MODELLING AND OPTIMIZATION OF CLOSED-LOOP SUPPLY CHAINS WITH CARBON POLICIES UNDER UNCERTAINTY

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ABSTRACT

Climate change, increased carbon regulations, globalized supply chains, volatile energy and material prices, and competitive marketing pressures are driving industry practitioners and supply chain decision makers to implement various carbon regulatory mechanisms to curb carbon emissions. One of the effective approaches to reduce carbon emissions is the adoption of closed-loop supply chain (CLSC). Optimal supply chain network design (SCND) is crucial to the success of industrial concerns nowadays because design decisions should be viable enough to function well under complex and uncertain business environments. Also, it plays a vital role in determining the total carbon footprint across the supply chain and the total cost. Therefore, it is essential to make decisions such a way that it could not only configure optimal network but also reduce supply chain total cost and carbon footprint in the presence of uncertainty. In this context, this research proposes optimization models for design and planning of a multi-period, multi-product CLSC network considering carbon footprint under uncertainty to quantify and compare both economic and environmental impacts of carbon emission policies, namely carbon cap, carbon tax, and carbon trade on SCND and planning decisions. This study involves extensive mathematical modelling where SCND considerations are formulated into mixed-integer linear programming (MILP). The proposed models address uncertainty in products demand, returned products, and processing costs. To overcome complexity in scenario-based stochastic programming approach for dealing uncertainty, robust optimization model is developed and validated using two test scenarios of different sizes. The proposed models capture trade-offs between supply chain total cost and carbon emissions. The results suggest that carbon cap policy is only favourable to certain carbon amount. Beyond this limit, there is no economic benefit. The number of opening various facilities is significantly reduced as carbon tax rate increases. The results indicate that carbon trade policy is the most flexible and efficient policy as compared to the other two policies. Moreover, this policy motivates firms to emit less carbon units even when the carbon allowance is available more than needed. Further, the results show that the stochastic model is constantly outperformed the deterministic model in terms of total cost. However, when considering robust optimization to deal with uncertainty, the total cost incurred by the robust models are greater than the values obtained from deterministic model. The additional costs are due to larger solution space to accommodate possible realization of uncertainties in a given uncertainty set. The findings of this study provide evidence that the decision makers are not only able to configure optimal SCND but also reduce carbon emissions without significantly increasing the total cost. Moreover, this study guides decision makers to decide which policy to be chosen well in advance to minimize the total cost and carbon emissions. Finally, the proposed optimization models with different carbon policies can be valuable to manufacturers, researchers, and decision makers to predict the impact of these policies on SCND, overall supply chain costs, and carbon emissions.

ABSTRAK

Perubahan iklim, peraturan karbon yang meningkat, rantaian bekalan global, tenaga dan harga bahan yang tidak menentu, dan tekanan pemasaran yang kompetitif mendorong pengamal industri dan pembuat keputusan rantaian bekalan untuk melaksanakan pelbagai mekanisme pengawalseliaan karbon untuk membendung pelepasan karbon. Salah satu pendekatan berkesan untuk mengurangkan pelepasan karbon adalah penggunaan rantai bekalan gelung tertutup (CLSC). Reka bentuk rangkaian rantaian bekalan yang optimum (SCND) adalah penting untuk kejayaan industri pada masa kini kerana keputusan reka bentuk harus cukup berdaya untuk berfungsi dengan baik di dalam lingkungan perniagaan yang rumit dan tidak menentu. Ia juga memainkan peranan penting dalam menentukan jejak karbon secara keseluruhan merentasi rantaian bekalan, dan juga jumlah keseluruhan kos. Oleh itu, adalah penting untuk membuat keputusan yang bukan sahaja boleh mengkonfigurasi rangkaian yang optimum tetapi juga mengurangkan kos keseluruhan dan kos karbon dalam suasana ketidakpastian. Dalam konteks ini, penyelidikan ini mencadangkan satu model pengoptimuman bersepadu bagi reka bentuk dan perancangan rangkaian pelbagai tempoh, pelbagai produk CLSC yang mempertimbangkan jejak karbon di bawah ketidakpastian untuk mengukur dan membandingkan kedua-dua kesan ekonomi dan polisi pelepasan karbon, iaitu had karbon, cukai karbon dan perdagangan karbon dalam rekabentuk SCND dan keputusan perancangan. Kajian ini melibatkan pemodelan metamatik yang mendalam di mana pertimbangan-pertimbangan SCND diformulasikan menjadi pengaturcara integer linear campuran (MILP). Model yang dicadangkan menangani ketidakpastian dalam permintaan produk, produk yang dipulangkan, dan kos pemprosesan. Untuk mengatasi kerumitan dalam pendekatan pengaturcaraan stokastik berasaskan senario dalam menangani ketidakpastian, model pengoptimuman yang mantap dibangunkan dan ditentu sahkan menggunakan dua senario ujian yang berlainan saiz. Keputusan menunjukkan bahawa dasar had karbon hanya menguntungkan sehingga batas jumlah karbon tertentu sahaja. Di luar batas ini, tiada manfaat ekonomi diperolehi. Bilangan pembukaan pelbagai kemudahan dikurangkan dengan ketara apabila kenaikan kadar cukai karbon. Hasilnya menunjukkan bahawa dasar perdagangan karbon adalah dasar yang paling fleksibel dan cekap berbanding dengan dua lagi dasar. Tambahan pula, dasar ini mendorong syarikat mengeluarkan lebih sedikit unit karbon walaupun peruntukan karbon tersedia lebih banyak daripada yang diperlukan. Selanjutnya, hasil kajian menunjukkan bahawa model stokastik sentiasa lebih baik daripada model deterministik dari segi jumlah kos. Walau bagaimanapun, apabila senario ketidakpastian diambilkira, jumlah kos yang ditanggung oleh model yang mantap adalah lebih besar daripada nilai yang diperoleh daripada model deterministik. Kos tambahan disebabkan oleh ruang penyelesaian yang lebih besar untuk menampung sebarang kemungkinan ketidakpastian. Penemuan kajian ini membuktikan bahawa pembuat keputusan bukan sahaja dapat mengkonfigurasi SCND yang optimum tetapi juga mengurangkan pelepasan karbon tanpa meningkatkan jumlah kos yang ketara. Tambahan pula, kajian ini membimbing para pembuat keputusan untuk memutuskan dasar mana yang harus dipilih lebih awal untuk meminimumkan jumlah kos dan pelepasan karbon. Akhir sekali, model pengoptimuman yang dicadangkan dengan dasar karbon yang berbeza boleh menjadi rujukan bernilai kepada pengilang, penyelidik, dan pembuat keputusan untuk meramalkan impak dasar-dasar ini pada SCND, kos rantaian bekalan keseluruhan, dan pelepasan karbon.

