SUSTAINABLE CLOSED-LOOP SUPPLY CHAIN MODEL WITH STOCHASTIC DEMAND AND RETURN

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is learned for its own sake. It is also dedicated to my mother, who taught me that even the most significant task could be accomplished if it is done one step at a time. And to my brother, who kept me on track to accomplish the required research

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ABSTRACT

The closed-loop supply chain (CLSC) represents the supply chain that contains recovery plans for used products to be reused later in the industry. The research gap in the previous CLSC literature regarding the sustainability aspects for the CLSC was the lack of consideration for the social aspect due to its complexity. Also, the effect of demand and product returns uncertainties on the sustainability aspects of CLSC have not been considered in the previous CLSC studies under centralized management and synchronized ordering policy (SOP). Moreover, the analysis of stochastic sustainable CLSC has not been investigated in industries such as home appliances. Finally, the CLSC sustainability has not been analyzed with previous consideration of CLSC tiers coordination. Thus, the objective of this research was to model a stochastic sustainable CLSC that included the environmental, economic, and social aspects while considering uncertainties in demand and returns quantities for home appliance products under SOP and centralized management. For the proper stochastic CLSC design and mathematical modeling of the sustainable stochastic CLSC, the mathematical model was developed as a multiproduct, multi-echelon single period CLSC model under the SOP and centralized management. The stochastic sustainable CLSC model added constraints related to inventory management for the SOP, production capacity, transportation capacity, and carbon emission. The sustainable stochastic CLSC model was described as a mixed-integer non-linear programming model. The sustainability objectives were optimized using the Pareto-based constrained optimization of non-linear approximation algorithm (Pareto-based COBYLA) by identifying the optimal quantities of parts and products for each CLSC tier and solving the optimization problem using the PYTHON program which was then compared with the non-dominated sorting genetic algorithm (NSGA). The optimization results showed the significance of the stochastic demand and product return parameters on the sustainability objectives in the stochastic sustainable home appliance CLSC following SOP. The current research has contributed to the CLSC studies by developing a stochastic sustainable CLSC mathematical model following the SOP assumption for home appliance products considering the economic, environmental, and social objectives and adding the Pareto-based COBYLA solution algorithm that provided a better optimal solution for stochastic sustainable CLSC optimization in comparison with the NSGA.

ABSTRAK

Rantaian bekalan gelung tertutup (CLSC) mewakili rantaian bekalan yang mengandungi pelan pemulihan bagi produk terpakai supaya ia dapat digunakan semula dalam industri. Jurang penyelidikan dalam literatur CLSC sebelum ini mengenai aspek kelestarian CLSC menunjukkan kekurangan pertimbangan dari segi aspek sosial yang disebabkan oleh kerumitannya. Selain itu, kesan ketidakpastian permintaan serta pulangan produk terhadap aspek kelestarian CLSC tidak dipertimbangkan dalam kajian CLSC di bawah pengurusan berpusat dan dasar pesanan selaras (SOP). Tambahan pula, analisis CLSC lestari-stokastik belum dikaji dalam industri seperti perkakas rumah. Akhir sekali, kelestarian CLSC belum dianalisa dengan mengambil kira penyelarasan peringkat dalam CLSC. Oleh itu, objektif penyelidikan ini adalah untuk memodelkan CLSC lestari-stokastik yang dapat merangkumi aspek alam sekitar, ekonomi dan sosial rantaian bekalan, serta mengambil kira ketidaktentuan dalam permintaan dan kuantiti pulangan untuk produk perkakas rumah di bawah dasar pesanan selaras (SOP) dan pengurusan berpusat. Dari segi reka bentuk CLSC stokastik yang tepat dan pemodelan matematik CLSC lestari-stokastik, model matematiknya dianggap sebagai model CLSC berbilang produk, pelbagai peringkat, tempoh tunggal di bawah SOP dan pengurusan berpusat. Model CLSC lestari-stokastik menambah kekangan yang berkaitan dengan pengurusan inventori untuk SOP, kapasiti pengeluaran, kapasiti pengangkutan dan pelepasan karbon. Model CLSC lestari-stokastik digambarkan sebagai model pengaturcaraan bukan linear integer campuran. Objektif kelestarian telah dioptimumkan menggunakan pengoptimuman kekangan berasaskan Pareto bagi algoritma penghampiran bukan linear (COBYLA berasaskan Pareto) dengan mengenal pasti kuantiti komponen dan produk yang optimum bagi setiap peringkat CLSC dan diselesaikan menggunakan program PYTHON yang kemudiannya dibandingkan dengan algoritma genetik tersusun tidak mendominasi (NSGA). Keputusan pengoptimuman menunjukkan kepentingan permintaan stokastik dan parameter pulangan produk pada objektif kelestarian dalam CLSC lestari-stokastik perkakas rumah mengikut SOP. Penyelidikan ini telah menyumbang kepada kajian CLSC dengan membangunkan satu model matematik CLSC lestari-stokastik berdasarkan andaian SOP bagi produk perkakas rumah yang mengambil kira objektif ekonomi, alam sekitar dan sosial serta menambah algoritma penyelesaian COBYLA berasaskan Pareto yang menyediakan penyelesaian optimum yang lebih baik untuk pengoptimuman CLSC lestari-stokastik berbanding dengan NSGA.

