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DEVELOPMENT OF A ROBUST BI-OBJECTIVE MODEL FOR CLOSED LOOP SUPPLY CHAIN NETWORK

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DEVELOPMENT OF A ROBUST BI-OBJECTIVE MODEL FOR CLOSED LOOP SUPPLY CHAIN NETWORK

By

GHAZALEH TAHOORI

Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia, in fulfillment of the requirements for the Degree of Master of Science

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DEDICATION

To my beloved parents who are the meaning of life to me and gave me unconditional love and support.

Abstract of thesis to be presented to the senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

DEVELOPMENT OF A ROBUST BI-OBJECTIVE MODEL FOR CLOSED LOOP SUPPLY CHAIN NETWORK

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December 2014

Chairman: Rosnah Binti Mohd Yusuff, PhD
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Closed Loop Supply Chain (CLSC) is very influential in improving the company's reputation and business competitiveness. One of the most critical strategic decisions in CLSC planning is network design. Decision makers and supply chain planners are struggling with conflicting objectives with uncertain and ambiguous data. Furthermore, uncertainty results in infeasibility and most of the methods applied for dealing with uncertainty are unable to incorporate this infeasibility and only focus on the improvement of the obejective value. Therefore, decision makers need to apply methods which enable them to strike a balance between model feasibility and solution optimality. In order to address this issue, a bi-objective model applying robust optimization in CLSC network design is proposed in this research work. This model minimizes total cost and total environmental impact of the supply chain while defining the location of facilities and the quantities of products transported among different facilities, quantity of products to be produced, total cost and total environmental impact of different configurations. Measuring environmental impact of the supply chain is implemented using a method based on LCA (Life Cycle Assessment), i.e., ReCipe 2008. The data used regarding environmental impact scores were derived from ECO-it software. The augmented ε-constraint method is used to solve the bi-objective model. To be more precise, this study gives an insight to managers in striking a balance between economic and environmental aspects of the supply chain. The results of this research were able to define the optimum network design with minimum cost and environmental impact under uncertain demand of customers. The proposed robust model has been validated by obtaining some basic data from a case study conducted by various authors in a pulp and paper industry in Europe. However, further relevant information required for the model was obtained from various sources. The efficiency of the robust model was then verified by a comparison with the equivalent deterministic model using two

performance measures: mean value to validate the solution quality and standard deviation. Computational results of the model show that robust solution reduces mean and standard deviation of total cost and total environmental impact comparing to deterministic model.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PEMBANGUNAN MODEL TEGUH DWI OBJEKTIF UNTUH RANGKAIAN BEKALAN TERTUTUP

Oleh

GHAZALEH TAHOORI

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Rantaian Bekalan Gelung Tertutup (RBGT) sangat berpengaruh dalam meningkatkan reputasi dan daya saing syarikat. Salah satu keputusan strategik yang paling penting dalam RBGT ialah reka bentuk rangkaian. Pembuat keputusan dan perancang rantaian bekalan bergelut dengan objektif yang bercanggah dan data yang kabur serta tidak menentu. Tambahan pula, ketidaktentuan menyebabkan ketakbolehlaksanaan dan kebanyakan kaedah yang digunakan bagi menguruskan ketidaktentuan ini tidak dapat menampung ketakbolehlaksanaan tetapi hanya tertumpu kepada penambahbaikan nilai objektif sahaja. Oleh sebab itu, pembuat keputusan perlu menggunakan kaedah yang membolehkan mereka mendapat keseimbangan antara model kebolehlaksanaan dan pengoptimuman penyelesaian. Bagi menangani isu ini, model dwi objektif yang menggunakan pengoptimuman teguh dalam reka bentuk rangkaian RBGT dicadangkan dalam kajian ini. Model ini meminimumkan jumlah kos dan jumlah impak persekitaran rantaian bekalan serta pada masa yang sama menjelaskan lokasi kemudahan dan kuantiti produk yang dikeluarkan, jumlah kos dan jumlah impak persekitaran bagi konfigurasi yang berbeza. Pengukuran impak persekitaran bagi rantaian bekalan dilaksanakan menggunakan kaedah berasaskan-LCA, iaitu ReCipe 2008. Data yang digunakan untuk skor impak persekitaran diperoleh daripada perisian ECO-it. Kaedah imbuh ε-kekangan digunakan bagi menyelesaikan model dwi-objektif. Tuntasnya, kajian ini memberi tanggapan kepada pengurus terhadap kepentingan mewujudkan keseimbangan antara ekonomi dan aspek persekitaran dalam rantaian bekalan. Hasil kajian ini dapat menjelaskan reka bentuk jaringan yang optimum dengan kos dan impak persekitaran yang minimum dalam keadaan ketidaktentuan permintaan pelanggan.Model teguh yang dicadangkan telah disahkan dengan mendapatkan beberapa data asas daripada kajian kes yang dilakukan oleh beberapa orang penulis dalam industri palpa dan kertas di Eropah. Walau bagaimanapun, maklumat lanjut yang berkaitan diperlukan kerana model diperoleh daripada pelbagai sumber. Keberkesanan model teguh tersebut telah diverifikasikan dengan membuat perbandingan dengan model deterministic yang

setara mengguna dua ukuran prestasi: nilai min untuk mengesah kualiti penyelesaian dan sisihan piawai. Hasil pengiraan menunjukkan penyelesaian teguh mengurangkan min dan sisihan plawai kos menyeluruh dan impak persekitaran berbanding dengan model deterministik.

