4x_2^{-2} - x_2 - 3$	$= 3y_2^{-2} - 4y_2 + 1$	$= 9u_2^{-2} - 5u_2 - 4$
PA(facility 3) =	$= 0.0975e^{6.95x_3}$	$= 0.253e^{5.17y_3}$	$= 0.34e^{6.37u_3}$
F(facility 3) =	$= 9x_3^{-2} - 11x_3 + 2$	$= 11y_3^{-2} - 9y_3 - 2$	$= 26u_3^{-2} - 11u_3 - 10$
OC(facility 3) =	$= 8x_3^{-2} - 3x_3 - 5$	$= 2y_3^{-2} - 3y_3 + 1$	$= 7u_3^{-2} - 12u_3 + 5$
PA(facility 4) =	$= 0.02685e^{8.4x_4}$	$= 0.3817e^{4.87y_4}$	$= 0.49e^{6.27u_4}$
F(facility 4) =	$= 12x_4^{-2} - 13x_4 + 1$	$= 7y_4^{-2} - 3\mathrm{y}_4 - 3$	$= 17u_4^{-2} - 18u_4 + 1$
OC(facility 4) =	$= 6x_4^{-2} - 5x_4 - 1$	$= 3y_4^{-2} - 2y_4 - 1$	$=8u_4^{-2} - 2u_4 - 6$
PA(facility 5) =	$= 0.0099e^{9.27x_5}$	$= 0.395e^{4.81y_5}$	$= 0.0445e^{7.81u_5}$
F(facility 5) =	$= 14x_5^{-2} + 19x_5 - 30$	$= 9y_5^{-2} - 1\mathrm{y}_5 - 6$	$= 24u_5^{-2} - 10u_5 - 14$
OC(facility 5) =	$= 11x_5^{-2} + 7x_5 - 18$	$= 7y_5^{-2} - 1y_5 - 6$	$= 5u_5^{-2} - 12u_5 + 7$
PA(facility 6) =	$= 0.095e^{6.88x_6}$	$= 0.97e^{3.958y_6}$	$= 0.47e^{5.75u_6}$
F(facility 6) =	$= 17x_6^{-2} + 12x_6 - 26$	$= 16y_6^{-2} - y_6 - 16$	$= 21u_6^{-2} - 13u_6 - 7$
OC(facility 6) =	$= 9x_6^{-2} + 5x_6 - 14$	$= 5y_6^{-2} - 4y_6 - 1$	$= 8u_6^{-2} - 10u_6 + 2$

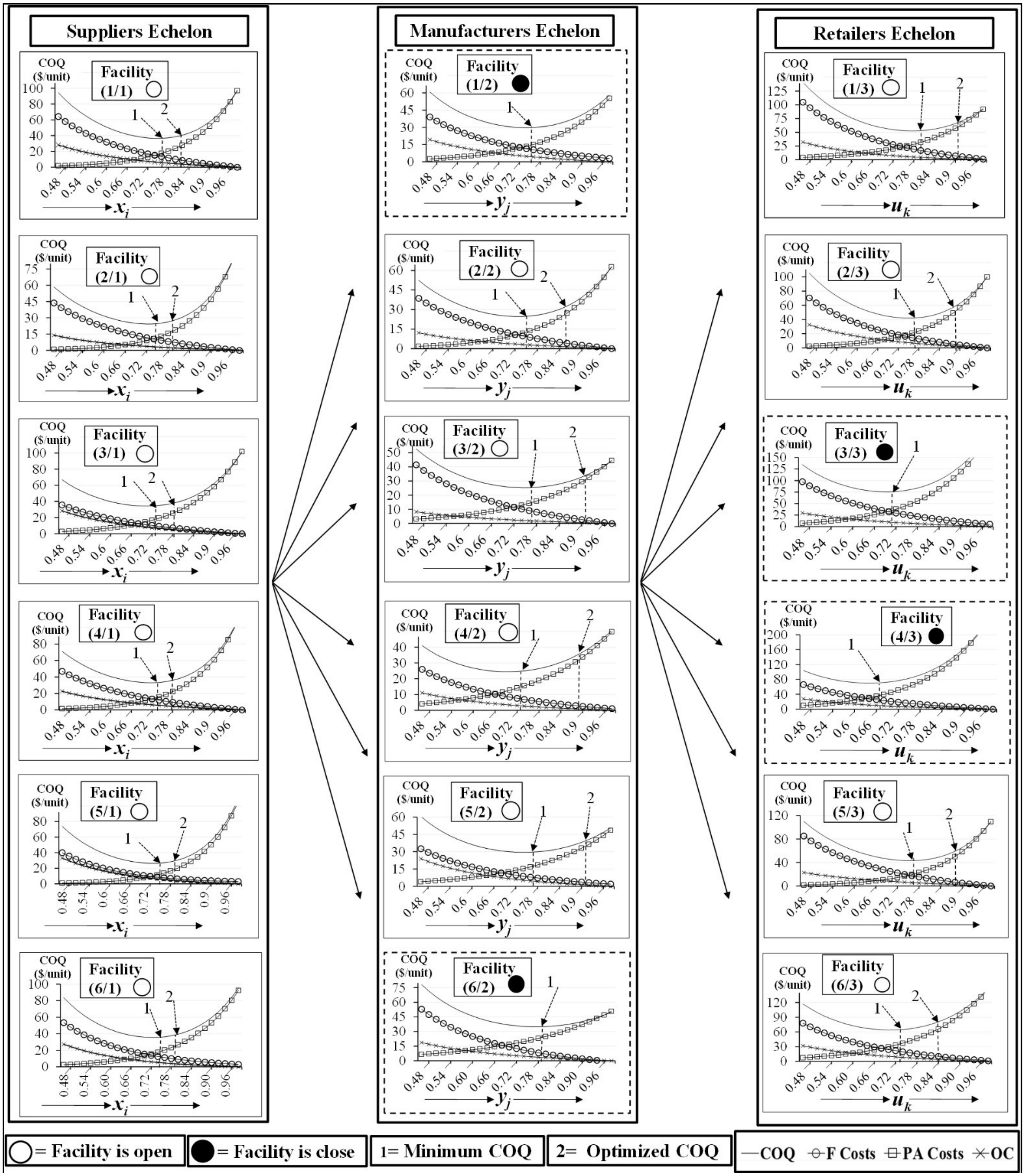
Appendix II

COQ distribution for Model A



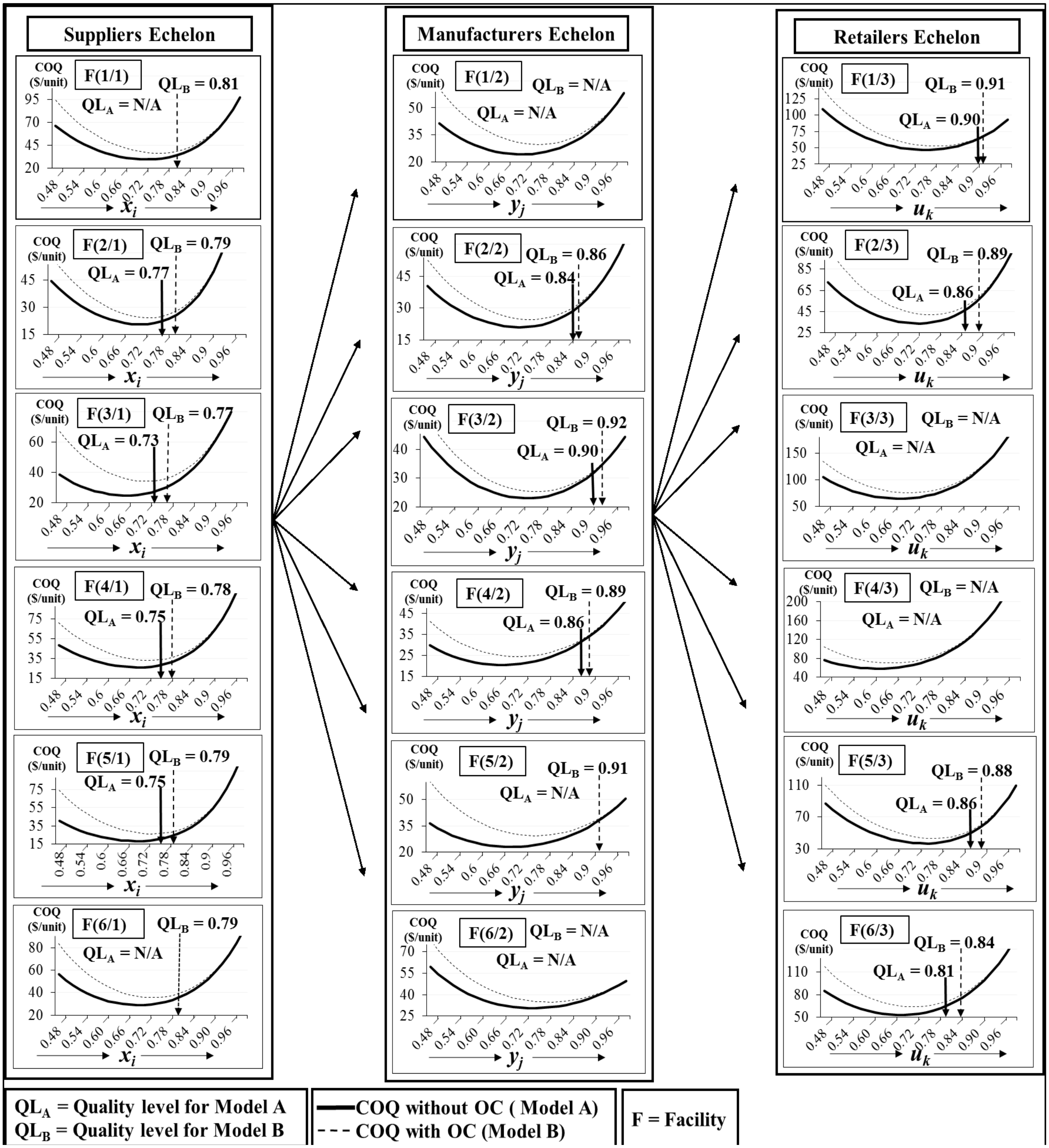
Appendix III

COQ distribution for Model B



Appendix IV

COQ distribution for Model A and Model B



Appendix V

COQ decision variables (SCND)