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LIST OF ABBREVIATIONS

CLSC	-	Closed-loop Supply chain
SSC	-	Sustainable supply chain
GSC	-	Green supply chain
ICA	-	Imperialist competitive algorithm
MILP	-	Mixed-integer linear programming
GA	-	Genetic algorithm
PSO	-	Particle swarm optimization
NSGA		Non – dominating sorted genetic algorithm
COBYLA		Constrained optimization of nonlinear approximation
UTM	-	Universiti Teknologi Malaysia
PLM	-	Product life cycle management
SSCM	-	Sustainability supply chain management

LIST OF SYMBOLS

X_t - Input variable model (Forecast customer demand in CLSC case)

Y_t - Output variable model (Product Return in CLSC case)

$v(B)$ - Impulse value: a statistical value for probabilistic estimation of the output variable

X_t - Input variable model (Forecast customer demand in CLSC case)

Y_t - Output variable model (Product Return in CLSC case)

TS_S - Transportation cost made from the supplier to the manufacturer per order.

TS_M - Transportation cost made from manufacturer to distributor per order.

TS_D - Transportation cost made from distributor to retailer per order.

TS_{RT} - Transportation cost made from retailer to the third party per order.

TS_{TP} - Transportation cost made from the third party to the manufacturer per order.

C_{TP} - Collection cost of recovering used products from customers.

F_{RT} - Facility opening cost for the recovery center.

H_S - Holding cost of the supplier for a single component per unit time

H_M - Holding cost held by the manufacturer for every product unit per unit time.

H_{MS} - Holding cost held by the manufacturer for a single supplied component per unit time.

H_D Holding cost held by the distributor of product unit per unit time

H_{RT} - Holding cost held by the retailer of product unit in the forward cycle per unit time.

H_{TP} - Holding cost held by the third-party disassembler of a used product unit ("Remanufactured "per unit time).

S_S - Ordering cost per order of the supplied components (an air conditioning for home appliances stochastic CLSC).

S_{MS} - Ordering cost by manufacturer per for the supplied component from the supplier

S_{Mj} - Setup cost by manufacturer per order of manufactured products

B_m - Order processing cost performed by the manufacturer for delivered products.

S_D Ordering cost per order by the distributor of manufactured products.

S_R - Ordering cost per order by the retailer for manufactured products

S_{MTP} - Ordering cost per order by the manufacturer of the recovered components from the third party.

S_{TP} - Setup cost per order by the third party for the disassembly performed.

C_{TP} - Collection cost per recovered product unit for the third party.

i_D - Counting index of the distributor.

i_M - Counting index of the manufacturer.

n_D - The number of cycle times for the sent products to the distributor.

n_M - The number of cycle times for the products produced by the manufacturer.

n_S - The number of cycle times for the supplied parts to the manufacturer.

U_j - Demand rate of the consumers for each product type 'j' per unit time.

μ - Probability of having a returned component in good condition after the first screening.

α - percentage of return for the used product from the consumers.

γ - Probability of having a returned part after disassembly and second screening in good condition.

S_{jfS} - The number of available fixed jobs in the supplier tier.

S_{jfM} - The number of available fixed jobs in the manufacturer tier.

S_{jfD} - The number of available fixed jobs in the distributor tier.

S_{jfRT} - The number of available fixed jobs in the retailer tier.

S_{jfTP} - The number of available fixed jobs in the third-party collector tier.

S_{jVS} - The number of variable jobs provided by the supplier tier.