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I certify that a Thesis Examination Committee has met on 30 December 2014 to conduct the final examination of Ghazaleh Tahoori on her thesis entitled "Development of a Robust Bi-Objective Model for Closed-Loop Supply Chain Network" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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LIST OF ABBREVIATIONS

CLSC	Closed Loop Supply Chain
RL	Reverse Logistic
SC	Supply Chain
APP	Aggregate Production Planning
CLM	Council of Logistics Management
CLSCM	Closed Loop Supply Chain Management
OEM	Original Equipment Manufacturer
WCED	World Commission on Environment and Development
SSCN	Sustainable Supply Chain Networks
MILP	Mixed Integer Linear Programming
LP	Linear Optimization
SDP	Semi-Definite Optimization
SOCP	Second Order Cone Optimization
OR	Operations Research
VaR	Value-at-Risk
DM	Decision Maker
NBI	Normal Boundary Intersection
NC	Normal Constraint
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
LCA	Life Cycle Assessment
SETAC	Society of Environmental Toxicology and Chemistry
UNEP	United Nations Environment Programme
ISO	International Organization for Standardization
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
AoPs	Areas of Protection
CML	Center of Environmental Science of Leiden University
NPV	Net Present Value
APME	Association of Plastics Manufacturers in Europe
MOMP	Multi-Objective Mathematical Programming
RHS	Right Hand Side
GAMS	General Algebraic Modeling Language

CHAPTER ONE

INTRODUCTION

1.1 Network Design in Closed Loop Supply Chain

Closed Loop Supply Chain (CLSC) is concerned with simultaneous management of the forward and reverse chain in order to create value from the return flow of materials, products or components and meanwhile reduce the environmental impacts of the system (Zarandi, et al., 2011; Krikke, et al., 2001). The primary objective of CLSC is maximizing economic benefit, adding the reverse chain and closing the loop in order to minimize the environmental impact. This will consequently improve the company's reputation and business competitiveness (Stindt and Sahamie, 2012; Neto, et al., 2010).

One of the most critical strategic decisions in supply chain planning is network design which defines the structure of the supply chain and the interconnections of the facilities. Generally, network design is concerned with determining the numbers, locations and capacities of facilities, the material flow and transportation links between them (Correia, et al., 2012; Pishvaee, et al., 2011). The real world problems in network design area are multi-period and multi-objective. Besides, using deterministic supply chain is completely unrealistic since there are various sources of uncertainty in supply chain. Generally, it is impossible to completely remove uncertainty from the supply chain therefore different techniques are applied for optimization under uncertainty. Optimization of supply chain under uncertainty is usually a complex task and requires application of efficient methods capable of incorporating perturbations of data which is an inherent characteristic of real life supply chains (Klibi, et al., 2010; Sabri and Beamon, 2000).

1.2 Problem Statement

Nowadays there is a growing trend for developing multi-period and multi-objective models at strategic level of supply chain incorporating the uncertainty by applying *robust optimization*. In fact it is highly important to contemplate the uncertainty in supply chain because in real world problems a small uncertainty in the data would make the usually-considered-optimal solutions completely meaningless.

Generally three major methods are applied to deal with the uncertainty in supply chain: *Fuzzy methods*, *stochastic programming* and *robust optimization*. Many research works in supply chain have applied stochastic programming in order to deal with uncertainty. However, *stochastic programming* is unable to incorporate the infeasibility in optimization and focuses more on improving the objective performance. Models applying *fuzzy method* were generally used when the mathematical model of the process under study is not available. *Robust optimization* is capable of striking a balance between model feasibility and solution optimality on one hand, and keeping the solution and performance immune against the uncertainty of vague parameters on the other hand.