	Model A			Model B			Model B 1st Scenario			Model B 2nd Scenario			Model B 3rd Scenario		
	S_i	M_j	R_k	S_i	M_j	R_k	S_i	M_j	R_k	S_i	M_j	R_k	S_i	M_j	R_k
PA(facility 1) =	N/A	N/A	49.4	21.6	N/A	55.5	42.4	N/A	59.3	21.6	42.8	57.0	21.9	N/A	70.6
F(facility 1) =	N/A	N/A	9.2	11.2	N/A	7.5	7.4	N/A	6.5	11.2	4.6	7.1	11.0	N/A	4.8
OC(facility 1) =	-	-	-	4.8	N/A	1.7	3.2	N/A	1.4	4.9	0.9	1.6	4.8	N/A	1.0
PA(facility 2) =	11.9	20.5	37.7	14.3	23.4	43.9	35.2	26.3	47.2	14.3	39.9	45.2	14.5	N/A	60.3
F(facility 2) =	9.8	5.8	7.8	8.7	5.0	6.3	5.7	4.3	5.7	8.7	2.9	6.1	8.6	N/A	4.4
OC(facility 2) =	-	-	-	2.6	1.6	3.1	1.7	1.4	2.8	2.6	0.9	2.9	2.6	N/A	2.1
PA(facility 3) =	15.5	26.8	N/A	21.0	29.6	N/A	N/A	33.4	N/A	21.0	N/A	N/A	21.4	30.1	N/A
F(facility 3) =	10.9	3.4	N/A	8.5	2.7	N/A	N/A	1.8	N/A	8.5	N/A	N/A	8.4	2.6	N/A
OC(facility 3) =	-	-	-	6.1	0.6	N/A	N/A	0.4	N/A	6.1	N/A	N/A	6.0	0.6	N/A
PA(facility 4) =	14.4	25.5	N/A	18.3	29.0	N/A	41.7	N/A	N/A	18.3	N/A	N/A	18.5	N/A	N/A
F(facility 4) =	12.7	3.8	N/A	10.8	3.2	N/A	7.4	N/A	N/A	10.8	N/A	N/A	10.7	N/A	N/A
OC(facility 4) =	-	-	-	5.1	1.0	N/A	3.5	N/A	N/A	5.1	N/A	N/A	5.0	N/A	N/A
PA(facility 5) =	10.5	N/A	36.7	14.6	31.5	41.9	35.6	N/A	44.9	14.6	N/A	43.1	14.8	31.9	58.5
F(facility 5) =	9.1	N/A	9.9	7.6	3.9	8.5	5.8	N/A	7.7	7.6	N/A	8.2	7.5	3.9	6.3
OC(facility 5) =	-	-	-	5.3	1.5	3.0	3.4	N/A	2.7	5.3	N/A	2.9	5.2	1.5	2.2
PA(facility 6) =	N/A	N/A	50.8	21.5	N/A	59.1	43.9	45.7	62.9	N/A	50.8	60.6	21.8	41.6	81.7
F(facility 6) =	N/A	N/A	14.1	10.8	N/A	11.8	7.7	0.0	10.9	N/A	0.0	11.4	10.7	0.8	8.8
OC(facility 6) =	-	-	-	4.4	N/A	4.9	2.7	0.4	4.5	N/A	0.0	4.8	4.4	0.7	3.6
Aver. PA	*13.1*	*24.3*	*42.6*	*16.7*	*27.7*	*48.5*	*39.8*	*35.1*	*53.6*	*17.9*	*44.5*	*51.5*	*18.8*	*34.5*	*67.8*
Aver. F	*10.6*	*4.3*	*9.6*	*9.2*	*3.5*	*7.9*	*6.8*	*2.0*	*7.7*	*9.3*	*2.5*	*8.2*	*9.5*	*2.4*	*6.1*
Aver. OC	-	-	-	*4.5*	*1.1*	*2.8*	*2.9*	*0.7*	*2.9*	*4.8*	*0.6*	*3.0*	*4.7*	*0.9*	*2.2*
Aver. COQ	*23.7*	*28.6*	*52.2*	*30.4*	*32.3*	*59.2*	*49.5*	*37.8*	*64.2*	*32.0*	*47.6*	*62.7*	*33.0*	*37.8*	*76.1*
Obj. Val. ($)	*719199.7*			*784439.0*			*880089.5*			*830010.5*			*825316.2*		

(S = Supplier, M = Manufacturer, R = Retailer and N/A = Closed facility)

Chapter 5 - A Decision Support System for Cost of Quality in Supply Chain

Abstract

This article aims at presenting a hybrid Decision Support System (DSS), which uses a mathematical model and System Dynamics (SD) model to analyze the Cost of Quality (COQ) in a supply chain (SC). This model is appropriate and effective with today's highly competitive and constantly fluctuating work and business environment. The mathematical and SD models are combined to integrate the optimization and SD simulation methodologies. The proposed mathematical model minimizes the COQ, which is presented in the form of Prevention, Appraisal, Failure and Opportunity Cost (PA-F-OC). The results of the optimization are then implemented in the SD simulation model to increase the number of new customers in the SC. The optimization is implemented again with more constraints to increase spending on PA costs to the high number of new customers. The results show that the PA costs can be increased to a certain limit at each facility, but afterwards any increase in PA costs will not attract more new customers due to the increase in the COQ and in the price of the product. The proposed hybrid DSS model finds the minimum COQ, which can be increased to attract more new customers and to increase the SC market share.

Keywords: Opportunity Cost, Cost of Quality, Supply Chain, PAF Model, System Dynamics.

5.1. Introduction

Quality has been long identified as a significant factor in the consumer's decision when a variety of products is offered in the market. However, it is not only the impressive quality which customers necessitate, but it is also high quality with an affordable price that interests them and ultimately permit companies to outperform the competition (Chopra & Singh, 2015). In order to gain more customers, organizations have to consider not only the quality level (QL) of their products but also the cost of achieving the required QL. Integrating tools to support their accounting system such as Cost of Quality (COQ) can, therefore, help businesses to minimize costs and at the same time improve the quality, thus achieving better customer satisfaction (e.g., Wilkes & Dale, 1998; Dreyfus et al., 1999; Mendes & Lourenço, 2014).

However, the idea of categorizing the COQ components and utilizing a COQ model is not straightforward, and there have been many differences in the categorization of these components (Cheahet et al., 2011; Yang, 2008; Machowski & Dale, 1998; Trehan et al., 2015). Tsai (1998) argues that there is no general method on how to assign expenses to COQ elements and no adequate method to trace COQ to their sources. Organizations which manage their COQ have to build an appropriate model, which comprises the elements and classifications of their COQ (Ramdeen et al., 2007; Akkoyun & Ankara, 2009; Omachonu et al., 2004; Daunoriene & Katiliute, 2016). According to American Society for Quality Control (ASQC, 1971) and British Standard (BS 6143 Part 2, 1990), quality costs are defined as those costs that confirm and ensure quality and the loss, which occurred when the quality requirements were not achieved. COQ comprises the commonly used traditional Prevention Appraisal Failure (PAF) model, which was proposed by Feigenbaum (1956). The total number of quality costs represents just a small percentage of the entire cost (Chiadamrong, 2003).

Carr (1992) claims that the concept of COQ has been applied effectively in service and manufacturing organization. The purpose of implementing COQ in the business practices is to increase the benefits of quality improvements and to connect it to customer satisfaction, as well as to relate these benefits to a matching cost in order to reduce total costs and increase the customer satisfaction and benefits (Iuliana et al., 2013). Schiffauerova and Thomson (2006) and Sawan, 2014 argue that the cost of quality is a tradeoff between the costs of conformance and costs of nonconformance. Businesses that have established a financial system to measure their quality cost have also gained dramatic positive results.

Based on the literature, various studies focused on addressing the COQ in individual companies, but studies which have been carried out in the context of the SC are rare. Srivastava (2008) was the first one who focused on analyzing the costs in the entire supply chain (SC) (Srivastava, 2008). Castillo-Villar et al. (2012) analyze the impact of COQ in SC network design, where their proposed model could find a significant solution that minimizes the COQ at the supplier, manufacturing plant, and retailer and maximized the profit. They used Genetic Algorithm and Simulated Annealing to solve their proposed nonlinear model. Lately, Lim et al. (2015) optimize the COQ by a proposed mathematical programming model. The model utilizes PAF framework, and it is linearized to provide awareness of the changes in COQ parameters. In order to improve QL and decrease quality risk, it is suggested to improve teamwork between the SC upstream and downstream (Liu & Xie, 2013). This paper aims at presenting a hybrid COQ model, which consists of a nonlinear mathematical model and an SD simulation model in the SC. This model is effective for today's highly competitive and constantly fluctuating work and business environment. The COQ which is presented in the form of Prevention, Appraisal, Failure and Opportunity Cost (i.e., PAF + OC) measured and analyzed by modeling of two methodologies, which are mathematical modeling and SD simulation methodologies. The COQ is optimized in the mathematical model and the results are then used in the SD simulation. The mathematical model provides the minimum COQ, while the SD model provides the sales forecast for the new customers. This combination is presented as a hybrid Decision Support System (DSS). The ultimate goal of such a system is to evaluate the COQ in the SC by fulfilling the constraints of the mathematical model and generate valuable COQ information, which can be simulated to provide a broader picture of how the COQ factors interact among each other.

Unlike tradition optimization-based models, the proposed hybrid modeling approach may be considered as a platform for on-time COQ analysis. This will help decision-makers to improve business decisions and allow them to update the information in their system. The remainder of this paper is organized as follows: first, a literature review on COQ is presented. Next, methodology and the proposed models for measuring the COQ in SC are provided, followed by the results and discussion. Finally, a summary of the work, concluding remarks and recommendations for the future work, are presented.

5.2. Literature review

The quality is an important factor because it greatly affects customers' decision when he/she selects among a variety of products. Thus, the differences among several products can be distinguished based on the quality and its costs (Anshul, 2015). In the past, companies were aggressively battling trying to provide best quality at the lowest possible cost and, therefore, only those who succeeded continued in the market (Bowbrick, 1992). Recently, the quality variances became a key element in competition (Chen & Hua, 2015; Nabin et al., 2016; Donauer et al., 2015). Therefore, an understandable definition of the COQ is necessary for any product for effective processes and competition (Ben-Arieh & Qian, 2003). Even though the clear definition of quality costs is vital for an attracting quality, there is no common description or general definition of the quality cist elements, it is defined as many authors define it in several ways (Chiadamrong, 2003; Dennis, 1999; Evans & Lindsay, 1999). Srivastava (2008) defines the COQ as a measurement system, which translates quality and its associated activities into financial terms to facilitate the understanding for managers. In his definition COQ is the sum of activity costs, which are needed to ensure satisfying the quality requirements.

