AN OPTIMUM CLOSED LOOP SUPPLY CHAIN NETWORK MODEL IN A STOCHASTIC PRODUCT LIFE CYCLE CONTEXT

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Especially dedicated to my beloved family

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ABSTRACT

Nowadays, closed loop supply chain network (CLSCN) receives considerable attention due to the growing awareness of the environmental destruction and depletion of natural resources. The establishment of a CLSCN is considered as a strategic decision that requires a lot of effort and intensive capital resources. Therefore, it is very crucial to make CLSCN design decisions taking into account multiple facets of uncertainties. Literature reviews to date reveals that uncertainties in product life cycle (PLC) or what has been called "product diffusion" have been vastly ignored. Particularly, the deterministic nature of the proposed diffusion models is a severe defect that can hinder the involvement of real-world uncertainties in design of a CLSCN. This study is an attempt to fill this gap by developing a cost-efficient CLSCN model for a product with dynamic and stochastic diffusion into the market that leads to an optimum design of the targeted CLSCN. Firstly, a geometric Brownian motion (GBM)-based diffusion forecast method was proposed and validated using a conventional approach namely, Holt's method. Then, a two-stage stochastic programming mathematical model for optimum design of the targeted CLSCN was developed. The developed stochastic CLSCN model provides the optimum design of the targeted CLSCN utilizing the values predicted for the product diffusion through the PLC based on the proposed forecast method. The developed mathematical model addresses two types of decisions namely, "here and now" and "wait and see" decisions within the PLC. The "here and now" decisions were made in the first stage. The results show optimum values for decisions concerning configuration of the CLSCN as well as dynamic capacity allocation and expansion decisions through the PLC. However, the "wait and see" decisions are made in the second stage within the frame provided by the first-stage solutions. Here, the results portray optimum values for decisions concerning with the flow quantities between the CLSCN facilities, backorder and inventory levels, and recovery of returns through the PLC. In order to test the applicability of the developed CLSCN model, the mathematical model was coded by CPLEX software and solved for secondary data from the case study from previous case study in literature. Finally, a sensitivity analysis was performed to investigate the effect of diffusion uncertainty on the total cost of the CLSCN, its configuration, and production capacity allocations and expansions. The results of the sensitivity analysis revealed that, for the higher levels of diffusion uncertainty, the total cost imposed to the supply chain increases due to the increase in the allocated production capacity as well as the increase in the number of involved facilities.