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LIST OF ABBREVIATIONS

SC	Supply Chain
SCM	Supply Chain Management
SCND	Supply Chain Network Design
CLSC	Closed-Loop Supply Chain
MILP	Mixed Integer Linear Programming
GHG	Greenhouse Gas
COP21	2015 United Nations Climate Change Conference
GAMS	General Algebraic Modelling System
CPLEX	IBM ILOG CPLEX Optimization Studio

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CHAPTER 1

INTRODUCTION

1.1 Background of the Research

Climate change, global warming, environmental issues and energy crisis led to introduction of more restrictive environmental regulations by policy makers around the globe. Greenhouse gas (GHG) emissions have risen to unprecedented levels. According to the 2014 report by the panel on climate change, it has increased by 10 billion metric tons during the period 2000-2010 though an increase in governmental legislations and carbon emission regulations to mitigate climate change (COP21). A wide range of carbon regulations such as strict carbon cap (allowable carbon emission), carbon tax (price per unit of carbon emission), carbon trade (buy and sell unused carbon amount) have been introduced by many industrialized countries around the globe to reduce carbon emissions. For example, the UK government has committed to lessen carbon emission by 60 % below of 1990 levels by 2050. By 2020, China aims to decrease carbon levels by 40–45 % of 2005 levels (COP21). In the recent Paris summit on climate change, one of the largest fossil fuels producers, Saudi Arabia has announced its pledge to reduce greenhouse gas (GHG) emissions and said up to 130 million tonnes of carbon dioxide equivalent annually would be avoided by 2030 through contributions to economic diversification and adaptation. In Malaysia, the government has pledged to cut 45% of its carbon emissions intensity by the year 2030 (COP21). Reducing and mitigating carbon emission proportion and in the meantime improving the energy usage efficiency are significant and necessary. In addition, due to customer awareness of environmental issues and the desire to have low carbon products, firms worldwide are undertaking carbon emission reduction initiatives to curb carbon footprint. The adoption of a closed-loop supply chain (CLSC) is one of the effective methods to minimize industries' environmental footprint.

Governments strive to mitigate GHG emissions by passing legislation and developing market-based environmental strategies. These strategies not only help in emission reduction but also provide economic benefits to firms. Examples of these strategies are the “Kyoto Protocol, 1997”, the “European Union Emission Trading System, 2009”, “New Zealand Emissions Trading Scheme, 2009”, and “Japan carbon tax scheme, 2012” etc. Kyoto Protocol was signed in by 181 countries under the “United Nations Framework Convention on Climate Change” to control GHG emissions (Ramudhin, Chaabane and Paquet, 2010). The Protocol introduced three mechanisms through which countries can cooperate to meet their emission reduction targets. First, emissions trading or carbon market, allows countries that pollute more than their target to buy used carbon amount (carbon credits) from countries that have excess credits i.e., pollute less in order to stay below their target or cap. Second, clean development mechanism that permits a country to acquire carbon emissions credit if it invests on climate change initiatives to reduce carbon emission in underdeveloped countries. Third, a country is allowed to get unused amount of carbon through joint implementation if it is carrying out emission reduction projects in another industrialized country committed to its emission reductions.

The efficient collection of used products from customers are critical for performance of recovery activities such as refurbishment, recycling, repair, recovery etc. in a CLSC network. The prime importance of used products recovery has two major advantages: (i) environmental sustainability, (ii) maximizing the value creation of entire lifecycle of a product with best possible recovery practices. Therefore, the need to introduce the means to increase the quantity and quality of products returns through different types of financial incentives such as acquisition price, cash rebate, and promotional offers such as discounts and product exchange which are the important factors in influencing the collection of product returns.

Since last decade, concerns due to uncertainties from various sources (external, internal) have prompted researchers to consider uncertainty in their supply chain network design (SCND) planning decisions, otherwise it leads to sub-optimal or infeasible solutions. There are two major sources of uncertainties addressed in the literature, categorized them as internal supply chain (operational risks) uncertainties and external (disruption risks) uncertainties. Uncertainty in supply chain such as operational costs, facility capacity, production and distribution quantities, demand, return rate etc., are called internal uncertainties which are caused due to implicit disruptions within an organization. Whereas external uncertainties are caused due to natural disasters such as earthquakes, floods, and man-made disasters such as terrorist attacks, fires etc. (Simangunsong, Hendry and Stevenson, 2012). SCND and strategic planning are long term (timescale of years) decisions. For example, network design, facility location, facility capacity, technology and transportation modes selection are all extremely costly and time taking decisions (difficult to change in the short run) during which critical parameters such as raw material supply and demand of customers will change i.e., quite uncertain (Pishvaee, Jolai and Razmi, 2009). Especially reverse logistics activities such as collection (return) rate of used products, variety of quality returns, tend to be highly uncertain in a short period. Thus, designing and planning of CLSC configuration under uncertainty is highly necessary to deal with uncertain parameters such that the impact of parameter fluctuations on network configuration will be less. To deal with uncertainty, different mathematical programming techniques, such as fuzzy programming, stochastic programming, dynamic programming, constrained programming, and robust optimization have been used to solve SCND problems. In order to deal with the issues enumerated above, there is a need to develop integrated optimization models for design and planning of CLSC by considering various carbon emission policies under uncertainty.

This research investigates a generalized closed loop supply chain network, as shown in Figure 1.1 as investigated by other researchers (Chaabane, Ramudhin and Paquet, 2012; Fahimnia et al., 2013). In the forward supply chain, the network includes multiple production centers (PCs), multiple distribution centers (DCs), and multiple markets. In the reverse supply chain, the network includes multiple collection centers (CCs), multiple recycling centers (RCs), and multiple disposal depots (DDs). In practice, such a CLSC network could span across several countries or continents.

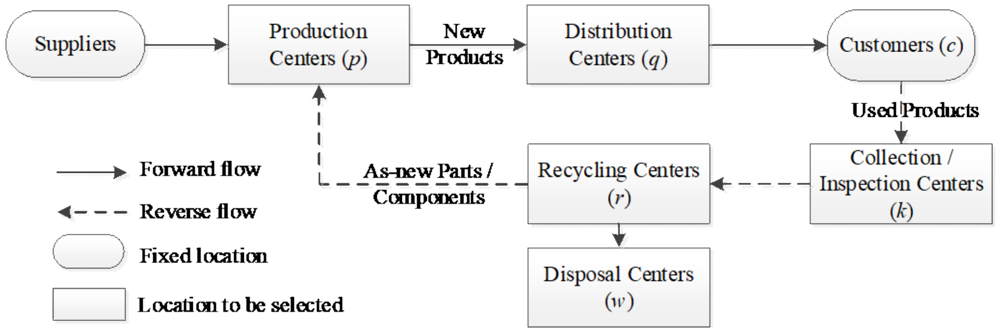

Figure 1.1 A general CLSC network

In the forward chain, PCs get new components through suppliers and recycled ones through the RC. Each PC could produce multiple product types using technologies that may differ from other producers. Each technology has its own acquisition, operation and production costs as well as carbon emission rate. Finished products are shipped to markets from the DCs. A variety of transportation modes are available for shipping products among facilities at different costs and fuel efficiency rates. In the reverse supply chain, the used products are collected by the CCs, collected products are shipped to RCs. At the RCs, products are disassembled into components, inspected and sorted into recycled and non-recyclable components. This study assumes that recycled components are as good as new components (Özkır and Başlıgil, 2013). Non-recyclable components are shipped to DDs for disposal purpose.