If COQ is carefully measured and implemented, the total costs will be reduced, and the product quality and reliability will increase (Tye et al., 2011). Chopra and Garg (2012) develop two models to measure the COQ. They state that the implemented COQ program can be applied to calculate the COQ in any manufacturing organization. Chopra and Garg (2012) verified their proposed model in a textile company in India. They constructed a COQ team to estimate the current level of COQ and to provide necessary recommendations to reduce the COQ level. The result helped the company to reduce the COQ by 23%. By assessing the COQ in industries, Sailaja et al. (2014) could reduce the failure costs from 50% to 60% and the COQ was reduced by almost 3%. They used statistical analysis to measure the COQ, and they could identify the areas of enhancements. Lately, Mahmood and Kureshi (2014) measured the Cost of Poor Quality (COPQ) in public sector infrastructure project (in a concrete bridge). They collected the data from machinery, labor, and material of the project. The results were interesting as they could successfully reduce the COPQ from around 36% to 15% in two months of the study period. Mahmood and Kureshi highly recommend measuring the COPQ and to use their developed system for future construction projects. If an efficient quality cost system is implemented, it is anticipated that the total COQ will be decreased, and the failure costs will decrease as well

(Takala, 2015; Trehan et al., 2015).

Hidden quality costs are difficult to measure and trace and not too many authors attempted to do so. Omar and Murgan (2014) analyzed these costs, and they find them equal to 66.7% of the overall total cost. Customer satisfaction is believed to have a direct effect on customer retention and organizations' market share. Increasing the quality level can increase the customer satisfaction by understanding and improving the process operation and identifying the problem (Annamalah & Tan, 2016; Liu, 2012; Liat et al., 2014; Sharma & Suri, 2017). Opportunity costs (OC) is a form of the hidden quality costs that do not characterize true money and that are difficult to quantify. In the literature, there are various types of OCs. Chiadamrong (2003) divided the OC into four main groups, which are batch and process waiting, idle costs, and loss of goodwill. Omar and Murgan (2014) find that the OC, which was calculated based on the prcocess inefficiency, is nearly 18.4%. Their study, which was carried out in South-East Asia on a semiconductor firm, presented that the nonconformance costs can be decreased with almost no subsequent investment in the conformance costs. In their conclusion, Omar and Murgan encourage conducting more research, especially in more complex production lines. The effect of OC as a loss of customer goodwill is rarely measured in the COQ models (Snieska et al. , 2013; Mäenpää, 2016). Sandoval-Chavez and Beruvides (1998) are the first authors to measure the COQ based on the OC and PAF model.

While there are numerous works on COQ measurement in individual organizations, so far, there are only a few studies that measured COQ in the entire supply chain (SC) network (Srivastava, 2008; Castillo-Villar et al., 2012; Ayati, 2013; Gueir, 2016). Srivastava (2008) was the first author to measure the performance of COQ in SC. Based on his work, the COQ in SC is the total amount of the costs of SC, which incurred to prevent poor quality of the product/service to reach the final consumer. The costs, which arise to ensure meeting the quality requirements and any other costs rise as consequence of poor quality. Ramudhin et al. (2008) developed a model to study a single product in a three-echelon SC. They proposed a model to minimize total quality and operational costs simultaneously while they considered the defects at the suppliers' level. Based on their model, adding quality costs to the supplier in the objective function could minimize defects at the supplier. They find by adding COQ to the objective function, the objective value increases by more than 15%.

Alglawe et al. (2017) studied the effect of the OC with its associated QL in an uncapacitated SC. They highlighted the importance of incorporating the OC into COQ in SC. However the idea of increasing the spending on PA costs to increase the customer satisfaction (e.g., reducing OC) in SC has not been studied yet. Hence, this work aims at improving the customer satisfaction beyond the optimum value for the PA costs. First, the paper considers the modelling approach based on a mathematical model. Second, the results of the mathematical model are used in an SD simulation model. The proposed hybrid DSS model will address increasing the number of new customers to a certain level beyond which the spending on PA costs will not be recommended anymore. Our finding indicates that COQ can be increased to reduce the nonconformance costs and increase the customer satisfaction. The findings suggest that using more than one methodology can be beneficial in measuring and monitoring the COQ.

5.3. Methods

The proposed DSS model aims to provide decision support for the higher management when they want to increase the SC QL. Our proposed model involves three stages as shown in Figure 5-1: a mathematical stage, a simulation stage, and another mathematical stage. In the first stage, we develop a mathematical model, which minimizes the COQ in an SC mathematical model. The optimization is expected to provide the minimum COQ values and the best QL in the SC. In the second stage, the results of the COQ of the mathematical model will be used as an input to the SD model and the model will then be run at different PA costs. The SD model will show the effect of increasing the PA costs on the number of the new customers in the SC. The best PA costs (i.e. resulting in higher number of new customers) will be used in the last stage. In the stage #3, the model will minimize the COQ with the same constraints as in the stage #1; in addition, we add a PA cost constraint to the constraint to increase the QL and the number of new customers (reduce OC).

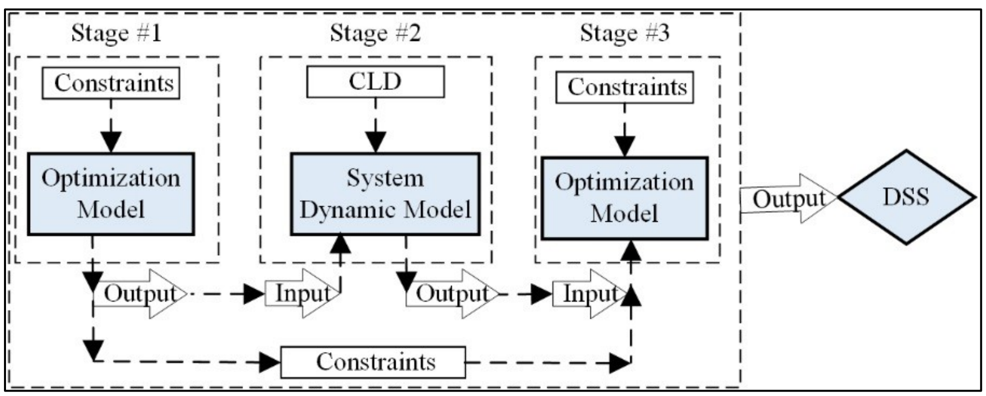


Figure 5-1: Hybrid decision support system based on COQ

5.3.1. Mathematical model (Stage #1)

In the mathematical model, the COQ incorporates OC to the PAF model, so the mathematical formula of the COQ becomes PA + F + OC. The OC represents a financial value of the unsatisfied customer (loss of customers' goodwill) at the time of investing in PA costs, which meets a certain QL in the model. The proposed mathematical model represents the COQ in SC, which is inspired by Alglawe et al. (2016), in which it represents a four-echelon SC system consisting of n suppliers, manufacturers, retailers, and customers as shown in Figure 5-2. The objective function of the model aims to provide the best solution that minimizes the fixed costs, COQ, and their associated products at the suppliers, manufacturers and retailers' echelon.

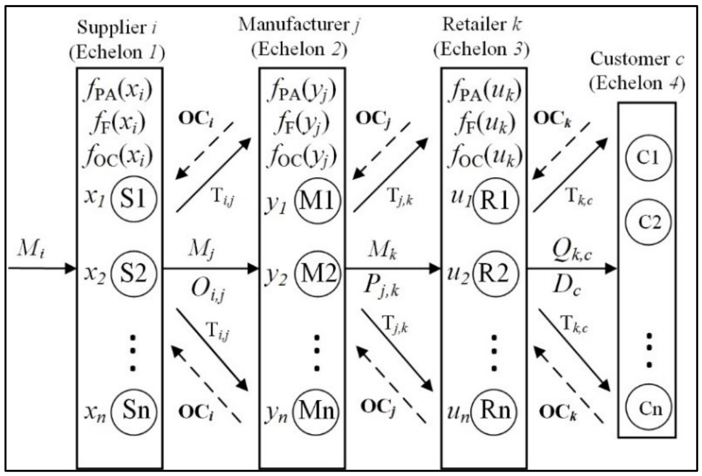


Figure 5-2: SC mathematical model

The proposed model input parameters, decision variables, and constraint parameters are explained in general forms in Table 5-1 as follows:

Table 5-1: Model notations for SC COQ

I: Set of suppliers, *J*: Set of manufacturers, *K*: Set of retailers, and *C*: Set of customers	
Decision variables	
M_i, M_j, and M_k	Supplied components to a supplier (*i*), manufacturer (*j*), and retailer (*k*), respectively; $i \in I, j \in J, k \in K$
$O_{i,j}$, $P_{j,k}$ and $Q_{k,c}$	Number of good components to exit from: a supplier (*i*), a manufacturer (*j*) and retailer (*k*), and to enter: a manufacturer (*j*), to a retailer (*k*), and to a customer (*c*), respectively; $i \in I, j \in J, k \in K, c \in C$
x_i, y_j, and u_k	Quality level (QL) at a supplier (*i*), manufacturer (*j*) & retailer (*k*), respectively; $i \in I, j \in J, k \in K$

Parameters (input data)	
$f_{PA}(x_i)$, $f_{PA}(y_j)$, and $f_{PA}(u_k)$	Prevention and appraisal cost functions at a supplier (*i*), manufacturer (*j*) & retailer (*k*), respectively; $i \in I, j \in J, k \in K$
$f_F(x_i)$, $f_F(y_j)$, and $f_F(u_k)$	Failure cost functions at a supplier (*i*), manufacturer (*j*) and retailer (*k*), respectively; $i \in I, j \in J, k \in K$
$f_{OC}(x_i)$, $f_{OC}(y_j)$, and $f_{OC}(u_k)$	Opportunity cost functions at a supplier (*i*), manufacturer (*j*) and retailer (*k*), respectively; $i \in I, j \in J, k \in K$
α_i, α_j, and α_k	Fixed costs per unit product at a supplier (*i*), manufacturer (*j*) and retailer (*k*), respectively; $i \in I, j \in J, k \in K$
$T_{i,j}$	Transportation costs of products from a supplier (*i*) to a manufacturer (*j*); $i \in I, j \in J$
$T_{j,k}$	Transportation costs of the products from a manufacturer (*j*) to a retailer (*k*); $j \in J, k \in K$
$T_{k,c}$	Transportation cost of the products from a retailer (*k*) to a customer (*c*); $k \in K$, $c \in C$
D_c	The production demand for a customer (*c*); $c \in C$