ABSTRAK

Pada masa kini, rangkaian rantaian bekalan gelung tertutup (CLSCN) menerima perhatian yang besar disebabkan oleh kesedaran yang semakin meningkat mengenai kemusnahan alam sekitar dan kesusutan sumber semula jadi. Penubuhan CLSCN dianggap sebagai keputusan strategik yang memerlukan banyak usaha dan sumber-sumber modal intensif. Oleh itu, ia adalah sangat penting untuk membuat keputusan-keputusan reka bentuk CLSCN yang mengambilkira pelbagai aspek yang tidak menentu. Kajian kesusasteraan dalam bidang CLSCNs setakat ini mendedahkan bahawa ketidakpastian dalam kitaran hayat produk (PLC) atau apa yang dipanggil sebagai "produk penyebaran" adalah terhad dan telah jauh diabaikan. Khususnya, jenis berketentuan model penyebaran dicadangkan dalam kesusasteraan ialah suatu kecacatan yang teruk yang boleh menghalang penglibatan dunia sebenar yang tidak menentu dalam reka bentuk CLSCN. Kajian ini merupakan satu percubaan untuk mengisi jurang ini dengan membangunkan sebuah CLSCN yang menjimatkan kos bagi produk dengan penyebaran yang dinamik dan stokastik ke dalam pasaran yang akan membawa kepada rekabentuk-rekabentuk yang lebih cekap daripada CLSCN yang disasarkan. Pertama sekali, kaedah ramalan penyebaran berasaskan geometri Brownian (GBM) telah dicadangkan dan disahkan dengan menggunakan kaedah unjuran yang konvensional, iaitu kaedah Holt. Kemudian, satu model matematik pengaturcaraan stokastik dua peringkat untuk reka bentuk optimum CLSCN yang disasarkan telah dibangunkan. Model stokastik CLSCN yang dibangunkan menyediakan reka bentuk optimum bagi CLSCN sasaran menggunakan nilai yang diramalkan untuk penyebaran produk melalui PLC berdasarkan kepada kaedah unjuran yang dicadangkan. Model matematik yang dibangunkan menangani dua jenis keputusan iaitu keputusan "di sini dan kini" dan "tunggu dan lihat" dalam PLC. Keputusan "di sini dan kini" dibuat pada peringkat pertama. Hasil menunjukkan nilai yang optimum bagi keputusan-keputusan yang berkaitan dengan konfigurasi CLSCN serta peruntukan kapasiti yang dinamik dan keputusan pengembangan melalui PLC. Walau bagaimanapun, jenis keputusan "tunggu dan lihat" dibuat di peringkat kedua dalam kerangka yang disediakan oleh peringkat pertama. Di sini penyelesaian menunjukkan nilai-nilai yang optimum hasil keputusan berkenaan dengan aliran kuantiti antara CLSCN kemudahan, tahap pesanan lewat dan inventori dan pemprosesan semula pulangan melalui PLC. Untuk menguji kesesuaian model matematik CLSCN yang dibangunkan ini ia juga telah dikodkan dalam perisian CPLEX dan diselesaikan menggunakan data sekunder daripada kajian terdahulu daripada literatur. Akhir sekali, analisis sensitiviti telah dijalankan untuk mengkaji kesan penyebaran ketidakpastian ke atas jumlah kos CLSCN, konfigurasi CLSCN, dan peruntukan kapasiti pengeluaran dan pengembangan. Keputusan analisis sensitiviti mendedahkan bahawa, lebih tinggi tahap ketidakpastian penyebaran, jumlah kos yang dikenakan ke atas rantaian bekalan akan meningkat disebabkan oleh peningkatan dalam kapasiti pengeluaran yang diperuntukkan dan juga pertambahan bilangan kemudahan yang terlibat.

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter imparts basic information concerning the present study. To this end, first a background of the research is presented. Then, the problem of the research is raised based on observed deficiencies in the relevant literature. Once the research problem is clarified, objectives of the study are defined. The objectives address the research problem and bridge the existing gaps in the literature. The chapter also discusses scope of the research within which the research is performed. Furthermore, significance of the research is discussed in detail. Finally, research questions which are expected to be addressed by the end of this study are presented.

1.2 Background of the Research

A well-designed supply chain network (SCN) is an influential strategy that enables organizations to be competitive in business sphere (Chopra and Meindl, 2007; Fallah *et al.*, 2015). In recent century, environmentalism and sustainability raise critical global issues (Talaei *et al.*, 2015). Sustainable supply chain network (SSCN) is sometimes referred as a “closed-loop” supply chain network (CLSCN) (Liu *et al.*, 2012). Nowadays, CLSCN receives considerable attention owning to the growing awareness to the environmental destruction and depletion of natural resources (*Gao et al.*, 2015). Asl-najafi *et al.* (2015) states closed loop supply chain is a green supply chain through introducing the recovery of products into design of SCN.

A CLSCN consists of various firms which are working together to bolster a dynamic and blooming economy through reduction or avoidance of waste from the initial phases to the end of life (EoL) stages of products (Winkler, 2011). A CLSCN includes both forward and reverse chains (Gu and Gao, 2012) through which products are taken back to the original and traditional forward chain for adding values and making more profits (Khatami *et al.*, 2015). Therefore, the members of a CLSCN are divided to those firms belonging to the traditional supply chain, and those that handle recovery activities such as remanufacturing, reuse, recycling, disposal, and incineration centers (Winkle, 2011).