1.2 Statement of the Problem

Most of the carbon emission reduction initiatives have focused largely on replacing energy inefficient equipment and facilities, redesigning products and packaging, finding less polluting sources of energy and implementing energy-saving programmes. While such efforts are valuable, many firms tend to ignore a potentially more significant source of emissions (industrial carbon footprint), which is driven by business practices, operational policies, and coordination in a long and complex supply chain. One of the effective approaches to reduce carbon emissions is the adoption of CLSC network. Moreover, environmental sustainability of collecting used products and maximizing the value creation of entire life-cycle of a product depend on the best possible recovery practices in the reverse supply chain network. However, existing mathematical models mainly focus on the separate issues relating to optimal configuration of CLSC network or incorporating carbon emission policies or financial incentives for acquiring used products or parameters uncertainty in SCND planning decisions. They tend to ignore integrating these issues in the context of configuring optimal CLSC network and reduce carbon emission. Therefore, there is a need to integrate these issues because (i) the decision regarding the design and planning of an optimal CLSC network plays a major role in determining the total carbon footprint across the supply chain; (ii) the performance of recovery activities in a CLSC mainly depends upon the effective and efficient collection process of used products; (iii) optimal configuration of a CLSC network under uncertainty is necessary to deal with uncertain parameters such that the impact of parameter fluctuations on network design will be less. Therefore, it is highly necessary to propose integrated optimization models for design and planning of CLSC network by considering all above-mentioned aspects.

1.3 Purpose of the Research

This research proposes optimization models to address a CLSC network design problem with carbon footprint consideration under uncertainty by quantifying and comparing both economic and carbon emission on SCND planning decisions under multiple planning periods. The proposed models extended further to analyse the effect of carbon emission policies such as carbon cap, carbon tax, and carbon trade policy on the SCND planning decisions. The proposed models with carbon policies is extended further to incorporate uncertainty issues in SCND and operational decisions. Supply chain total cost is minimized by determining optimal location of facilities, optimal acquisition price with respect to return rate and optimal manufacturing, remanufacturing, recycling, and transportation quantities.

1.4 Research Questions

The following key research questions will be investigated in this study through the research gaps addressed in the problem statement.

i. How carbon footprint to be incorporated in SCND planning decisions?
ii. How carbon policies effect on the CLSC network design decisions?
iii. What is the trade-off that exists between supply chain total cost and carbon emission under various carbon policies?
iv. How can the uncertainty dimension (parameters uncertainty) be included in a deterministic model?
v. What is the impact of parameters uncertainty on SCND planning decisions of the CLSC network?
vi. Considering various product recovery activities in reverse network, what is the impact of these activities on supply chain total cost and carbon emission?
vii. How the conservatism degree of various uncertain parameters under the robust model effects on net change in objective function value (total cost)?

1.5 Research Objectives

The objectives of this research are:

i. To propose an optimization model to address a multi-period CLSC network design and planning problem considering various carbon emission policies.
ii. To develop stochastic and robust CLSC models to deal with parameters uncertainty such that to minimize the total cost and carbon emission.
iii. To enhance the robust model for a CLSC network considering multi recoveries and return incentives.

1.6 Scope and Key Assumptions

This section provides scope of this study and relevant key assumptions.

Scope

i. Addressing CLSC network under multi product and multi period settings.
ii. Only operational (internal) uncertainty is considered and limited to scenario-based stochastic programming and robust optimization approaches to deal with uncertain parameters.

Key assumptions

i. The number, capacity and location of potential facilities in network is known in advance.
ii. The number and location of customer zones and secondary markets (products markets, spare part markets and materials markets) are fixed and predefined.
iii. Each processed product yields both components and raw materials having different quality levels.
iv. Procurement cost, customer demand, and returned products are assumed to be uncertain.
v. At the beginning of planning horizon, distribution centres have enough products for next time periods to satisfy customers demand.
vi. Returned products are classified according to their quality levels (high, medium, poor). Example, under warranty products and damaged products are considered as high-quality returns, end-of-use products are considered as medium quality returns, while end-of-life products are categorised as poor-quality returns.
vii. Components and materials are brought back to as good as new through the repair and recycling processes at repair and recycling centres respectively. Their processing costs are cheaper as compared to procurement cost of new components and raw materials from suppliers.

viii. Unit cost of collection, recovery, disassembly, repair, and recycling are quality dependent.

ix. Emissions generated due to processing of products at facilities and emissions generated due to shipping products between the facilities are known.

x. Emission cost for storing a product at facilities is negligible when compared to the overall cost of carbon emissions in supply chain network (Fahimnia et al., 2013).

xi. Inventory holding cost and shortage cost are incurred due to holding inventory and penalizing for not satisfying demand requirement respectively.

1.7 Importance of the Research

This research extends current optimization models which emphasizes not only on minimizing the total cost but also reducing the carbon emissions across the supply chain by considering carbon footprint criteria under various carbon emission policies. Policy makers can use these models to analyse the effect of policy parameters on SCND planning decisions. This will allow them to choose most suitable carbon reduction policy based on strict carbon cap, carbon tax rate, carbon market price over total emissions. Furthermore, these models can help decision makers to predict the impact of these policies on SCND planning decisions based on overall supply chain costs and carbon emissions. Moreover, the prime importance of considering multiple recovery activities of the used products in a CLSC has three folds; (i) maximizing the remaining economic value of a used product with best possible recovery practices, (ii) improving environmental sustainability of collecting used products, and (iii) increasing the quality and quantity of returned products as well as prosperity of business in the reverse logistics by offering financial incentives for collecting used products from the customers.

In addition, consideration of uncertainties in the model parameters leads to more realistic problems. Developing stochastic and robust optimization models which can withstand (absorb) uncertainty of input parameters help managers and decision makers in making proper decisions. Because SCND decisions' effects last for several years, during which critical parameters change i.e., quite uncertain. While not considering uncertainty issues in the models leads to sub-optimal or infeasible solutions.

With these considerations while designing and planning a CLSC, the proposed optimization models with different carbon policies can be valuable to the companies, researchers, and decision makers to forecast the effect of these policies on SCND and planning decisions. Therefore, decision makers can choose the suitable carbon policy to meet their needs. In addition, the proposed stochastic and robust models considering three carbon policies can be valuable for decision makers based on the properties of a selected uncertainty set.

1.8 Definitions of Terms

This section provides definitions of the terms which are important and currently used in this research.

a) Mixed Integer Linear Programming

Mixed integer-linear programs (MILP) are linear programs arising naturally in many real-life applications, in which some of the decision variables are constrained to be integer values at the optimal solution.

b) Carbon Cap Policy

A firm is allowed to emit a limited amount of carbon emission over the planning horizon. The emitted carbon could be due to production, storage, and transportation activities. The imposed carbon allowance is referred to as the carbon cap or maximum allowable carbon emission.

c) **Carbon Tax Policy**

A financial penalty is incurred per unit of carbon emission through taxes.

d) **Carbon trade Policy**

A firm is allocated to emit a limited amount of carbon emission over the planning horizon which is same as in carbon cap policy. In addition, it is allowed to trade its carbon allowance. If a firm emits less than its prescribed carbon cap, then it allows to sell the unused amount of carbon credits. Vice-versa, if a firm emits more than its prescribed carbon cap then it allows to purchase additional carbon emission credit to maintain its supply chain activities or it can reduce its carbon emissions and to implement more environmental friendly manners of conducting its business.

e) **Uncertainties**

There are two major sources of uncertainties addressed in the literature, categorized them as internal (operational risks) uncertainties and external (disruption risks) uncertainties. Internal uncertainties are attributed to implicit disruptions within the organization such as operational costs, facility capacity, production and distribution quantities, demand, return rate etc. Whereas external uncertainties are attributed to natural disasters such as earthquakes, floods, and man-made disasters such as terrorist attacks, fires etc.

f) **Single Recovery and Multi Recoveries**

In reverse supply chain network, returned product goes through various recovery practices including collection, disassembly, remanufacture, recycling, disposal etc., to recover the used product, component, module, material as good as new to; (i) improve the environmental sustainability, (ii) maximize the economic value of the used product, and (iii) increase economic benefits of a firm. As such, single recovery refers to only one entity (product or component or module or material) recovered and multi recoveries refer to more than one entity recovered.

g) Return Incentives

The means to increase the quality and quantity of used products returns from customers through various types of financial incentives and promotional offers such as acquisition price, cash rebate, discounts and product exchange which are the important factors in influencing the collection of product returns.