The objective function for the SC mathematical model is nonlinear because the COQ components are functions in the unknown QL, and they are presented in second-degree equations multiplied by the unknown number of products. The objective function minimizes fixed costs, COQ, product quantity, and transportation costs in the SC and it is presented as follows:

$$\text{Min} \sum_{i\in I}\alpha_i M_i + \sum_{i\in I}\begin{pmatrix} f_{\text{PA}}(x_i) \\ + f_{\text{F}}(x_i) \\ + f_{\text{OC}}(x_i) \end{pmatrix} * M_i + \sum_{i\in I}\sum_{j\in J} O_{i,j} T_{i,j}$$

$$+ \sum_{j\in J}\alpha_j M_j + \sum_{j\in J}\begin{pmatrix} f_{\text{PA}}(y_j) \\ + f_{\text{F}}(y_j) \\ + f_{\text{OC}}(y_j) \end{pmatrix} * M_j + \sum_{j\in J}\sum_{k\in K} P_{j,k} T_{j,k} \qquad (1)$$

$$+ \sum_{k\in K}\alpha_k M_k + \sum_{k\in K}\begin{pmatrix} f_{\text{PA}}(u_k) \\ + f_{\text{F}}(u_k) \\ + f_{\text{OC}}(u_k) \end{pmatrix} * M_k + \sum_{k\in K}\sum_{c\in C} Q_{k,c} T_{k,c}$$

Subject to:

$$\sum_{k\in K} Q_{k,c} = D_c \quad \forall c \qquad (2)$$

$$M_k u_k = \sum_{c\in C} Q_{k,c} \quad \forall k \qquad (3)$$

$$\sum_{j\in J} P_{j,k} = M_k \quad \forall k \qquad (4)$$

$$M_j y_j = \sum_{k\in K} P_{j,k} \quad \forall j \qquad (5)$$

$$\sum_{i\in I} O_{i,j} = M_j \quad \forall j \qquad (6)$$

$$M_i x_i = \sum_{j\in J} O_{i,j} \quad \forall i \qquad (7)$$

$$0 < x_i \le 1,\ 0 < y_j \le 1, \text{and } 0 < u_k \le 1 \qquad (8)$$

$$M_i \ge 0,\quad M_j \ge 0,\ M_k \ge 0, O_{i,j} \ge 0,\ P_{j,k} \ge 0,\ Q_{k,c} \ge 0 \qquad (9)$$

The constraints from (2) to (9) perform the following: Constraint (2) satisfies the customers' demand from the retailers. Constraint (3) ensures that the retailers, good products satisfy the customers demand. Constraint (4) ensures that the manufacturers' good products satisfy the retailer's demand. Constraint (5) is the equality constraint for the supplied good products from manufacturers to retailers. Constraint (6) is the equality constraint for the supplied good products from the supplier to satisfy manufacturers' demand. Constraint (7) is the constraint for the good products from the supplier to satisfy the manufacturers' demand. Constraints (8) are the QL constraint for suppliers, manufacturers, and retailers, respectively. Constraints (9) impose the non-negativity restrictions on the decision variables. The objective function and the constraints are presented to be applicable in a multi-facility SC, however, to conduct the proposed mathematical experiment we provide a descriptive example, in which we consider only one uncapacitated facility in each echelon as shown in Figure 5-3. To obtain one facility in each echelon in the mathematical model we substitute i =1, j =1, and k =1. The model simplification will allow us to find the values of the QL, PA, F, and OC in each echelon and the whole SC. In addition, it will enable us to use the obtained results in the SD model. The transportation costs are neglected from the model as they will not affect the QL decision in the model and also there is only one facility in each echelon.

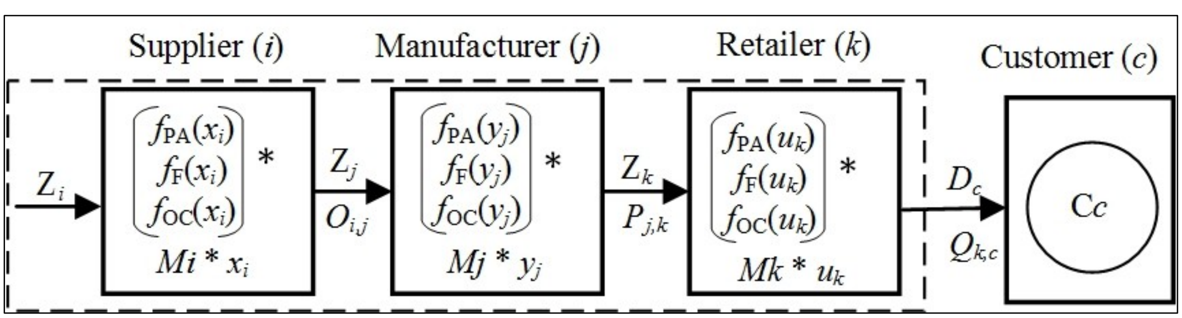


Figure 5-3: Uncapacitated SC mathematical model

5.3.2. SD model (Stage #2)

SD provides the dynamic interaction among different cost factors. Since the manufacturing processes are interrelated and affect one another, PAF and OC should not be treated individually, because any investment in PA costs can change the other F and OC costs. The SD model can also highlight the most influential cost factors to achieve the estimated QL and to increase the customer satisfaction. Thus, a dynamic approach was judged to be adequate to enhance the COQ analysis and to determine the impact of cost factors on the future of the manufacturing processes. The model is based on the SC model is developed by Alglawe et al. (2017). Extensive collaboration with the SC participants was necessary, which assisted us to visualize our model in order to incorporate the COQ at each facility. The SD model integrates three echelons: a supplier, a manufacturer, and a retailer. The model implies that if the number of new customers of each echelon rises, the sales increase and the SC facilities supply the products to each immediate downstream echelon (toward the customers).

The SD model suggests that any investment in PA costs will increase the expected number of the new customers and accordingly it will increase the number of total customers in the SC. However, when the COQ reaches a certain high cost, the products will not attract the customers any more due their increased price and, consequently, the number of new customers will start decreasing. In addition, the number of new customers decreases as the F and OC costs increase. In each echelon, the shape of the COQ functions which are used in the SD model to represent a set of continuous data were formed based on the mathematical equations presented in the mathematical model in Stage #1. These equations also comply with Juran's (1951) COQ model. The model can be simulated using the input variables obtained from the optimized COQ factors of Stage #1. The model is intended to run at different COQ scenarios to provide an overall relationship among the OC, COQ variables, and the number of new customers.

5.3.2.1. SD model development

The developed SD model is run to simulate a single product in manufacturing SC. The SC consists of three uncapacitated facilities, which are one supplier, manufacturer, and retailer. The SD model shown in Figure 5-4 implements the PAF model principles and considers the OC (i.e., COQ = PA + F + OC) at each facility. Material flow is also considered in the model at each uncapacitated facility. Good materials are supplied from the supplier to the manufacturer, where they are equal to the amount of the material available at the supplier's multiplied by the supplier QL. Then the manufacturer provides the materials to the retailer, which are equal to the amount of the material available in the manufacturer multiplied by the manufacturer QL. The retailer provides the products to the customers, what they are equal to the number of the good products produced at the retailer. The total COQ for each product is the aggregate of the COQ at each echelon. The supplier, manufacturer, and retailer use various quality measures and instruments such as in-process inspection, by selecting random samples from each process at specific times. The supplied lots to each echelon should have a QL value, which was obtained from the optimization in Stage #1, to be processed to the next immediate echelon. If there is a problem in QL of the received products, they are returned and compensated by other lots. The rejected parts are then retested and remanufactured at the assigned echelon again.