S_{jVM} - The number of variable jobs provided by the manufacturer tier.

S_{jVD} - The number of variable jobs provided by the distributor tier.

S_{jVRT} - The number of variable jobs provided by the retailer tier.

S_{jVTP} - The number of variable jobs provided by the third-party recovery tier.

S_U - The employee satisfaction regarding working at the third-party disassembler that aims to recover and refurbish used products..

S_{RT} - The customer satisfaction for the recovered products after usage.

S_{ds} - The number of lost days from injuries or work damage at the suppliers.

S_{dM} - The number of lost days from injuries or work damage at the manufacturer.

S_{dD} - The number of lost days from injuries or work damage at the distributor.

S_{dRT} - The number of lost days from injuries or work damage at the retailer.

S_{dTP} - The number of lost days from injuries or work damage at the third-party recovery center.

Factors of environmental elements for each CLSC tier

E_Q - Emission from the production line in manufacturing.

E_{TP} - Emission from the material disposal and recovery of used parts.

E_{TS} - Emission from the transportation made by the supplier.

E_{TM} - Emission from the transportation made by the manufacturer.

E_{TD} - Emission from the transportation made by the distributor.

E_{TR} - Emission from the transportation made by the retailer.

E_{TTP} - Emission from the transportation made by the third party.

T_{S_j} - The cycle time of the supplied parts.

P_{M_C} - The total production capacity for the manufactured products (determined monthly or annually).

P_{M_j} - The production rate of the manufactured products for each product type j (determined monthly or annually).

Q_{D_j} - Quantity of products ordered by the distributor for each product type j.

Q_{M_j} - Quantity of products manufactured per production cycle for each product type j.

Q_{RT_j} - Quantity of products ordered by the retailer for each product type j.

Q_{S_j} - Quantity of components supplied by the supplier for each component type j.

Q_{TP_j} - Quantity of used components returned by the disassembler for each component type j.

T_j	-	The cycle time for the finished product at the retailer. The stochastic CLSC is assumed to be a single period for each product type j.
T_{S_j}	-	The cycle time of the supplied parts for each product type j.
T_{M_j}	-	The cycle time of finished products at the manufacturer for each product type j.
T_{D_j}	-	The cycle time of the finished products at the distributor for each product type j.
T_{tp}		The cycle time of the supplied parts for each product type j.
TC_D	-	The total cost of the distributers.
TC_M	-	The total cost for the manufacturer of the product.
TC_{RT}	-	The total cost for the retailer.
TC_S	-	The total cost for the supplier.
TC_{SC}	-	The total cost of the supply chain.
TC_{TP}	-	The total cost of the third party.

CHAPTER 1

INTRODUCTION

1.1 Background of research

The supply chain is defined as the path that material travels, starting from being a raw material extracted by a supplier until it reaches the customer. With the increase in global trading, there is an increase in the need for a capable supply chain that meets the global and local demand. As a result, many multinational firms and stakeholders have tried to develop their supply chain to become more sustainable by enhancing the recycling processes to meet future needs and customer demands. As a result, various multinational firms started to implement sustainable practices in the supply chain according to Mathivathanan *et al.* (2018), to develop a sustainable supply chain (SSC). The SSC is defined as the supply chain aiming to implement sustainability practices for the prolonged life of the supply chain. On the other hand, other firms have tried to develop a closed-loop supply chain (CLSC) to reduce wastage and allow the retrieval of the used products to be re-used in different forms. The CLSC is the supply chain that contains the recovery of the product to be reused in the supply chain. The recovered products are either remanufactured, refurbished, or reused depending on the intended function needed for the recovered products. The focus of the current research is on refurbishing the recovered products due to the target of selling them to a second-hand market after recovery.

The two concepts of (SSC) and (CLSC) seem to be divergent from the research point of view while there should be a merge of both concepts, as the CLSC is considered part of the SSC practices. Thus, there is an emerging need to review the CLSC and SSC and identify the techniques that aid in recyclability and sustainability. The sustainable closed-loop supply chain is developed by merging the CLSC and SSC concepts providing a supply chain model that covers the sustainability aspects and the product recovery from customers for different usages.