A wave of new research works applying *robust optimization* in supply chain is increasing during very recent years. However, most of these research works are focused on tactical and operational levels of supply chain (Wang and Huang, 2013; Mirzapour Al-E-Hashem, et al., 2011; Leung, et al., 2007; Wu, 2006) and the application of *robust optimization* at strategic level is still scarce and limited to single objective models (Ramezani, et al., 2013b; Alumur, et al., 2012a; Pishvaee, et al., 2011; Pan and Nagi, 2010). Consequently, lack of a bi-objective robust model incorporating both environmental and economic aspects of sustainable supply chain is observed in strategic supply chain planning. Therefore, the necessity of proposing a model incorporating all multi-period, multi-objective and uncertain features which enables the contemplation of vagueness and uncertain environment is evident. Considering the comprehensiveness and flexibility of *robust optimization* and scarce number of robust models integrating both environmental and economic aspects of sustainability in supply chain network design, developing such model to deal with uncertainty would be significantly beneficial to overcome the real world challenges in strategic level of supply chain.

1.3 Objectives of the Study

This research study is an effort to develop a Mixed Integer Linear Programming (MILP) bi-objective multi-period model in CLSC network design applying *robust optimization* in order to define the optimal facility location and optimal flows among nodes while minimizing both total cost and total environmental impact of the network. To be more precise, the major objectives of this research work are:

1- Develop a robust CLSC network incorporating the economic and environmental aspects.

2- Validate the proposed robust model in a case study for the pulp and paper industry.

This research is one of the scarce applications of bi-objective robust optimization in CLSC network design.

1.4 Significance of Study

Most of the models previously presented by researchers in supply chain area applying robust optimization are either single objective or developed at operational or tactical level. Therefore, the main contribution of this study is that the model proposed in this research work is one of the first bi-objective robust models in strategic level of CLSC incorporating economic and environmental aspects of supply chain.

1.5 Scope and limitation

Some of the assumptions and limitations of the proposed model are as follows:

First of all the validation of the proposed model is limited to a case study of paper industry in Europe. However, this model could be applied in other industries as well specially in process industries such as steel industry or chemical industry.

One of the limitations of this study is the difficulty of accessing data for environmental impacts assessment of the supply chain concerning different material and processes. The required data is available in different international or national, general or industrial based databases. If there is no data regarding a specific process or activity in the supply chain, some assumptions should be made in the life cycle assessment process by model developers or decision makers in order to incorporate the insufficiency of information.

Since the supply chain network design is targeted in this research study which is a strategic decision, regarding some of the environmental impact information the average data is used, however this is not possible for tactical or operational level decision making such as Aggregate Production Planning (APP) or Scheduling.

1.6 Organization of the Thesis

This thesis is aimed to practice the application of bi-objective robust optimization in CLSC network design. This work is done through chapters one to five of this research study.

The first chapter of this thesis provides an introduction of the current research work, problem statement, research objectives and significance of study, scope and limitations, and the organization of the thesis.

The second chapter is reviewing the available literature regarding CLSC, the evolution of supply chain, different issues in supply chain, optimization under uncertainty, robust optimization, its background and applications, and different multi-objective optimization approaches. Furthermore, Life Cycle Assessment (LCA), LCA structure and components, software and databases, and the role of LCA in Green Supply Chain (GSC) are discussed as well. At the end a brief discussion of major issues in pulp and paper industry is presented.

The third chapter describes the detailed outline of the methodology of the current research. Also comprehensive explanation of robust optimization and augmented ε-constraint method (as the multi objective methodology) are presented in this chapter.

Chapter four presents the mathematical modeling, model assumptions, objective functions and constraints of the proposed model. This chapter also reports the results of the model after implementing the case study. Moreover, analysis of data and efficiency of the proposed model is illustrated by graphs and figures.

Chapter five presents the conclusions of the model in order to fulfill the objectives of this research study and address recommendations for future researches and possible development areas in the field of study.

REFERENCES

Adida, E., and Perakis, G. (2006). A robust optimization approach to dynamic pricing and inventory control with no backorders. *Mathematical Programming, 107*(1-2), 97-129.

Akçalı, E., Cetinkaya, 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.

Al-e, S. M. J. M., Aryanezhad, M. B., and Sadjadi, S. J. (2012). An efficient algorithm to solve a multi-objective robust aggregate production planning in an uncertain environment. *The International Journal of Advanced Manufacturing Technology, 58*(5-8), 765-782.

Alumur, S. A., Nickel, S., and Saldanha-da-Gama, F. (2012a). Hub location under uncertainty. *Transportation Research Part B: Methodological, 46*(4), 529-543.

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

Amin, S., and Zhang, G. (2012). A proposed mathematical model for closed-loop network configuration based on product life cycle. *The International Journal of Advanced Manufacturing Technology, 58*(5-8), 791-801.

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.

Assavapokee, T., Realff, M. J., Ammons, J. C., and Hong, I. (2008). Scenario relaxation algorithm for finite scenario-based min–max regret and min–max relative regret robust optimization. *Computers & Operations Research, 35*(6), 2093-2102.

Atamtürk, A., and Zhang, M. (2007). Two-stage robust network flow and design under demand uncertainty. *Operations Research, 55*(4), 662-673.