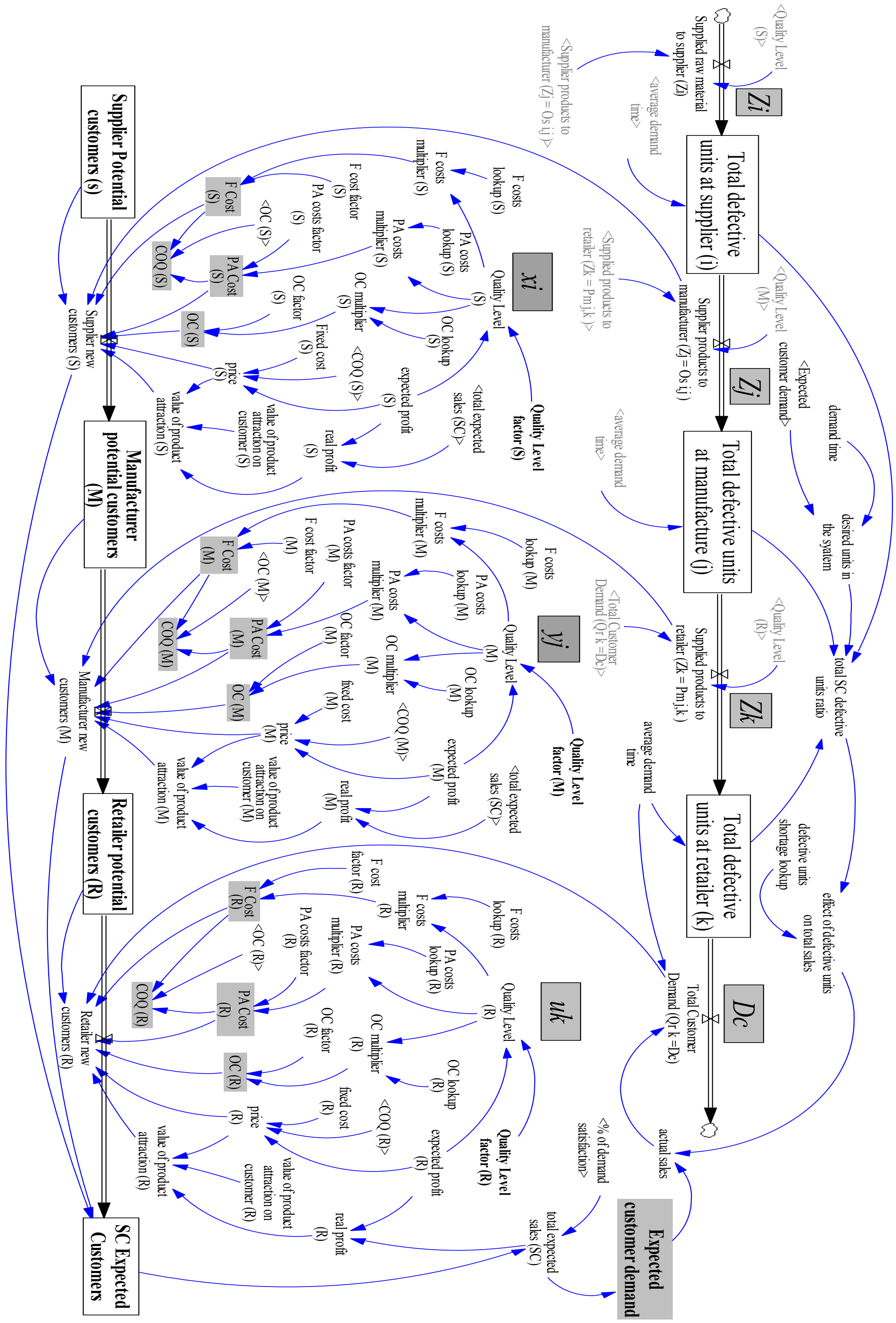


Figure 5-4: SC SD model

5.3.2.2. Casual loop diagram

System Dynamics depends on a causal loop diagram (CLD) to analyze the model and to map simple relationships among the variables. The SD defines the dynamic links among several factors, and it is capable of reflecting the influence of each variable on the other ones at the same time. For the SD, we constructed a CLD to examine the effect of the COQ in the SC. The relationships among the COQ variables and SC entities were generated according to literature organization (Alglawe et al., 2017) and with close interaction with SC as shown in Figure 5-5. Several factors influence the SC new customers, the main positive (+) reinforcement loop shows the increase in the number of new customers increases the following variables: total customers, sales, supplier production, manufacturer production and retailer production.

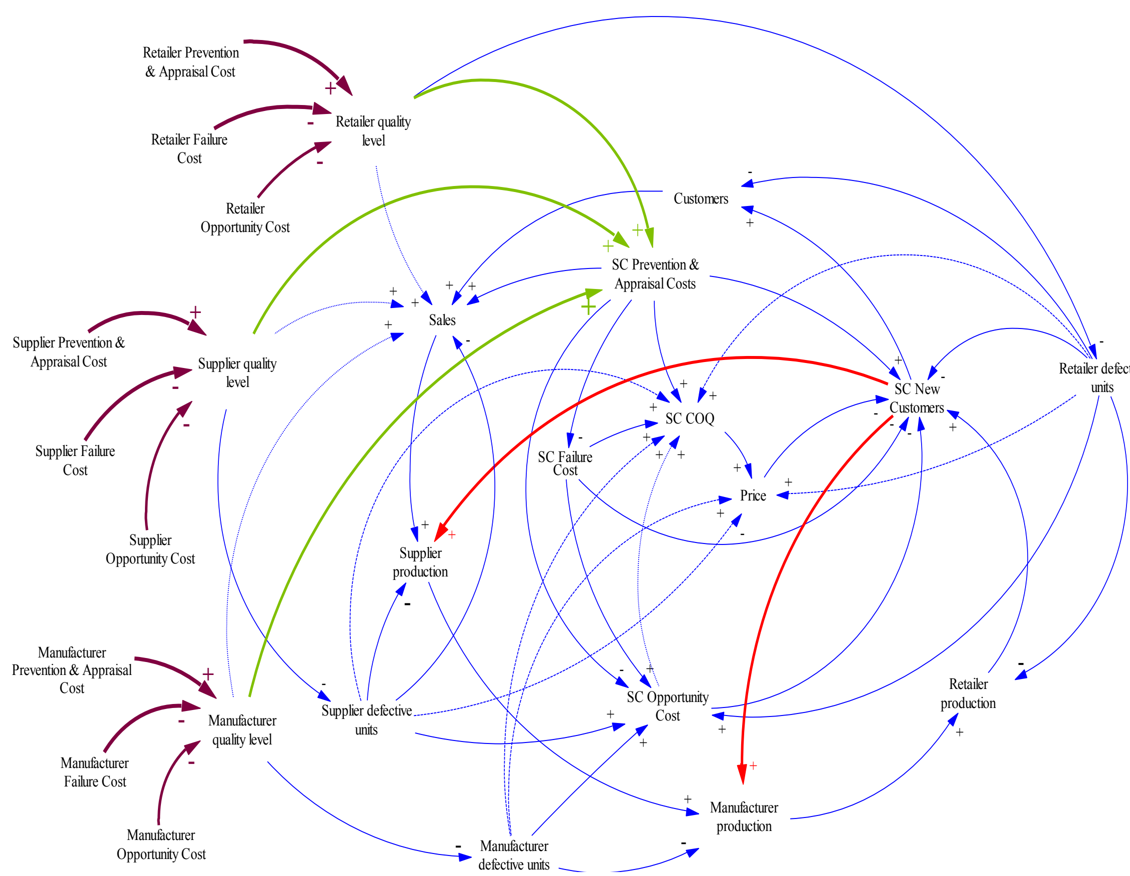


Figure 5-5: SC CLD

On the other hand, there are three cost factors, which have negative (-) impact on the number of new customers, which are the price of the product, SC OC, SC F cost and defective units received from the retailer. Another three factors, which are shown in the CLD have positive (+) effect on QL, are the PA of supplier, manufacturer, and retailer. The PA costs also have a positive influence on the SC COQ. However, PA costs present a negative relationship with F and OC costs in the SC. Similarly, for each echelon, the QL decreases as F and OC increase. Also, the CLD shows a positive (+) relationship among defective units and COQ (due to the increase in F and OC), the price of the products, and SC OC. Conversely, the defective units at each echelon have a negative (-) relationship with new customers, SC customers, and products to be supplied from the previous immediate echelon.

5.3.2.3. SD model validation

There is no general test which can be applied to validate the SD model. Confidence in the SD model builds up gradually as the model passes more tests. Testing of a model can be achieved by comparing the model to a realistic case study, which means the model needs to be tested in different aspects other than numerical statistics to approve or disprove the model (Forrester & Senge, 1996). The structure and behavior of our model were discussed with the quality engineers in the SC for which we collected our data. They accepted the structure of the SD model and assured its suitability for the SC. Furthermore, since the COQ functions were inspired from Juran's (1951) and Alglawe et al. (2017) models, the relationship among the COQ variables were compared with Juran and Alglawe et al.'s models to confirm the behavior of the COQ is well-matched with their model. For Parameter-verification test, we considered the QL factor at each echelon as a constant variable, which affects the SC QL directly, and consequently it influences COQ variables: PA, F, OC and the price of the products. The results of this test were compatible with the real system. According to Forrester and Senge (1996), the parameters of a system dynamic model can be tested and proved against observations of the real system. The structure of the model was thus compared to the real system. Finally, we conducted the extreme conditions test on the model, in which Forrester and Senge (1996) recommend that the structure in an SD model should permit different combinations of the variables at different levels in the represented system. Adding knowledge about extreme conditions will result in an improved model in the normal operating region. In this regard, our SD model was tested against the extreme conditions, which is at the maximum and minimum points. This is done for the model auxiliaries, for example, QLs, which is used in the SD model as the main auxiliary variable to analyze new customers. We found the outputs are equal to zero at the zero "minimum" extreme point. Therefore, extreme conditions test is applicable and suitable for our model.

5.3.3. Mathematical model (Stage #3)

In this stage, the mathematical model is used to increase the number of new customers in the model. After running the simulation, we change the value of the PA in the SD model, and the OC will change accordingly (e.g., increase or decrease) based on the PA cost. At some point, increasing the PA will not increase the number of new customers because the product attractively will diminish due to the increase in the COQ and in the total price of the product. By running the SD model in Stage #2 at different PA costs, we can identify the best point at which we can bring the highest number of new customers at the highest value. Therefore, the model in Stage #3 will increase the spending on PA costs only to the level determined by the SD model. Then we add a PA constraint to the model, which was presented in Stage #1 to raise the QL.

5.4. Results

In the first subsection, we present the results and analyses of the mathematical model, in which we optimized the proposed nonlinear model using Excel Solver (GRG Nonlinear). Afterward, we use the results in the SD model using simulation Vensim.

5.4.1. Mathematical model

5.4.1.1. Mathematical model inputs and assumptions

In our proposed example for stage #1, we use three cost functions and one QL in each echelon. In total, there are nine cost functions and three QLs in the whole mathematical model. The COQ functions of each echelon are presented in Table 5-2. The total COQ functions are quadratic functions, and they are greatly affected by the QL. When the QL is small, the COQ is high and as the QL increases the COQ decrease until a certain point when it starts to increase again. In addition, the QL directly affects the number of supplied components to each echelon (i.e., M_i, M_j & M_k) and the output components from each echelon ($O_{i,j}$, $P_{j,k}$, & $Q_{k,c}$).

Table 5-2: PA, F, and OC cost functions

Supplier	Manufacturer	Retailer
$f_{PA}(x_i) = 0.085e^{6.41x}$	$f_{PA}(y) = 0.18e^{6.01y}$	$f_{PA}(u_k) = 0.27e^{5.69u}$
$f_F(x_i) = 8x^{-2} - 5x - 2$	$f_F(y) = 11y^{-2} - 8y - 3$	$f_F(u_k) = 21u^{-2} - 7u - 14$
$f_{OC}(x_i) = 5x^{-2} - 5x$	$f_{OC}(y_j) = 5y^{-2} - 5y$	$f_{OC}(u_k) = 5u^{-2} - 5u$
$f_{COQ}(x_i) = f_{PA}(x_i) + f_F(x_i) + f_{OC}(x_i)$	$f_{COQ}(y_j) = f_{PA}(y_j) + f_F(y_j) + f_{OC}(y_j)$	$f_{COQ}(u_k) = f_{PA}(u_k) + f_F(u_k) + f_{OC}(u_k)$

The retailer is considered to work at certain QL, for which it spends a certain COQ, which depends on the optimization result. We set the production cost/unit (α_i, α_j, and α_k) at the supplier, manufacturer and retailer to be equal to \$10/unit. The total customer demand (D_c) is 4500 components. We assume that the $f_{OC}(x_i)$, $f_{OC}(y_j)$ and $f_{OC}(u_k)$ functions are identical among the SC entities, however, after the optimization, the OC will be different in each echelon according to the optimum QL. We assume that there is one facility at each echelon in the model to be compatible with the developed SD model and therefore I, J, and K = 1. We used Excel Solver (GRG Nonlinear) to solve the mathematical model. Although the the nonlinearity exists in the objective function and the constraints, Solver, could provide the same solution for different runs. It gives the best solution for the proposed model (Stage #2). According to Ramudhin et al. (2008), the model can be linearized and solved as a linear model using different methodologies, which are available in the literature. Based on the mathematical model, the solution minimizes the COQ functions at each echelon simultaneously. Table 5-3 presents the best (minimum) obtained solution for the following parameters: total PA, F and OC costs at the supplier, manufacturer and retailer, as well as, total PA, F and OC costs for the whole SC, which is the aggregate of PA, F, and OC at the supplier, manufacturer and retailer. In addition, the table provides the total COQ at each facility and the equivalent COQ for the whole SC. Moreover, the QL and material flow into and out of each facility are provided in the table. The objective value of the model is equal to \$850,264.8. In general, the results show that to obtain the best minimum value for the model; the supplier spends the lowest portion of COQ, then manufacturer the medium, and the highest portion of COQ is allocated at the retailer. The retailer spends on PA costs more than what the supplier and manufacturer spend together. The manufacturer and retailer will work at a lower F costs, while the supplier incurs in the highest F costs in the model.