A CLSCN significantly contributes to mitigating the environmental and economic impacts of wastes and to do so some regulations were issued for some certain products (Tucker, 2010). In the European Union, some regulations associated with collecting and recycling of the electrical and electronic equipment wastes (WEEE) have been considered compulsory since 2003 (Govindan *et al.*, 2014). The growing number of legislations in the area of producer duty, take-back obligations, establishment of collecting and recycling systems (e.g., WEEE and end-of life vehicles) (Talaei *et al.*, 2015) accompanied by the economic value of recovery activities convince the decision makers to expand the scope of supply chains by drawing attention to the reverse chains (Özkır and Başlıgil, 2012). Particularly, CLSCNs flourish for those companies with relatively high recoverable values. Examples of this type of companies can be found in automotive and electronics industries including Kodak and Xerox remanufacture used cameras and toner cartridges respectively (Easwaran and Üster, 2010) . Moreover, Dell, HP, and General Motors corporations are pioneers in conducting recovery activities (Qiang *et al.*, 2013) and they enjoy considerable success (Üster *et al*., 2007). In general, three factors of regulatory, competitive, and economic pressures are frequently mentioned in the extant literature as the most significant motives for the implementation of CLSCNs.

Furthermore, the establishment of a CLSCN is considered as a strategic decision that requires a lot of effort and intensive capital resources (Chopra and Meindl, 2007). Supply chain network design entails a huge amount of investment and once the decisions are made, they remain for a long time and are not likely to be altered due to the significant cost of alteration that may be imposed to the system. However, for a relatively long time period, situation does not remain intact and supply chain may undergo massive changes including fluctuations in demand, price, and competitive environment, etc. (Chopra and Meindl, 2007). As a result, the configuration of network that is optimal under the current circumstances may not be potent under a new business environment and situation. In this regard, it is very crucial to make CLSCN design decisions with an eye to multiple facets of uncertainties.

Reviewing the literature in the area of CLSCNs reveals that in spite of huge body of literature on modelling CLSCNs in uncertain environment, uncertainties in the product life cycle (PLC) or what has been called "product diffusion into the market" has not received enough attention. In other words, although in the separate areas of "product diffusion" and "CLSCN" design efforts have been made to address uncertainty (Qin and Nembhard, 2010; Gupta and Palsule-Desai, 2011; Qin and Nembhard, 2012; Scitovski and Meler, 2002; Rastogi *et al.*, 2011; Almansoori and Shah, 2012; Rodriguez *et al*, 2014), the effect of "uncertain product diffusion" on design of the developed CLSCN models have been vastly ignored.

According to Scitovski and Meler (2002), diffusion is defined as the process through which an innovation is accepted by the market. Since the introduction of the Bass model in 1969, it has been applied for diffusion in many areas including industrial technologies, retail services, agriculture, education, pharmaceuticals, and consumer durable goods markets (Mahajan *et al.*, 1990) . The theory of diffusion shapes a scientific basis for studying the PLC phenomenon. The focus of many developed diffusion models is on the development and evolution of the associated PLC curve (Mahajan *et al.*, 1990). However, the deterministic nature of proposed diffusion models in the literature is a severe defect that can hinder involving uncertainties of demand growth in developing marketing strategies and strategic plans (Martínez-Costa *et al*., 2014). Although few studies have been conducted in response to modeling uncertain product diffusion into the market (e.g., Qin and Nembhard, 2010; Gupta and Palsule-Desai, 2011; Qin and Nembhard, 2012; Scitovski and Meler, 2002), the application of these diffusion models in designing supply chain networks has been ignored by the scholars. Instead, uncertainties in demand have been addressed by constructing stochastic mathematical models (e.g., Almansoori and Shah, 2012; Pan and Nagi, 2010; Rastogi *et al.*, 2011; Rodriguez *et al.*, 2014) in which the connections between CLSCN design and diffusion theories are ignored. In other words, the existent diffusion theories by which the speed of growth in a product demand is predicted are not reflected in design of the developed CLSCN models. The present study is a determined attempt to bridge this gap and establish a connection between marketing efforts and CLSC network planning problems. The next section provides more detailed account with respect to the disconnection between the two aforementioned areas.