1.9 Overview of Research Methodology

This research proposes a deterministic MILP model to address a CLSC network design problem with carbon regulations consideration, by integrating the carbon emission into SCND planning decisions. To make the model more realistic, this research addresses the SCND and planning decisions focusing on selection of technologies at the production facilities, transportation mode selection, multiple recovery options for returned products based on their different quality levels, incentive-based quality returns, capacity limits on potential facilities and transportation. The model extends further to incorporate uncertainty issues in the input parameters. Stochastic scenario-based programming and robust optimization approaches are used to represent the imprecise input parameters as scenarios and bounded uncertainty sets respectively. These approaches provide a framework to deal with uncertainties in optimization problems that could sustain optimal solutions i.e., protect against infeasibility or sub-optimality in a given realization or scenario. A detailed description about each approach is provided in chapter 3 of the thesis.

1.10 Summary of Research Contributions

This study proposes optimization models for CLSC network design and planning considering carbon footprint under uncertainty to quantify and evaluate both supply chain total cost and carbon emissions based on the key parameters of various carbon policies by determining the optimal number of potential facilities to be opened, determining the optimal quantities in both forward supply chain network and in the reverse network, transportation quantities, type of transportation mode to be used between the facilities, and type of available technologies to be used at production centres so that the total supply chain cost and carbon emissions are minimized. To make supply chain becomes more realistic, this research incorporates multiple recovery options in the reverse network and incentive offers for collecting used products at collection centres for maximizing the value creation of entire life of a product. In addition, this research develops stochastic and robust optimization approaches to deal with effect of parameters uncertainty. Numerical results provide some insightful observations with respect to supply chain total cost and carbon emission on SCND planning decisions.

Figure 1.2 briefly illustrates the hierarchical of research development stages and research contribution. Previous research in the area of forward SCND has extensively focussing in terms of network structure, location of facilities (from suppliers to customers), modelling features (different sources of uncertainty), performance measures (cost, profit), and solution approaches (exact methods, meta heuristics). Reverse SCND is based on facility type for reuse, recycle, repair of retuned products and type of return. CLSC network design is an emerging area because its goal is to strive for sustainability by improving economic and environmental performance measures simultaneously. The prime importance of used products recovery has two major advantages: (i) environmental sustainability of collecting used products by various means (incentives/promotional offers), (ii) maximizing the economic value of a used product with best possible recovery practices. To address the problem of carbon emissions reduction from supply chain and logistics perspective, the logistics network should be designed in a way that it could reduce both the cost and the carbon footprint across the supply chain because the decision concerning the design an optimal network of the CLSC plays a vital role in determining the total carbon footprint across the supply chain and also the cost. Therefore, it is essential to make these decisions such a way that it could not only configure optimal network but also reduce total cost and carbon footprint. Moreover, not considering operational uncertainty while design and planning of CLSC network leads to sub-optimal and infeasible solutions. Therefore, in order to address above issues, this research proposes optimization models for CLSC network design with carbon policies under uncertainty.

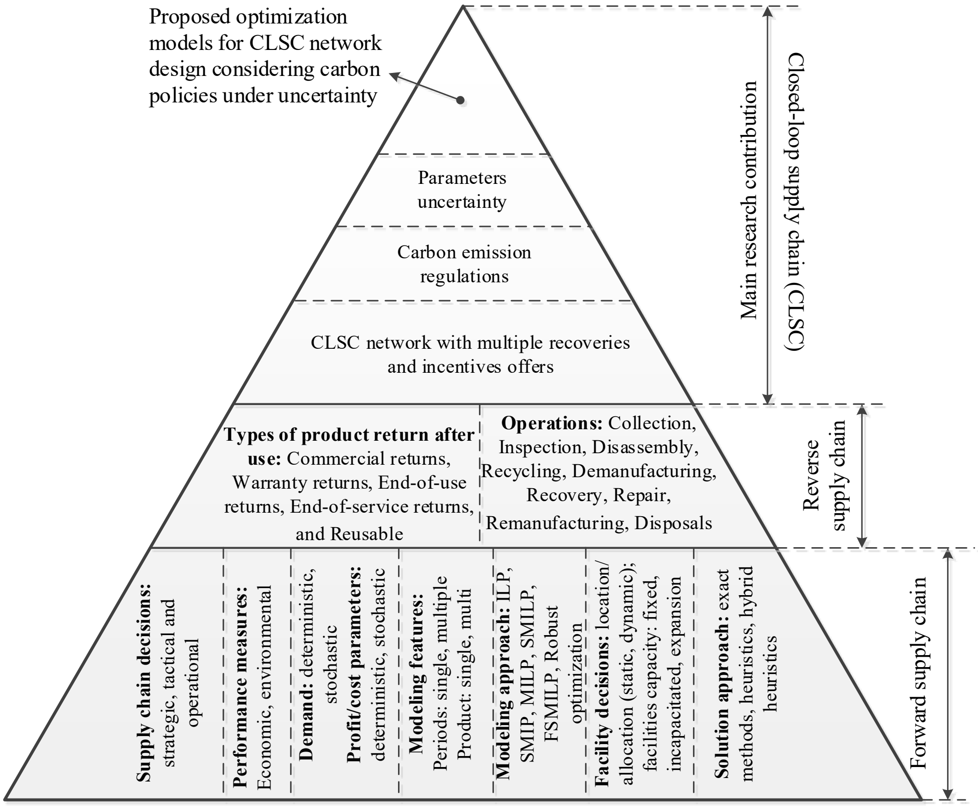

Figure 1.2 Hierarchy of research development stages and contributions

1.11 Organization of the Thesis

As shown in Figure 1.3, this work is structured into eight chapters. The foundation of the research is presented in Chapter 1. Chapter 2 covers literature review which provides contextual information in the interrelated subjects of this research. Chapter 3 describes the research methodology and its rationale. Chapter 4 presents deterministic MILP model for a multi-period CLSC network design problem with consideration of carbon policies and provides numerical results at the end of the chapter. Chapter 5 is an extension of Chapter 4 by considering uncertainty in product demand and used products returns. This research used scenario-based stochastic approach and robust optimization approach to deal with uncertainty. Chapter 6 is also extension of Chapter 4 by (i) incorporating multiple recovery options in the reverse logistic of the network, (ii) considering returned products with different quality levels, and financial incentives are offered that are based on the quality level of each returned product to maximize economic value of the used products with best possible recovery practices. Moreover, (incorporated uncertainty in supply, demand, and used products availability at customer zones) a robust counterpart of the proposed model is developed to immunize the effect of uncertainty on supply chain planning and operational decisions. Chapter 7 provides an overall discussion on the research findings. Chapter 8 summarizes the conclusions, and contributions of this research. Moreover, the limitations of this research as well as suggestions for future research are provided at the end the chapter.