Table 5-3: Optimum results for each scenario in the centralized SC

	Supplier (i)	Manufacturer (j)	Retailer (k)	Total SC	Customer Demand (unit)
PA_i, PA_j & PA_k ($/unit)	15.8	28.8	47.5	92.2	4500
F_i, F_j & F_k ($/unit)	6.0	5.7	5.1	16.8	
OC_i, OC_j & OC_k ($/unit)	3.5	2.8	1.5	7.8	
COQ_i, COQ_j & COQ_k ($/unit)	25.3	37.3	54.2	116.8	
M_i, M_j & M_i (unit)	7209	4870	4959	-----	
x_i, y_j & u_k	0.81	0.84	0.91	-----	
$O_{i,j}$, $P_{j,k}$ & $Q_{k,u}$ (unit)	5870	4959	4500	-----	
Objective Value ($)	850,264.8				

5.4.2. SD model

To run the SD model and to obtain more logical and accurate results, we have constrained our SD model by imposing a set of assumptions on it. These assumptions may, however, limit the external usability of the SD model. The model assumptions are as follows:

1 All supplied parts from the supplier are accepted by the manufacturer.

2 All supplied parts from the manufacturer are accepted by the retailer.

3 All supplied parts from the retailer are accepted by the customers.

4 The initial values of the potential customers are the same for each echelon and redefined.

5 The number of new customers at each echelon depends on the QL of each echelon.

6 The SC products are 100% inspected at each echelon.

After considering the inputs from the mathematical model, which are based on the optimization results, the SD model was run at higher PA values than the PA obtained in the Table 5-3 (i.e., supplier = $15.8/unit, manufacturer = $28.8/unit and retailer = $47.5/unit). The results show that at the supplier, the number of new customers can be increased from around 20 to 44 customer/month (higher by 120%). This happens by increasing the PA from $15.8/unit to about $28.2/unit, after which that the number of new customers decreases as shown in Figure 5-6 (run no. 5). In addition, it is found that the number of manufacturer's new customers can be increased to reach around 54 new customers per month (higher by 32%) by increasing the PA from $28.8/unit to about $35.5/unit.

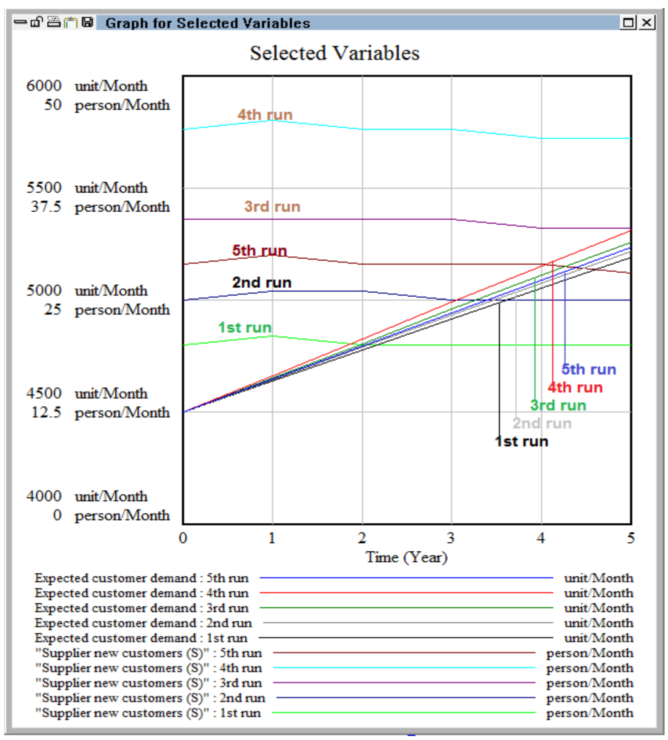


Figure 5-6: The SD model results for the supplier

As shown in Figure 5-7, run no. 5 resulted in less new customers than run no. 4. Finally, in Figure 5-8, run no. 5 was computed with around 92 new customers, which is less than the number of new customers in run no. 4. Therefore the retailer's new customers can be increased from an average of 76 to 114 new customers per month (higher by around 50%) by increasing the PA from \$47.5/unit to about \$54.6/unit. Figure 5-9 shows the overall effect of the five runs of the supplier, manufacturer, and retailer on the expected sales. It is obvious that the expected SC sales decrease as the number of new customers decreases in the SC, which occurred in the fifth run.

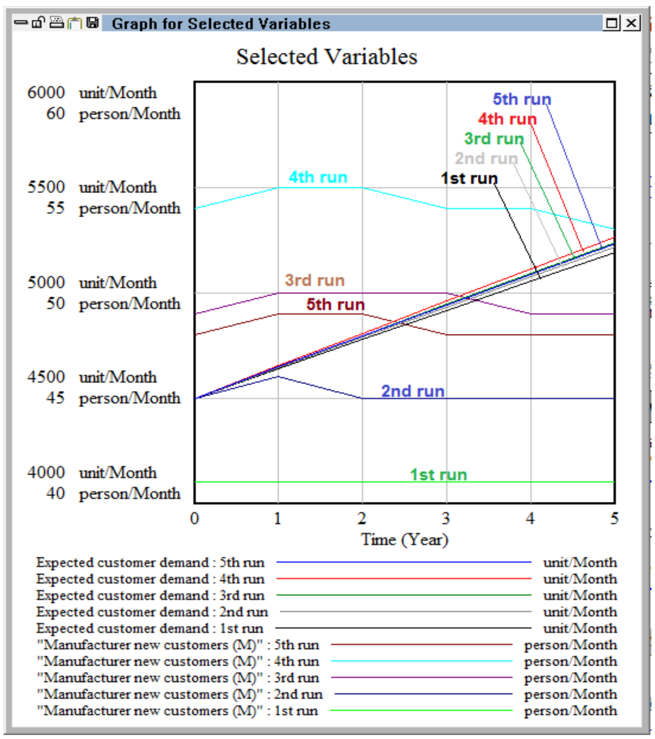


Figure 5-7: The SD model results for the manufacturer

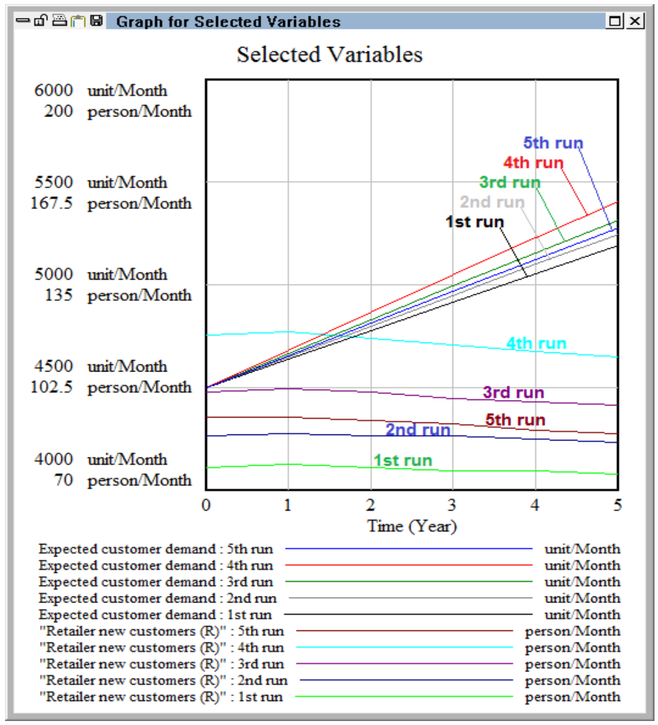


Figure 5-8: The SD model results for the retailer

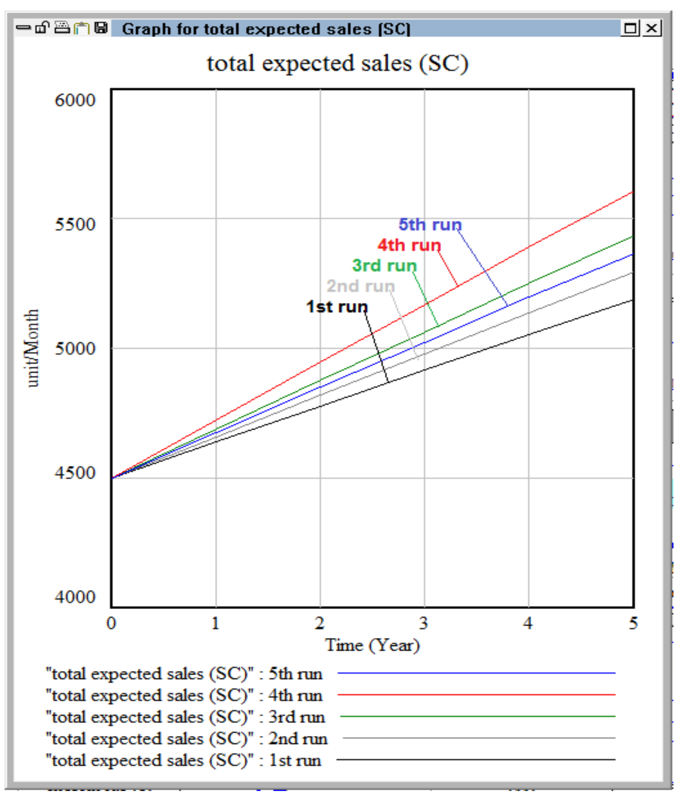


Figure 5-9: The SD model results for the SC expected sales

5.4.3. Mathematical model

After adding the constraint to the supplier only, the constraint becomes $PA_s = SD_s$. For the manufacturer and retailer, the added constraints are $PA_m = SD_m$ and $PA_r = SD_r$, respectively. For the whole SC, the constraint is $PA_s + PA_m + PA_r = SD_{SC}$

Where:

PA_s, PA_m, and PA_r are the Prevention and Appraisal costs for the supplier, manufacturer, and retailer, respectively. SD_s, SD_m, SD_r, and SD_{SC} are the SD values, which resulted in the highest number of new customers for the supplier, manufacturer, retailer, and SC, respectively. Excel Solver (GRG Nonlinear) is also used to solve the mathematical model in this subsection. For the first constraint when $PA_s = SD_s$ = \$28.2/unit, the results are shown in Figure 5-10, in which the QL distribution for the supplier, manufacturer and retailer are 0.90, 0.85 and 0.91, respectively. For the supplier constraint, the results show that the retailer has to work at the same (highest) QL and he should also spend the highest amount of COQ on PA costs for the products. Accordingly, the value of new objective function increased to \$875,098.3.