Various factors need to be considered for modeling the sustainable closed-loop supply chain. The most critical factor is identifying if the CLSC parameters are deterministic or stochastic. The deterministic CLSC model is the closed-loop supply chain where all the parameters are well known and constant. The deterministic CLSC is a simplified case and does not provide a realistic model representation. On the other hand, the stochastic CLSC model has been defined by Zhou *et al.* (2014) as the implementation of a supply chain that undergoes forward regular logistics to supply new products to customers, in parallel with recovery logistics for used products retrieval under the consideration of uncertain supply chain parameters.

Various design elements are considered for modeling and designing the sustainable CLSC. The design elements that affect the sustainable CLSC are the number of echelons in CLSC, the number of products involved in CLSC, and the number of periods taken into consideration while designing the supply chain. Finally, the considered stochastic parameters in the sustainable CLSC, which is believed to be a critical step in modeling the CLSC according to Zeballos *et al.* (2013). The consideration of stochastic parameters in the CLSC provides a realistic output for the CLSC model. Zeballos *et al.* (2013) considered customer demand and return rates as the main stochastic parameters under study.

The uncertainty is usually modeled in the CLSC by following specific scenarios, and each scenario has a probability of occurrence. an example will be known customer demand and return rate at fixed values in each event, and each event has a probability of occurring at a significant period. Thus, some stochastic CLSC models are analyzed in multi-period parameters. In the current research, the stochastic CLSC has been modeled for a home appliances plant as a single period for simplicity in a short period of one month.

The sustainable CLSC is considered recent research and a trending topic. The sustainable CLSC aims to review the effect of recovering used products economically, environmentally, and socially. The benefits of implementing a CLSC according to Zarandi *et al.* (2011) are as follows, for the economic aspects, the stochastic CLSC provides a cost-efficient supply chain, as it saves the costs of extracting new raw materials and resources. From the environmental aspect, CLSC is considered an environmentally friendly supply chain as it reduces resource wastage through recycling. Also, CLSC reduces the CO_2 emission from the manufacturing of new products. Finally, social benefits can be gained from increasing customer and employee satisfaction. Thus, the sustainable CLSC implementation brings a competitive advantage to any multinational firm. The main research question is to identify the optimal settings that will provide a sustainable CLSC under stochastic demand and product return values under synchronized ordering policies. The optimal setting provided will result in a sustainable CLSC and the optimal settings are obtained through the Pareto-COBYLA optimization algorithm

1.2 Problem Statement

There is a research gap in the previous CLSC literature review regarding the sustainability aspects for the CLSC. As stated by Aldemir and Bolat (2018), the social aspect was rarely examined in any closed-loop supply chain due to its complexity. Also, the effect of demand and product returns uncertainties on the sustainability aspects of CLSC have not been considered in the previous CLSC studies under the synchronized ordering policy and require further investigations. Moreover, the analysis of stochastic sustainable CLSC has not been investigated in industries such as home appliances. Finally, the CLSC sustainability has not been analyzed with the consideration of CLSC tiers coordination under centralized management as synchronized ordering policies with stochastic parameters such as demand and product return amounts. Furthermore, some metaheuristic algorithms provided optimal solution set after a long computation time due to the complexity of the stochastic CLSC designs, constraints, and the slow exploration rate of the previous metaheuristic solution algorithms used such as non-dominating sorted genetic algorithm (NSGA). Thus, it is required to develop a mathematical model for stochastic sustainable CLSC that analyses the supply chain's environmental, economic, and social aspects while considering uncertainties in demand and returns quantities for house appliance products under the synchronized ordering policy and centralized management. Also, it is needed to identify the optimal quantities of products and parts for each stochastic CLSC tier to meet the sustainability objectives under a synchronized ordering policy using a faster and more reliable algorithm. Furthermore, the optimization solution set to the designed stochastic sustainable CLSC model provided by an appropriate solution algorithm must be verified and validated with a commonly used metaheuristic algorithm such as NSGA. Finally, sensitivity analysis must be conducted to understand the significance of stochastic demand and stochastic return rate on sustainability objectives in the stochastic sustainable home appliance CLSC model under a synchronized ordering policy between tiers.