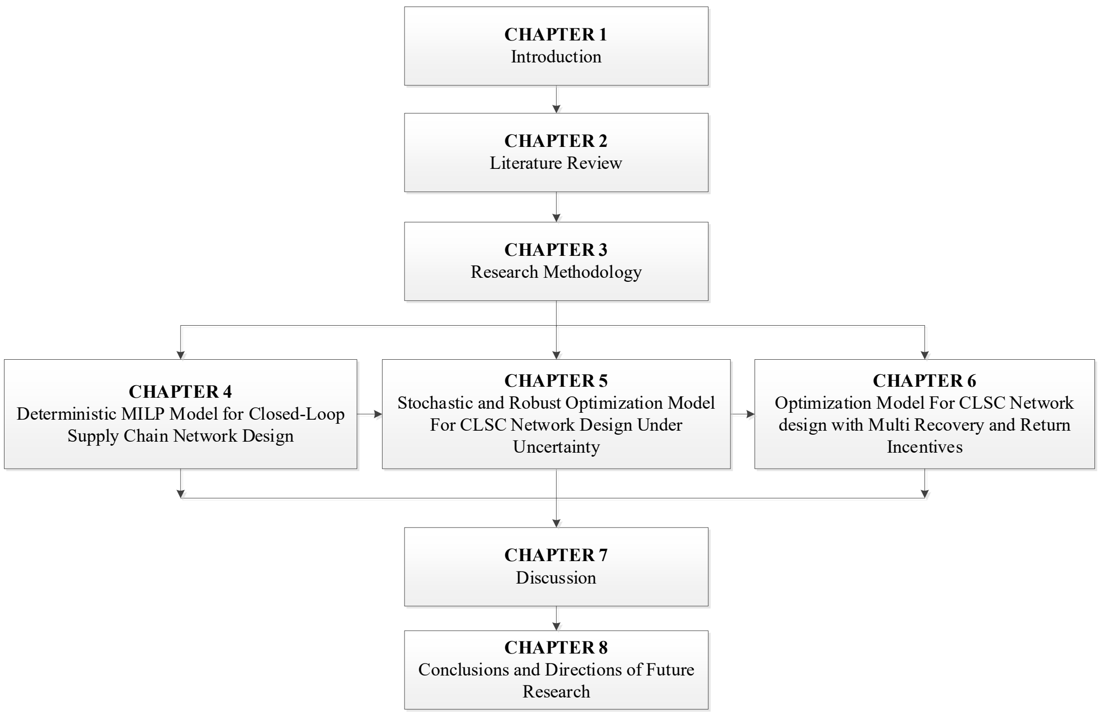

Figure 1.3 Organization of the thesis

1.12 Summary

An essential introduction to this research is presented in this chapter. Started with background of this research in which research issues are discussed and research gaps are highlighted. Followed by the statement of the problem in which the problem of this research is outlined. Subsequently, purpose, objectives, scope and key assumptions, and importance of this research is presented. A brief overview of research methodology is provided. At the end of this chapter, contributions of this research are highlighted, and organization of the thesis is outlined.

REFERENCES

Abdallah, T., Farhat, A., Diabat, A. and Kennedy, S. (2012) 'Green supply chains with carbon trading and environmental sourcing: Formulation and life cycle assessment', *Applied Mathematical Modelling*, 36(9), 4271-4285.

Akçalı, E., Çetinkaya, S. and Üster, H. (2009) 'Network design for reverse and closed-loop supply chains: An annotated bibliography of models and solution approaches', *Networks*, 53(3), 231-248.

Alshamsi, A. and Diabat, A. (2015) 'A reverse logistics network design', *Journal of Manufacturing Systems*, 37, 589-598.

Alumur, S.A., Nickel, S., Saldanha-da-Gama, F. and Verter, V. (2012) 'Multi-period reverse logistics network design', *European Journal of Operational Research*, 220(1), 67-78.

Amin, S. H. and Zhang, G. (2013) 'A multi-objective facility location model for closed-loop supply chain network under uncertain demand and return', *Applied Mathematical Modelling*, 37(6), 4165-4176.

Amin, S. H. and Baki, F. (2017) 'A facility location model for global closed-loop supply chain network design', *Applied Mathematical Modelling*, 41, 316-330.

Aras, N. and Aksen, D. (2008) 'Locating collection centers for distance-and incentive-dependent returns', *International Journal of Production Economics*, 111(2), 316-333.

Aras, N., Boyaci, T. and Verter, V. (2010) '*Designing the reverse logistics network* (pp. 67-97). Boca Raton, FA: Auerbach Publications.

Benjaafar, S., Li, Y. and Daskin, M. (2013) 'Carbon footprint and the management of supply chains: Insights from simple models', *IEEE transactions on automation science and engineering*, 10(1), 99-116.

Ben-Tal, A. and Nemirovski, A. (1999) 'Robust solutions of uncertain linear programs', *Operations research letters*, 25(1), 1-13.

Bertsimas, D. and Sim, M. (2003) 'Robust discrete optimization and network flows', *Mathematical programming*, 98(1-3), 49-71.

Bertsimas, D. and Sim, M. (2004) 'The price of robustness', *Operations research*, 52(1), 35-53.

Bookbinder, J.H. and Reece, K.E. (1988) ‘Vehicle routing considerations in distribution system design’, *European Journal of Operational Research*, 37(2), 204-213.

Cardoso, S. R., Barbosa-Póvoa, A. P. F. and Relvas, S. (2013) ‘Design and planning of supply chains with integration of reverse logistics activities under demand uncertainty’, *European Journal of Operational Research*, 226(3), 436-451.

Chaabane, A., Ramudhin, A. and Paquet, M. (2012) ‘Design of sustainable supply chains under the emission trading scheme’, *International Journal of Production Economics*, 135(1), 37-49.

Chen, X. and Wang, X. (2016) ‘Effects of carbon emission reduction policies on transportation mode selections with stochastic demand’, *Transportation Research Part E: Logistics and Transportation Review*, 90, 196-205.

Cheraghalipour, A. and Farsad, S. (2018) ‘A bi-objective sustainable supplier selection and order allocation considering quantity discounts under disruption risks: A case study in plastic industry’, *Computers & Industrial Engineering*, 118, 237-250.

Choudhary, A., Sarkar, S., Settur, S. and Tiwari, M. (2015) ‘A carbon market sensitive optimization model for integrated forward–reverse logistics’, *International Journal of Production Economics*, 164, 433-444.

Clarke, L., Edmonds, J., Jacoby, H., Pitcher, H., Reilly, J. and Richels, R. (2007) ‘Scenarios of greenhouse gas emissions and atmospheric concentrations.

Das, D. and Dutta, P. (2013) ‘A system dynamics framework for integrated reverse supply chain with three-way recovery and product exchange policy’, *Computers & Industrial Engineering*, 66(4), 720-733.

Das, D. and Dutta, P. (2015) ‘Design and analysis of a closed-loop supply chain in presence of promotional offer’, *International Journal of Production Research*, 53(1), 141-165.

Dasci, A. and Verter, V. (2001) ‘A continuous model for production–distribution system design’, *European Journal of Operational Research*, 129(2), 287-298.