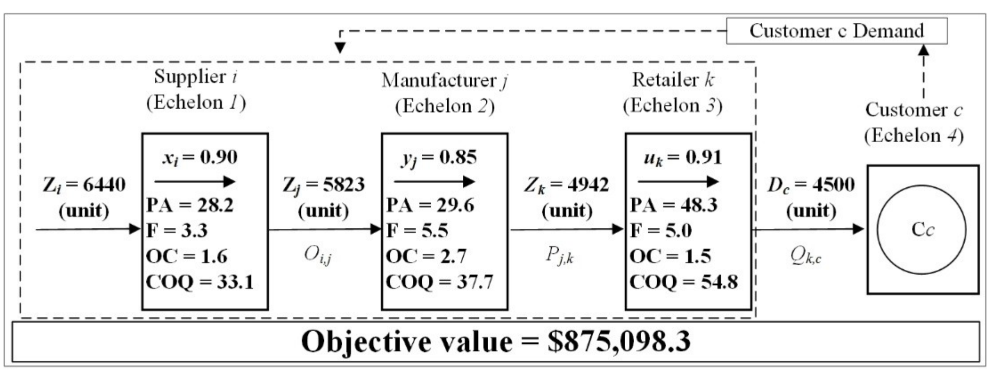


Figure 5-10: PA constraint subject to the supplier

Figure 5-11 shows the results after applied the PA constraint at the manufacturer (PA_m = SD_m = \$35.5/unit), where the QL for the supplier, manufacturer and retailer are 0.81, 0.88 and 0.91 respectively. The retailer still has to work at the highest QL and it should also spend the highest amount of COQ on PA costs for the products. The overall increase in the objective function is lower than what was observed when the PA constraint was applied at the supplier. The increase is only around 2% with the final value of the objective value of \$854,621.5. When we subject the objective function to the PA constraint at the retailer (i.e., PA_r = SD_r = \$54.6/unit), the results show that the QL for the retailer should be 0.93 to satisfy the constraint (see Figure 5-12). The overall increase in the objective value as seen in Figure 5-12 is even less than the increase of the objective function at the supplier or manufacturer cases.

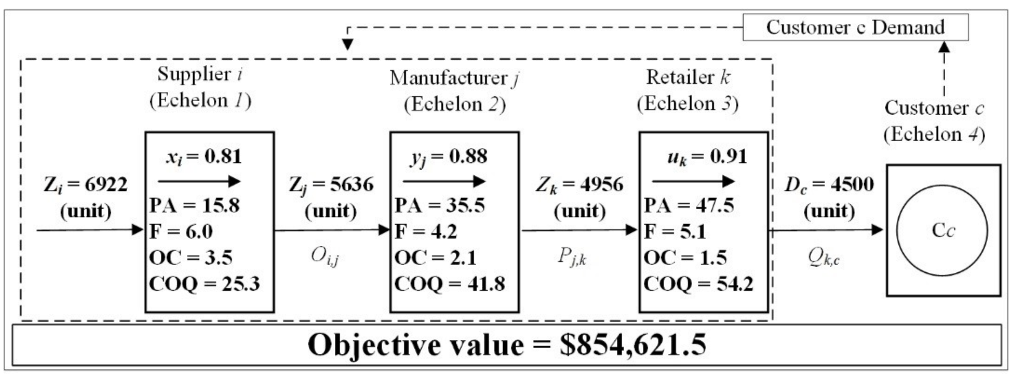


Figure 5-11: PA constraint is applied to the manufacturer

This implies that increasing the number of new customers at the retailer (downstream of the SC) requires lower investment in the COQ. In Figure 5-13, we subject the model to a general SC PA cost constraint. The constraint is the summation of the lowest PA costs of SD, i.e. $PA_s + PA_m + PA_r = SD_{SC}$ = (\$28.2/unit + \$35.5/unit + \$54.6/unit = \$118.25 /unit). This is done to distribute the PA costs freely among the SC entities. According to the results in Figure 5-13, we can notice that the optimization suggests to allocate a high portion of PA costs at the supplier (\$62.9/unit), then the second-highest portion of PA costs at the manufacturer ($36.5/unit) and the smallest portion of PA costs is allocated at the retailer.

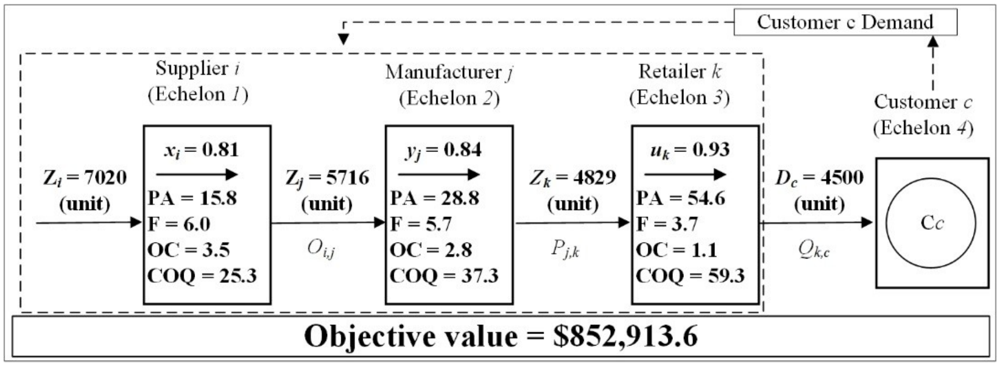


Figure 5-12: PA constraint is applied to the retailer

The optimization results recommend that to allocate the PA costs in a different way than they suggested by SD i.e. by 33% (less), 3% (high), and 15% (high) for the supplier, manufacturer, and retailer, respectively. We conclude that using one methodology is inadequate for our model and integrating the two methodologies (hybrid SC DSS) is beneficial and recommended to improve the decision variables.

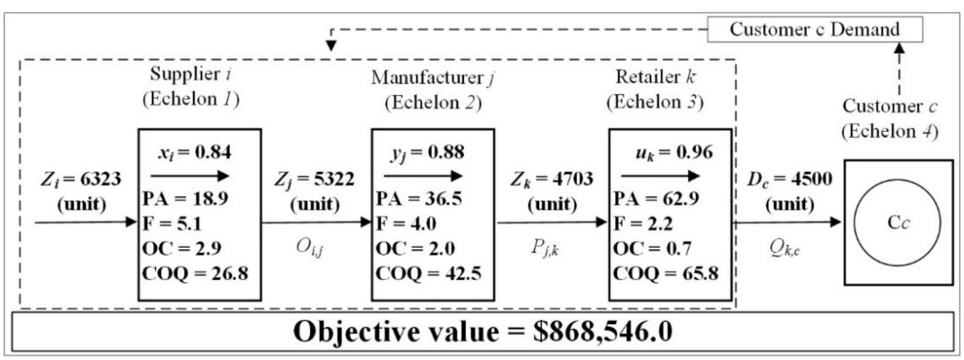


Figure 5-13: PA constraint subject to the whole SC

5.5. Discussion and conclusion

Marketing strategies involve crucial decisions which have a great influence on the successful existence of industries in vibrant competitive markets. Companies need to monitor the behavior of the market carefully and observe the changes every day. They should also deal in a professional and tactical relationship with their competitors. Companies face great challenges in the development of their strategies related to quality of products, price, advertising effort, coordination, warranty, and customer satisfaction policy. To continue competing in the market, companies have to improve their QL (Ab Rahman et al., 2008). COQ has thus become strategic issue for numerous organizations.

In the quality literature, several studies attempt to measure COQ in theory and practice; however, there are only few studies which attempt to measure OC within COQ. Moreover, it is asserted that there are few studies that measure the COQ in the whole SC. In this research, we propose a hybrid model which considers OC and quantifies COQ in the content of the SC, which combining optimization and simulation methodologies. The resulting hybrid DSS will help quality control engineers, decision makers, and top management to control and improve their quality.

According to the results, the optimization could provide the best solution for the mathematical model, which means that the model is suitable for static evaluation (Selvakumar et al., 2015). The results of the proposed mathematical model show that the retailer should spend on PA costs more than what the supplier and manufacturer spend together. As a consequence, the manufacturer and retailer incur lower F costs, while the supplier end up with the highest F costs. However, when it comes to prediction and forecasting, dynamic perspective is necessary (Tigist, 2015).

Therefore, an SD model is developed to provide the forecast effect of simulating the COQ parameters in the proposed model. The proposed SD model, which simulated PA costs for the decentralized SC entities, uses higher PAs values than the values of the optimization results. The simulation results for the supplier show that the number of new customers can be doubled by increasing the PA costs. In addition, by increasing PA costs at the manufacturer, the number of new customers increases by almost one-third higher when compared to the results of the optimum (best) situation for the new customers. Finally, with a slight increase in PA costs at the retailer, the number of new customers can be increased by almost a half (comparing to the results from the mathematical model).

In general, simulation results show that when PA costs increase, the number of new customers increases at the SC echelons. However, after a certain value any increase in PA costs will raise the COQ and thus the price of the product. As a result, the attraction of the customer diminishes and the number of new customers, therefore, decreases. The results of implementing the DSS are in line with the findings of Khataie et al. (2011), who stated that the DSS leads to the improvement of business decisions due to the updated information.

5.6. Summary and conclusion

This paper introduces a modeling methodology which integrates a mathematical model and a System Dynamics model in order to develop a hybrid COQ Decision Support System (DSS) for the supply chain strategic management. The developed DSS aims to assist the SC upper management in monitoring, to analyze, organizing, and to forecast the consequences of the decision-making and to monitor their business effectively.