1.3 Statement of the Problem

Closed-loop supply chains (CLSCs) are perceived as an extension of old supply chains' structures that accounts for the return of used products (Gomes et al., 2011). A major problem in developing a CLSCN can be referred to a plethora of variables and parameters that should be included in the process of designing the desired network. The situation significantly exacerbates when it comes to the planning for real-world cases with the uncertainties involved. In other words, the development of a CLSCN model with respect to real-world uncertainties requires significantly more computational efforts as it involves a higher number of decision variables and input parameters. Reviewing the literature in this area reveals that to avoid the complexity in computational aspects, most of the developed stochastic CLSCN models have been designed to address small-scale stochastic problems that put forward solutions to specific and limited number of scenarios for environmental uncertainties (Lin and Wu, 2014, Sazvar et al., 2014, Ramezani et al., 2013, Zeballos et al., 2013). Particularly, uncertainty in customers demand has been the most common concern for the scholars in this area (Lin and Wu, 2014; Sazvar et al., 2014; Ramezani et al., 2013). However, there is a drawback in the way of representing demand uncertainties in the previously conducted literature. In general, two representations of uncertainty are dominated in the literature. The first one deals with some limited discrete scenarios as representative of possible events of future demand (Lin and Wu, 2014; Sazvar et al., 2014) and in the second one uncertainty in demand is addressed through assigning a probability distribution function with constant mean and variance through the considered time horizon (Oliveira et al., 2014b). However, in both of the representations mentioned above, the growth curve of demand or what is called "product diffusion" time series has been neglected. In other words, due to the constant growth of demand considered for the entire time horizon, the aforementioned approaches fail to respond to dynamic growth of demand as time elapses through the product life cycle (PLC) in developing stochastic CLSCN models and stochasticity in demand growth is neglected. However, understanding growth curve of demand in a stochastic situation provides more accurate forecast of the product penetration in the market and consequently offers more realistic view of required resources in the future. Having provided such realistic view helps to meet customer demand more efficiently and enhances supply chain responsiveness. The focus on demand growth curve and dynamic growth speed of demand led the researcher to apply "stochastic product diffusion" models as they account for dynamic growth of demand as well as stochasticity of demand during the PLC.

As pointed by Wright and Charlett (1995), a key element of a diffusion process is "time". Diffusion models issue a forecast of the dynamic growth speed and predict the potential market penetration of products. In many industries, growth speed of demand is uncertain and a deterministic assumption can lead to setting inaccurate marketing policies and strategic planning (Tseng and Hu, 2009). In addition, a variable representing the product diffusion has several dimensions that each represents market penetration in the corresponding time period (Mahajan et al., 1990). Involvement of such multi-dimensional diffusion variables in a CLSCN model increases the complexity of the model. Consequently, pursuing appropriate approaches is required to pinpoint and rectify such a complex stochastic CLSCN problem.

To be more specific, the lack of CLSCN models that account for both dynamic and stochastic growth curve of demand can be referred as the main deficiency in the extant literature which is to be addressed by this study. In this respect, an appropriate method should be applied in order to forecast the extent to which the product penetrates to the market when dealing with a stochastic PLC. However, the available methods such as those suggested by Goodwin et al. (2014) and Lee et al. (2014) can only respond to deterministic environments and do not address diffusion forecasting issues in dynamic and stochastic situations. Therefore, to put it in a nutshell two main gaps in the literature are to be addressed by this study as follows:

i. Existing disconnection between diffusion theories and CLSCN design
ii. Lack of diffusion forecast methods that account for dynamic and stochastic demand growth during the PLC

This study is intended to shed light on the aforementioned gaps through defining some research objectives as presented in the following section.