Dembo, R. S. (1991) ‘Scenario optimization’, *Annals of Operations Research*, 30(1), 63–80.

Demirel, N.Ö. and Gökçen, H. (2008) ‘A mixed integer programming model for remanufacturing in reverse logistics environment’, *The International Journal of Advanced Manufacturing Technology*, 39(11-12), 1197-1206.

Diabat, A. and Simchi-Levi, D. (2009) December. A carbon-capped supply chain network problem. In *2009 IEEE international conference on industrial engineering and engineering management*. 8-11 December. Hong Kong, China: IEEE, 523-527.

Diabat, A., Abdallah, T., Al-Refaie, A., Svetinovic, D. and Govindan, K. (2013) ‘Strategic closed-loop facility location problem with carbon market trading’, *IEEE Transactions on Engineering Management*, 60(2), 398-408.

Du, F. and Evans, G.W. (2008) ‘A bi-objective reverse logistics network analysis for post-sale service’, *Computers & Operations Research*, 35(8), 2617-2634.

Dutta, P., Das, D., Schultmann, F. and Fröhling, M. (2016) ‘Design and planning of a closed-loop supply chain with three-way recovery and buy-back offer’, *Journal of Cleaner Production*, 135, 604-619.

Easwaran, G. and Üster, H. (2010) ‘A closed-loop supply chain network design problem with integrated forward and reverse channel decisions’, *IEE transactions*, 42(11), 779-792.

Fahimnia, B., Sarkis, J., Choudhary, A. and Eshragh, A. (2015) ‘Tactical supply chain planning under a carbon tax policy scheme: A case study’, *International Journal of Production Economics*, 164, 206-215.

Fahimnia, B., Sarkis, J., Dehghanian, F., Banihashemi, N. and Rahman, S. (2013) ‘The impact of carbon pricing on a closed-loop supply chain: an Australian case study’, *Journal of Cleaner Production*, 59, 210-225.

Farahani, R.Z., Rezapour, S., Drezner, T. and Fallah, S. (2014) ‘Competitive supply chain network design: An overview of classifications, models, solution techniques and applications’, *Omega*, 45, 92-118.

Fleischmann, M., Beullens, P., Bloemhof-Ruwaard, J. M. and Wassenhove, L. N. (2001) ‘The impact of product recovery on logistics network design’, *Production and operations management*, 10, 156-173.

Francas, D. and Minner, S. (2009) ‘Manufacturing network configuration in supply chains with product recovery’, *Omega*, 37(4), 757-769.

Gao, N. and Ryan, S. M. (2014) ‘Robust design of a closed-loop supply chain network for uncertain carbon regulations and random product flows’, *EURO Journal on Transportation and Logistics*, 3(1), 5-34.

Garcia, D.J. and You, F. (2015) ‘Supply chain design and optimization: Challenges and opportunities’, *Computers & Chemical Engineering*, 81, 153-170.

Garg, K., Kannan, D., Diabat, A. and Jha, P. C. (2015) ‘A multi-criteria optimization approach to manage environmental issues in closed loop supply chain network design’, *Journal of Cleaner Production*, 100, 297-314.

Geoffrion, A.M. and Graves, G.W. (1974) ‘Multicommodity distribution system design by Benders decomposition’, *Management science*, 20(5), 822-844.

Georgiadis, P. and Besiou, M. (2008) ‘Sustainability in electrical and electronic equipment closed-loop supply chains: a system dynamics approach’, *Journal of Cleaner Production*, 16(15), 1665-1678.

Georgiadis, P. and Besiou, M. (2008) ‘Sustainability in electrical and electronic equipment closed-loop supply chains: a system dynamics approach’, *Journal of Cleaner Production*, 16(15), 1665-1678.

Ghisolfi, V., Chaves, G.D.L.D., Siman, R.R. and Xavier, L.H. (2017) ‘System dynamics applied to closed loop supply chains of desktops and laptops in Brazil: A perspective for social inclusion of waste pickers’, *Waste Management*, 60, 14-31.

Ghomi-Avili, M., Naeini, S. G. J., Tavakkoli-Moghaddam, R. and Jabbarzadeh, A. (2018) ‘A fuzzy pricing model for a green competitive closed-loop supply chain network design in the presence of disruptions’, *Journal of Cleaner Production*, 188, 425-442.

Golroudbary, S.R. and Zahraee, S.M. (2015) ‘System dynamics model for optimizing the recycling and collection of waste material in a closed-loop supply chain’, *Simulation Modelling Practice and Theory*, 53, 88-102.

Govindan, K., Soleimani, H. and Kannan, D. (2015) ‘Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future’, *European Journal of Operational Research*, 240(3), 603-626.

Govindan, K., Jha, P. C. and Garg, K. (2016) ‘Product recovery optimization in closed-loop supply chain to improve sustainability in manufacturing’, *International Journal of Production Research*, 54(5), 1463-1486.

Govindan, K., Fattahi, M. and Keyvanshokooh, E. (2017) ‘Supply chain network design under uncertainty: A comprehensive review and future research directions’, *European Journal of Operational Research*, 263(1), 108-141.

Guide, V. D. R. and Van Wassenhove, L. N. (2001) ‘Managing product returns for remanufacturing’, *Production and operations management*, 10(2), 142-155.

Guide Jr, V. D. R., Teunter, R. H., and Van Wassenhove, L. N. (2003) ‘Matching demand and supply to maximize profits from remanufacturing’, *Manufacturing & Service Operations Management*, 5(4), 303-316.

Haddadsisakht, A. and Ryan, S. M. (2018) ‘Closed-loop supply chain network design with multiple transportation modes under stochastic demand and uncertain carbon tax’, *International Journal of Production Economics*, 195, 118-131.

Hakimi, S.L. (1964) ‘Optimum locations of switching centers and the absolute centers and medians of a graph’, *Operations research*, 12(3), 450-459.

Hakimi, S.L. (1965) ‘Optimum distribution of switching centers in a communication network and some related graph theoretic problems’, *Operations research*, 13(3), 462-475.

Hasani, A., Zegordi, S.H. and Nikbakhsh, E. (2012) ‘Robust closed-loop supply chain network design for perishable goods in agile manufacturing under uncertainty’, *International Journal of Production Research*, 50(16), 4649-4669.

Hoen, K.M.R., Tan, T., Fransoo, J.C. and Van Houtum, G.J. (2014) ‘Effect of carbon emission regulations on transport mode selection under stochastic demand’, *Flexible Services and Manufacturing Journal*, 26(1-2), 170-195.

Hua, G., Cheng, T.C.E. and Wang, S. (2011) ‘Managing carbon footprints in inventory management’, *International Journal of Production Economics*, 132(2), 178-185.

Jabbarzadeh, A., Fahimnia, B., Sheu, J.B. and Moghadam, H.S. (2016) ‘Designing a supply chain resilient to major disruptions and supply/demand interruptions’, *Transportation Research Part B: Methodological*, 94, 121-149.

Jayaraman, V., Guide Jr, V. and Srivastava, R. (1999) ‘A closed-loop logistics model for remanufacturing’, *Journal of the operational research society*, 50(5), 497-508.

Jayaraman, V. and Pirkul, H. (2001) 'Planning and coordination of production and distribution facilities for multiple commodities', *European journal of operational research*, 133(2), 394-408.