Sustainability in the CLSC has been considered an essential criterion for ensuring the long-term survival of any industry. Various stakeholders gain benefits when sustainability is implemented in CLSC. The first stakeholder is the customer. After recovery, the products are either remanufactured, refurbished, or reused. The home appliances are most likely refurbished as the components are in better condition than the final products. The customers must be satisfied with the refurbished products, and customer satisfaction is considered a critical part of the social sustainability aspect. The second stakeholder is the employees in the sustainable CLSC entities, as they benefit from the profit representing the economic sustainability aspect. The third stakeholder is the manager of the CLSC firm, who also benefits from profit and ensures a long-term return from their investment in sustainable CLSC. The government as a stakeholder needs to ensure that the environmental emissions have decreased to reduce the environmental hazards and maintain the environmental aspect of sustainability. Finally, the whole community will benefit from the availability of stochastic sustainable CLSC implemented in the system from the increased number of jobs, providing products at a lower selling price and fewer emissions.

1.3 Research objectives

The main objective of the research is to:

(a) Identify all the parameters needed for stochastic CLSC to meet the sustainability aspects of home appliances types produced

(b) Develop a mathematical model for sustainability aspects of stochastic sustainable CLSC with demand and returns quantities uncertainties under the synchronized ordering policy.

(c) Validate the mathematical model for stochastic CLSC, solve the optimization problem for stochastic CLSC using Pareto-based COBYLA, and comparing the Pareto-COBYLA results with the NSGA to obtain the best optimal quantities for the sustainable stochastic CLSC.

1.4 Research scope

The analysis of sustainable CLSC in the home appliance considers stochastic demands and sustainability aspects in terms of social, environmental, and economic enhancements. Furthermore, the model development for CLSC type is restricted to a home appliance company in Egypt using various solution algorithms in optimizing sustainability aspects under stochastic demand and return rates. The solution algorithms optimizing stochastic sustainable CLSC are preference-based Pareto-COBYLA and NSGA. The stochastic sustainable CLSC model has tackled a single period, multi-product, stochastic demand, stochastic return product rates, and considered at least a three-echelon level supply chain for the mathematical model formulation. Furthermore, The stochastic CLSC model was validated for the same assumption through computation and a comparison between pareto-COBYLA and NSFA was performed to obtain the optimal sustainable CLSC under economic, environmental and social objective function under synchronized ordering policies implementation for CLSC tiers.

1.5 Research significance

This outcome of the research will benefit various stakeholders to consider realistic and essential design elements in stochastic CLSC such as uncertainty modeling, number of echelons, number of products considered, and product type. The research also considers sustainability aspects in the stochastic CLSC model and provides managers with measuring techniques to analyze the environmental and social aspects in sustainable stochastic CLSC. Moreover, this research provides a detailed classification for uncertainty models in the stochastic CLSC. Furthermore, this research reviews the previous algorithms used in optimizing stochastic CLSC designs and suggests the best optimization algorithm managers could use according to the stochastic CLSC design complexity.

The research outcome will provide a proper measurement tool to assess various sustainable CLSC models in home appliances industries. The measurement tools could be considered criteria for local governments to analyze any firm's sustainability and recovery logistics. The model has been optimized using various algorithms such as NSGA and preference-based Pareto-COBYLA as discussed in the solution techniques of the stochastic CLSC model. Also, the mathematical formulation has been applied to one of the Egyptian manufacturing industries for home appliances. As a result, the managers could determine the optimal inventory management quantities while handling a sustainable CLSC with stochastic demand and returns under a synchronized ordering policy and providing the customers with a proper indication of the expected product quality before purchasing refurbished products. The study has provided some recommendations for the proper managerial practices that will aid in developing the stochastic sustainable CLSC and overcoming the obstacles that inhibit sustainable CLSC implementation in the future.

1.6 Thesis outline

The thesis contains six chapters classified as follows. Chapter one contains a brief introduction about the research, an explanation regarding the problem statement as a concrete base for the research, the objective, and the scope of the study. Chapter two contains the literature review covering forward supply chain, green supply chain, sustainable supply chain, CLSC, stochastic, and sustainable CLSC designs. Later there is a review of solution algorithms and the sensitivity analysis that could be applied to the sustainable CLSC model. Chapter three explains the methodology regarding the problem statement development, sustainable CLSC model design, solution algorithm, analysis, and evaluation performed on the CLSC. Chapter four represents the development of the sustainable CLSC model under synchronized ordering policy consideration and sustainability aspects. Chapter five contains more about the results and analysis for the stochastic sustainable CLSC and the effect of stochastic demand and return rates on the sustainability objectives in the CLSC. Finally, chapter six contains a conclusion related to the analysis of the stochastic sustainable CLSC and the future recommendations of the stochastic sustainable CLSC research.

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