In the first stage of the hybrid DSS of the SC, we developed a COQ mathematical model based on PAF traditional approach while incorporating OC. The mathematical model minimizes the COQ model and provides the best solution for the decision variables such as PA, F, OC, QL, and materials flow, which are needed for each facility to satisfy the customer demand. In the second stage, the obtained decision variables of the mathematical model were used as inputs to the SD model. The developed SD simulation model is run many times at different PA costs to provide results for the best spending on PA costs, which can gain the highest number of new customers. Another optimization process is implemented as a third stage of the hybrid DSS. It considers the PA costs, which were obtained at the second stage as a constraint that increases the PA costs in the model. The last stage combines the results from the optimization and the SD stages.

The increase in PA costs leads to the gain of new customers at each echelon of the SC. According to the results, if the supplier, manufacturer, and retailer increased the PA costs by 78%, 23% and 15%, respectively the number of new customers will increase by around 120%, 32% and 50%, respectively.

The proposed hybrid DSS model can be implemented to investigate and examine the COQ by running the sensitivity analysis among the PA, F, OC, QL and the number of products in the SC and forecast the further expenditures and demands. While the findings of our study are based on a model involving a three-echelon single facility SC, it is worth noting that the outcomes can be generalized, because the proposed hybrid DSS methodology is not merely designed for small enterprises and can be applied by different organizations regardless of their sizes.

This work can be extended to be implemented in a capacitated SC, which could have more than one facility at each echelon. The difficulty of such a problem would necessitate formulating a methodology that uses metaheuristics such as genetic algorithms. In addition, the SD model which encompasses the mathematical model needs to be developed.

Chapter 6 - Conclusion and Future Research

6.1. Conclusion Remarks

Cost of Quality (COQ) is increasingly becoming a crucial aspect of manufacturing and research area, not only to manage the quality systems but also to understand its impact on customer satisfaction. The COQ is considered as a good indicator to show the cost of a given Quality Level (QL) for an organization. Reducing the quality costs while maintaining good QL allows decreasing of total organizational costs. This could result in reducing the price of manufactured goods, enhancement of customer's satisfaction, improvement of organization's performance and boosting of its revenue.

The cost of satisfying a customer can be considered as a hidden quality cost that is challenging to measure and trace. A failure to properly measure the loss of unsatisfied customers is a crucial issue, which may affect an organization's position in the market. Therefore the cost of not satisfying a customer is an opportunity cost (OC) that needs to be included in the organizations (quality management systems). While measuring the COQ in individual companies has gained much interest in the literature, only a few research had considered integrating it in the strategic level design of a Supply Chain Network (SCN). No work has been done so far to integrate the fundamental concept of COQ and OC as a function of a given QL into the design decisions of SC. This dissertation addresses the incorporation of OC into the COQ in a manufacturing SC and supply chain network design (SCND).

In order to integrate the COQ factors in SCND and understand its impact, system dynamics and mathematical modeling have been used as decision making methods. Based on the assumption that the relations among the COQ factors for a given QL are nonlinear, constructing a causal loop diagram (CLD) allows to explain the relationships among the COQ parameters. Afterwards, the simulation (system dynamics) model is constructed and run at different QL values. The system dynamics (SD) enables defining the nonlinear relationship among the PA, F, OC, and QL as well as their influence on the number of new customers in the SC.

Given a manufacturing SC structure, COQ data, and customer’s satisfaction analysis, we developed a simulation model for an uncapacitated SC. The data is mainly collected from the operation, quality, sales, and customer service departments of the SC. To capture the customer satisfaction cost (i.e., OC), we distributed a survey targeting the SC customers and customers of competitive organizations. OC related to customer’s goodwill is calculated based on quality deployment planning matrix function, which was used in the literature to measure the loss of unsatisfied customers. We measured the cost of OC in SC referring it to monetary value and incorporate it to the proposed COQ model. To generalize the COQ in the proposed methodologies, we considered PAF model. Complying with Juran’s (1951) model, our proposed COQ model implies that any investment in the PA costs reduces the OC and F costs. The COQ elements were denoted by cost functions in the simulation.

Next, we developed a mathematical that incorporates the COQ within SC as a function of the unknown QL. The nonlinear mathematical model is used to minimize the COQ in a single-echelon SC, in which the model considered the PA, F, OC, and QL at the SC facilities. Furthermore, the mathematical model was expanded to illustrate the usage of COQ in SC facilities selection, i.e., SCND problem. The relationship among the PA, F, OC, and QL for the proposed SCND model were identified by conducting sensitivity analysis.

For the mathematical methodology, we developed an uncapacitated and capacitated SC models. The objective function for the models minimizes the facility fixed costs, COQ, material flow and transportation costs in the SC and SCND. Using the COQ elements in the form of cost functions enabled us to draw general conclusions among the COQ elements at different quality levels. In addition, the advantage of using the COQ functions is that they can be altered to characterize a given COQ of another SC. Moreover, the COQ functions can be represented or exchanged with sets of COQ data of other SCs.

Using the benefits of representing nonlinear relationships, causal loops of SD and the optimization approach in SCND, a hybrid Decision Support System (DSS) is developed. The proposed DSS consists of three main stages: in the first stage, DSS uses a mathematical model to minimize the COQ in the SC. Then, an SD model is developed to analyze the PA, F, OC and QL with the number of customers. In the final stage, the mathematical model is reused again to minimize the COQ with more constraints on PA costs based on the results obtained from SD.

The results of the Chapters 2-5 clearly presented the relationship among the PA, F, OC, and QL. According to the SD model presented in Chapter 2, it was found that the incorporation of the OC to the COQ model would lead to a decrease in the number of new customers. Similarly, the amount of production units running in both supplier and manufacturer systems decreases. However, in order to reach the original expected number of customers and to satisfy the targeted production quantity in the SC, a small investment in the QL is recommended. As a result, any investment in the PA costs decreases the OC and F costs. In the simulation, the value of the OC was found to be close to threshold zone of the investment. We concluded that when the spending on the COQ is exceeds 80% of QL, the COQ will be costly and it will attract few customers.

However, the results implied that the COQ is affected by the selected curvature of PA, OC, and F cost function.

For designing the SC based on the COQ, the results of the Chapter 3 presented the best scenario among different available scenarios. This scenario resulted the minimum (best) COQ in the SC model. To satisfy the customer demand in the best scenario, the results shwo that allocating the highest, medium, and the smallest amount of the COQ at the supplier, manufacturer, and retailer echelons, respectively results in the minimum spending on COQ. These results were found to be applicable for the centralized and decentralized SC. However, more importantly, the minimum COQ in the centralized SC is less than the COQ in the decentralized SC. This implies that the the centralized SC outperforms the decentralized in presenting high QL at lower COQ. In addition, the chapter provides how the spending limitations on PA could affect the decisions, including the relationships among the PA, F, OC, and QL and with objective values. It is found that a slight reduction on PA expenditure will slightly increase the objective function and QL.

Although the mathematical model which presented in Chapter 4 is more difficult to solve than that of Chapter 3, it could provide an insightful results for PA, F and QL with and without OC. The model in Chapter 4, which is a Mixed Integer Nonlinear Programming (MINLP) model, enabled us to construct the SC network based on the COQ and QL. As a result of incorporating the OC into the COQ model, the SC network slightly changes with the increase of the QL and the objective value. According to the results, it is recommended to allocate the investment at the retailers' echelon because it improves the average QL of the SC at the smallest investment cost compared to the allocation of PA at the suppliers or manufactures echelons. In this chapter, the findings also revealed that as the transportation costs is increased, the average COQ of SC also increases, which imposes to increase the average QL of SC for each echelon. Consequently, we observe that the number of products in the SC is reduced as the transportation cost increases, indicating that the model tends to reduce the transportation of defected products by increasing the QL.

By combining the two methodologies of Chapters 2-4 (i.e. system dynamics and mathematical modeling), in Chapter 5, we developed a hybrid DSS to obtain the advantages of the two methodologies. In the first stage, DSS uses a mathematical model to minimize the COQ in the SC. The results of this stage showed that to obtain the best minimum objective value in the model; the supplier spends the lowest portion of COQ, then manufacturer the medium, and the highest portion of COQ is allocated at the retailer. As a consequence, the manufacturer and retailer result a lower F costs, while the supplier incurs in the highest F costs in the model. In the second stage i.e., SD model, the results demonstrated that when the PA costs of the SC increase, the number of new customers will increase until it attains a certain value at each facility. It is followed by investing in PA costs, which will increase the COQ and the price of the product. In the final stage, the mathematical model is reused again to minimize the COQ with more constraints on PA costs based on the results obtained from SD.For the supplier constraint, the results show that the retailer has to work at the same (highest) QL and it should also spend the highest amount of COQ on PA costs for the products. The retailer still has to work at the highest QL and it should also spend the highest amount of COQ on PA costs for the products. The optimization results presented different results than they suggested by, and therefore, we conclude that using the two methodologies (hybrid SC DSS) is beneficial and recommended to improve the decision variables.

6.2. Future Research

Immediate extensions of this thesis can be considered around the following directions:

6.2.1. Increasing the cost functions in the model

Further research could decompose the COQ into more parameters (different costs functions), which can be disintegrated with SC costing activities either visible or invisible costs, for example, auditing, testing, designing and downtime costs. Modeling and optimizing different costs functions can provide more in-depth COQ analysis. In addition, further research could address a multi-product sourcing with different COQ and QL. Studying the COQ of different products may help in better analyses of the overall COQ and could reduce the OC.

6.2.2. Developing efficient solution approaches

In this dissertation, excel solver has been used to solve the proposed nonlinear mathematical models, which presented the minimum (best) solution for our models. However, it is advisable to propose some approaches to find an exact solution within a reasonable computational such as by linearizing the model. In addition, excel solver will not be suitable to solve large volume (facilities) of functional problem. To this purpose, the use of metaheuristic methods is recommended.

6.2.3. Adding inventory costs to the models

Inventory is a crucial parameter in SC network design. It is integrated with many SC models in the literature. Inventory related costs are important in providing the products to the customer at the right time and it may have a reflection on their satisfaction and OC. Thus, future work could address the possibilities of adding inventory related costs and studying the issues of articulating an empirical formula which describes the relationship between COQ (i.e. PAF + OC) and inventory related costs. The work may also study the effect of inventory deficiencies on increasing or decreasing COQ and QL.

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