Jayaraman, V., Patterson, R.A. and Rolland, E. (2003) 'The design of reverse distribution networks: models and solution procedures', *European journal of operational research*, 150(1), 128-149.

Jayaraman, V. and Ross, A. (2003) 'A simulated annealing methodology to distribution network design and management', *European Journal of Operational Research*, 144(3), 629-645.

Jeihoonian, M., Zanjani, M. K. and Gendreau, M. (2016) 'Accelerating Benders decomposition for closed-loop supply chain network design: Case of used durable products with different quality levels', *European Journal of Operational Research*, 251(3), 830-845.

Jeihoonian, M., Zanjani, M. K. and Gendreau, M. (2017) 'Closed-loop supply chain network design under uncertain quality status: Case of durable products', *International Journal of Production Economics*, 183, 470-486.

Jin, M., Granda-Marulanda, N. A. and Down, I. (2014) 'The impact of carbon policies on supply chain design and logistics of a major retailer', *Journal of Cleaner Production*, 85, 453-461.

Kalaitzidou, M.A., Longinidis, P. and Georgiadis, M.C. (2015) 'Optimal design of closed-loop supply chain networks with multifunctional nodes', *Computers & Chemical Engineering*, 80, 73-91.

Kara, S.S. and Onut, S. (2010) 'A two-stage stochastic and robust programming approach to strategic planning of a reverse supply network: The case of paper recycling', *Expert Systems with Applications*, 37(9), 6129-6137.

Kaut, M. and Wallace, S. W. (2007) 'Evaluation of scenario-generation methods for stochastic programming', *Pacific Journal of Optimization*, 3(2), 257–271.

Keyvanshokooh, E., Fattahi, M., Seyed-Hosseini, S.M. and Tavakkoli-Moghaddam, R. (2013) 'A dynamic pricing approach for returned products in integrated forward/reverse logistics network design', *Applied Mathematical Modelling*, 37(24), 10182-10202.

Keyvanshokooh, E., Ryan, S. M. and Kabir, E. (2016) 'Hybrid robust and stochastic optimization for closed-loop supply chain network design using accelerated

Benders decomposition’, *European Journal of Operational Research*, 249(1), 76-92.

Kisomi, M. S., Solimanpur, M. and Doniavi, A. (2016) ‘An integrated supply chain configuration model and procurement management under uncertainty: a set-based robust optimization methodology’, *Applied Mathematical Modelling*, 40(17-18), 7928-7947.

Li, Z., Ding, R. and Floudas, C.A. (2011) ‘A comparative theoretical and computational study on robust counterpart optimization: I. Robust linear optimization and robust mixed integer linear optimization’, *Industrial & engineering chemistry research*, *50*(18), 10567-10603.

Lieckens, K. and Vandaele, N. (2007) ‘Reverse logistics network design with stochastic lead times’, *Computers & Operations Research*, 34(2), 395-416.

Listeş, O. and Dekker, R. (2005) ‘A stochastic approach to a case study for product recovery network design’, *European Journal of Operational Research*, 160(1), 268-287.

Marufuzzaman, M., Eksioglu, S. D. and Huang, Y. (2014) ‘Two-stage stochastic programming supply chain model for biodiesel production via wastewater treatment’, *Computers & Operations Research*, 49, 1-17.

Masoudipour, E., Amirian, H. and Sahraeian, R. (2017) ‘A novel closed-loop supply chain based on the quality of returned products’, *Journal of cleaner production*, 151, 344-355.

Meixell, M.J. and Gargeya, V.B. (2005) ‘Global supply chain design: A literature review and critique’, *Transportation Research Part E: Logistics and Transportation Review*, 41(6), 531-550.

Melo, M.T., Nickel, S. and Saldanha-da-Gama, F. (2009) ‘Facility location and supply chain management–A review’, *European journal of operational research*, 196(2), 401-412.

Mohajeri, A. and Fallah, M. (2016) ‘A carbon footprint-based closed-loop supply chain model under uncertainty with risk analysis: A case study’, *Transportation Research Part D: Transport and Environment*, 48, 425-450.

Mula, J., Peidro, D., Díaz-Madroñero, M. and Vicens, E. (2010) ‘Mathematical programming models for supply chain production and transport planning’, *European Journal of Operational Research*, 204(3), 377-390.

Özceylan, E., Paksoy, T. and Bektaş, T. (2014) 'Modeling and optimizing the integrated problem of closed-loop supply chain network design and disassembly line balancing', *Transportation research part E: logistics and transportation review*, 61, 142-164.

Özkır, V. and Başlıgil, H. (2013) 'Multi-objective optimization of closed-loop supply chains in uncertain environment', *Journal of Cleaner Production*, 41, 114-125.

Paksoy, T., Bektaş, T. and Özceylan, E. (2011) 'Operational and environmental performance measures in a multi-product closed-loop supply chain', *Transportation Research Part E: Logistics and Transportation Review*, 47(4), 532-546.

Palak, G., Ekşioğlu, S.D. and Geunes, J. (2014) 'Analyzing the impacts of carbon regulatory mechanisms on supplier and mode selection decisions: An application to a biofuel supply chain', *International Journal of Production Economics*, 154, 198-216.

Pishvaee, M. S., Jolai, F. and Razmi, J. (2009) 'A stochastic optimization model for integrated forward/reverse logistics network design', *Journal of Manufacturing Systems*, 28, 107-114.

Pishvaee, M.S. and Torabi, S.A. (2010) 'A possibilistic programming approach for closed-loop supply chain network design under uncertainty', *Fuzzy sets and systems*, 161(20), 2668-2683.

Pishvaee, M.S., Kianfar, K. and Karimi, B. (2010) 'Reverse logistics network design using simulated annealing', *The International Journal of Advanced Manufacturing Technology*, 47(1-4), 269-281.

Pishvaee, M. S., Rabbani, M. and Torabi, S. A. (2011) 'A robust optimization approach to closed-loop supply chain network design under uncertainty', *Applied Mathematical Modelling*, 35(2), 637-649.

Pishvaee, M.S. and Rabbani, M. (2011) 'A graph theoretic-based heuristic algorithm for responsive supply chain network design with direct and indirect shipment', *Advances in Engineering Software*, 42(3), 57-63.

Pishvaee, M. S. and Razmi, J. (2012) 'Environmental supply chain network design using multi-objective fuzzy mathematical programming', *Applied Mathematical Modelling*, 36(8), 3433-3446.

Rad, R. S. and Nahavandi, N. (2018) 'A novel multi-objective optimization model for integrated problem of green closed loop supply chain network design and quantity discount', *Journal of cleaner production*, 196, 1549-1565.

Rahmani, D. and Mahoodian, V. (2017) 'Strategic and operational supply chain network design to reduce carbon emission considering reliability and robustness', *Journal of Cleaner Production*, 149, 607-620.

Ramezani, M., Kimiagari, A. M., Karimi, B. and Hejazi, T. H. (2014) 'Closed-loop supply chain network design under a fuzzy environment', *Knowledge-Based Systems*, 59, 108-120.

Ramudhin, A., Chaabane, A. and Paquet, M. (2010) 'Carbon market sensitive sustainable supply chain network design', *International Journal of Management Science and Engineering Management*, *5*(1), 30-38.