1.4 Research Objectives

This study pursues the following objectives:

i. To propose a forecast method by which the product diffusion/ PLC uncertainties can be reflected in the design of the targeted CLSCN.
ii. To develop a mathematical model for the optimum design of a cost efficient CLSCN in the context of the uncertain product life cycle (PLC).
iii. To validate the constructed mathematical CLSCN model.

1.5 Scope of the Research

i. The focus of this research is on the semiconductor industry due to the inherent uncertainties in diffusion of this type of products into the market.
ii. The research region of this study entails suppliers, manufacturers, distribution centers (DCs), collection/recovery facilities, and customers in an integrated closed loop supply chain network.
iii. The mathematical model is constructed based on a multi-echelon, single product, multi-period, and capacitated integrated forward/reverse logistics network.
iv. The results encompass tactical and operational decisions for a time horizon equal to the length of the PLC. The strategic decisions such as facility location, capacity allocation, and expansions are made with respect to the future uncertainties. Operational decisions to be made include supplier selection, flow between forward and reverse chains' nodes, and aggregate production planning related decisions. The operational decisions are made within the frame defined by strategic decisions.
v. Two state of the art software i.e. MATLAB (R2015b) and CPLEX (12.4) are run in order to code the problems and arrive at the optimum solution to the constructed CLSCN model.

1.6 Research Questions

In order to achieve the objective of this study, the following questions are established:

i. Is there any available mathematical model in the literature that can provide diffusion pattern for the semiconductor industry?
ii. How to utilize the available diffusion model in forecast method?

iii. What type of input parameters, decision variables and constraints should be considered when developing the mathematical CLSCN model?
iv. How to incorporate the uncertainties in the product diffusion into the process of designing a CLSCN?
v. How to validate the developed CLSCN model?

1.7 Significance of the Study

This study is significant for the sustainability aspects it suggests. A sustainable supply chain network significantly enhances competitive advantages of the involved organizations. Two crucial aspects of sustainability, i.e. cutting total cost as well as reducing environmental devastation (by minimizing product waste and recovery of used products) are dealt with by adopting the CLSCN model proposed by this research. Furthermore, to the best of researcher’s knowledge, scant research has been carried out in the area of CLSCN design that forges a link between marketing and SCN design areas by utilizing stochastic diffusion models by which the uncertainty in demand growth is emphasized. As constructing a CLSCN involves many key strategic decisions such as facility location, capacity allocation, and expansion, incorporating diffusion uncertainties in constructing the CLSCN can help preventing extra costs in the future. The aforementioned extra costs may impose a burden on the supply chain due to ignorance, wrong, or inaccurate assumptions about dynamic and stochastic growth of demand in the future.

1.8 Structure of the Thesis

This study has divided into seven chapters. Chapter 1 features an illustrative introduction to the research. In Chapter 2, a comprehensive review on the previously performed literature is provided while the main focus in reviewing the literature is on CLSCN design and product diffusion areas. Chapter 3 depicts the methodology followed in this research and describes all the steps to be taken in conducting this research including steps in proposing forecast method as well as those associated with developing and solving the mathematical CLSCN model. Furthermore, Chapter 3 provides some explanation on data collection phase. Details regarding to development of the targeted CLSCN model is presented in Chapter 4 through which the proposed forecast method is utilized, the targeted CLSCN model is developed and solution procedure is clarified. The procedures for validation and verification of the proposed forecast model as well as the developed mathematical model are described in details in Chapter 5. The numerical example and obtained results are discussed in Chapter 6 and finally Chapter 7 provides a summary of this research, its contributions and recommendations for further research.

1.9 Summary

In this chapter, some challenges and issues in designing a real-world CLSCN were discussed and a proposal for covering such issues was presented. The lack of incorporating uncertain and stochastic PLC in the proposed CLSCN models in the literature was introduced as the most prominent problem within the associated area which is to be addressed by this study. In addition, a general view on background of the problem as well as descriptions about objectives, scope, significance, and expected results of this study were provided through this chapter.

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