Rebs, T., Brandenburg, M. and Seuring, S. (2018) 'System dynamics modelling for sustainable supply chain management: A literature review and systems thinking approach', *Journal of Cleaner Production,* 208, 1265-1280.

Sabri, E.H. and Beamon, B.M. (2000) 'A multi-objective approach to simultaneous strategic and operational planning in supply chain design', *Omega*, 28(5), 581-598.

Salema, M.I.G., Barbosa-Povoa, A.P. and Novais, A.Q. (2007) 'An optimization model for the design of a capacitated multi-product reverse logistics network with uncertainty', *European Journal of Operational Research*, *179*(3), 1063-1077.

Selim, H. and Ozkarahan, I. (2008) 'A supply chain distribution network design model: an interactive fuzzy goal programming-based solution approach', *The International Journal of Advanced Manufacturing Technology*, 36(3-4), 401-418.

Shi, J., Zhang, G. and Sha, J. (2011) 'Optimal production planning for a multi-product closed loop system with uncertain demand and return', *Computers & Operations Research*, 38(3), 641-650.

Simangunsong, E., Hendry, L.C. and Stevenson, M. (2012) 'Supply-chain uncertainty: a review and theoretical foundation for future research', *International Journal of Production Research*, 50(16), 4493-4523.

Simchi-Levi, D., Kaminsky, P. and Simchi-Levi, E. (2004) '*Managing the Supply Chain: Definitive Guide*. Tata McGraw-Hill Education.

Soleimani, H., Seyyed-Esfahani, M. and Shirazi, M.A. (2013) 'Designing and planning a multi-echelon multi-period multi-product closed-loop supply chain utilizing genetic algorithm', *The International Journal of Advanced Manufacturing Technology*, 68(1-4), 917-931.

Soleimani, H. and Govindan, K. (2014) 'Reverse logistics network design and planning utilizing conditional value at risk', *European Journal of Operational Research*, 237(2), 487-497.

Soleimani, H. and Kannan, G. (2015) 'A hybrid particle swarm optimization and genetic algorithm for closed-loop supply chain network design in large-scale networks', *Applied Mathematical Modelling*, 39(14), 3990-4012.

Soleimani, H., Seyyed-Esfahani, M. and Shirazi, M.A. (2016) 'A new multi-criteria scenario-based solution approach for stochastic forward/reverse supply chain network design', *Annals of Operations Research*, 242(2), 399-421.

Souza, G.C. (2013) 'Closed-Loop Supply Chains: A Critical Review, and Future Research', *Decision Sciences*, 44(1), 7-38.

Subramanian, P., Ramkumar, N., Narendran, T.T. and Ganesh, K. (2013) 'PRISM: PRIority based SiMulated annealing for a closed loop supply chain network design problem', *Applied Soft Computing*, 13(2), 1121-1135.

Subulan, K., Taşan, A. S. and Baykasoğlu, A. (2015) 'Designing an environmentally conscious tire closed-loop supply chain network with multiple recovery options using interactive fuzzy goal programming', *Applied Mathematical Modelling*, 39(9), 2661-2702.

Syarif, A., Yun, Y. and Gen, M. (2002) 'Study on multi-stage logistic chain network: a spanning tree-based genetic algorithm approach', *Computers & Industrial Engineering*, 43(1-2), 299-314.

Taleizadeh, A.A., Haghighi, F. and Niaki, S.T.A. (2019) 'Modeling and solving a sustainable closed loop supply chain problem with pricing decisions and discounts on returned products', *Journal of Cleaner Production*, 207, 163-181.

Tao, Z. G., Guang, Z. Y., Hao, S. and Song, H. J. (2015) 'Multi-period closed-loop supply chain network equilibrium with carbon emission constraints', *Resources, Conservation and Recycling*, 104, 354-365.

United Nations Climate Change Conference. (2015, 30 November to 12 December) *COP 21Paris*.

Vahdani, B., Tavakkoli-Moghaddam, R., Modarres, M. and Baboli, A. (2012) 'Reliable design of a forward/reverse logistics network under uncertainty: A robust-M/M/c queuing model', *Transportation Research Part E: Logistics and Transportation Review*, 48(6), 1152-1168.

Vlachos, D., Georgiadis, P. and Iakovou, E. (2007) 'A system dynamics model for dynamic capacity planning of remanufacturing in closed-loop supply chains', *Computers & Operations Research*, 34(2), 367-394.

Wang, M., Liu, K., Choi, T.M. and Yue, X. (2015) 'Effects of carbon emission taxes on transportation mode selections and social welfare', *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 45(11), 1413-1423.

World Bank; Ecofys. 2017. Carbon Pricing Watch 2017. Washington, DC: © World Bank.

Xu, Z., Pokharel, S., Elomri, A. and Mutlu, F. (2017) 'Emission policies and their analysis for the design of hybrid and dedicated closed-loop supply chains', *Journal of cleaner production*, 142, 4152-4168.

Yamzon, A., Ventura, V., Guico, P. and Sy, C. (2016) 'Optimal planning of incentive-based quality in closed-loop supply chains', *Clean Technologies and Environmental Policy*, 18(5), 1415-1431.

Zakeri, A., Dehghanian, F., Fahimnia, B. and Sarkis, J. (2015) 'Carbon pricing versus emissions trading: A supply chain planning perspective', *International Journal of Production Economics*, 164, 197-205.

Zarbakhshnia, N., Soleimani, H., Goh, M. and Razavi, S. S. (2019) 'A novel multi-objective model for green forward and reverse logistics network design', *Journal of cleaner production*, 208, 1304-1316.

Zeballos, L. J., Méndez, C. A., Barbosa-Povoa, A. P. and Novais, A. Q. (2014) 'Multi-period design and planning of closed-loop supply chains with uncertain supply and demand', *Computers & Chemical Engineering*, 66, 151-164.

Corporate Value Chain (Scope 3) Accounting and Reporting Standard. World Recourse Institutes. https://ghgprotocol.org/standards/scope-3-standard

LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Mohammed, F**., Selim, S.Z., Hassan, A. and Syed, M.N., 2017. Multi-period planning of closed-loop supply chain with carbon policies under uncertainty. *Transportation Research Part D: Transport and Environment*, 51, 146-172. https://doi.org/10.1016/j.trd.2016.10.033. (**Q1, IF: 4.051**)

2. **Mohammed, F**., Hassan, A. and Selim, S.Z., 2018. Robust optimization for closed-loop supply chain network design considering carbon policies under uncertainty. *International Journal of Industrial Engineering: Theory, Applications and Practice*, 25(4), 526-558. (**Q4, IF: 0.565**)

Indexed Journal

1. **Mohammed, F**., Hassan, A. and Selim, S.Z., 2018. Carbon market sensitive robust optimization model for closed loop supply chain network design under uncertainty. Journal of Physics: Conf. Series 1150 (2019) 012009. doi:10.1088/1742-6596/1150/1/012009. **(Indexed by SCOPUS)**

Indexed Conference Proceedings

1. **Fareeduddin, M**., Hassan, A., Syed, M.N. and Selim, S.Z., 2015. The impact of carbon policies on closed-loop supply chain network design. In *12th Global Conference on Sustainable Manufacturing – Emerging Potentials*. *Procedia CIRP*, *26*, pp.335-340. https://doi.org/10.1016/j.procir.2014.07.042. **(Indexed by SCOPUS)**