Azaron, A., Brown, K., Tarim, S., and Modarres, M. (2008). A multi-objective stochastic programming approach for supply chain design considering risk. *International Journal of Production Economics, 116*(1), 129-138.

Azaron, A., Furmans, K., and Modarres, M. (2010). Multi-objective stochastic programming approaches for supply chain management *New Developments in Multiple Objective and Goal Programming* (pp. 1-14): Springer.

Baron, O., Milner, J., and Naseraldin, H. (2011). Facility location: A robust optimization approach. *Production and Operations Management, 20*(5), 772-785.

Beamon, B. M. (1998). Supply chain design and analysis:: Models and methods. *International Journal of Production Economics, 55*(3), 281-294.

Beamon, B. M., and Fernandes, C. (2004). Supply-chain network configuration for product recovery. *Production Planning & Control, 15*(3), 270-281.

Bede, B. (2013). *Mathematics of Fuzzy Sets and Fuzzy Logic*: Springer.

Ben-Tal, A., El Ghaoui, L., and Nemirovski, A. (2009). *Robust optimization*: Princeton University Press.

Ben-Tal, A., and Nemirovski, A. (2000). Robust solutions of linear programming problems contaminated with uncertain data. *Mathematical Programming, 88*(3), 411-424.

Ben-Tal, A., and Nemirovski, A. (2002). Robust optimization–methodology and applications. *Mathematical Programming, 92*(3), 453-480.

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

Beyer, H.-G., and Sendhoff, B. (2007). Robust optimization–a comprehensive survey. *Computer methods in applied mechanics and engineering, 196*(33), 3190-3218.

Blanquero, R., Carrizosa, E., and Hendrix, E. M. (2011). Locating a competitive facility in the plane with a robustness criterion. *European Journal of Operational Research, 215*(1), 21-24.

Branke, J., Deb, K., Miettinen, K., and Slowinski, R. (2008). *Multiobjective optimization: Interactive and evolutionary approaches* (Vol. 5252): Springer.

Calculator, T. D. (2013). Estimated Travel Distance between European Cities. Retrieved Nov 2013, from http://www.mapcrow.info/european_travel_distance.html

CML, C. o. E. S. o. L. U. (2009). CMLCA. Retrieved 14 Apr 2014, 2014, from http://www.cml.leiden.edu/software/software-cmlca.html

Communications, i. (2004). FACTS ABOUT PAPER AND PAPER WASTE.

Consultants, P. (2000). Eco-indicator 99 Manual for designers. *Ministry of Housing, Spatial Planning and the Environment*.

Consultants, P. (2008). SimaPro Database Manual Methods library. *PRé Consultants, The Netherlands*.

Cooper, J., Browne, M., and Peters, M. (1991). *European logistics: markets, management and strategy*: Blackwell Business.

Correia, I., Melo, T., and Saldanha-da-Gamac, F. (2012). Comparing classical performance measures for a multi-period, two-echelon supply chain network design problem with sizing decisions. *Computers & Industrial Engineering*.

De Brito, M. P., and Dekker, R. (2004). *A framework for reverse logistics*: Springer.

Dekker, R., Inderfurth, K., Van Wassenhove, L., and Fleischmann, M. (2004). Quantitative approaches to reverse logistics: Springer, Berlin Heidelberg New York.

Dreyer, L. C., Niemann, A. L., and Hauschild, M. Z. (2003). Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99. *The International Journal of Life Cycle Assessment, 8*(4), 191-200.

Du, X., and Chen, W. (2000). Towards a better understanding of modeling feasibility robustness in engineering design. *Journal of Mechanical Design, 122*(4), 385-394.

El-Sayed, M., Afia, N., and El-Kharbotly, A. (2010). A stochastic model for forward–reverse logistics network design under risk. *Computers & Industrial Engineering, 58*(3), 423-431.

El Ghaoui, L., Oustry, F., and Lebret, H. (1998). Robust solutions to uncertain semidefinite programs. *SIAM Journal on Optimization, 9*(1), 33-52.

Finnveden, G., and Ekvall, T. (1998). Life-cycle assessment as a decision-support tool—the case of recycling versus incineration of paper. *Resources, Conservation and Recycling, 24*(3), 235-256.

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*(2), 156-173.

Fleischmann, M., Krikke, H. R., Dekker, R., and Flapper, S. D. P. (2000). A characterisation of logistics networks for product recovery. *Omega*, *28*(6), 653-666.

Frischknecht, R., and Rebitzer, G. (2005). The ecoinvent database system: a comprehensive web-based LCA database. *Journal of Cleaner Production, 13*(13), 1337-1343.

Gabrel, V., Lacroix, M., Murat, C., and Remli, N. (2011). Robust location transportation problems under uncertain demands. *Discrete Applied Mathematics*.

Gabrel, V., Murat, C., and Thiele, A. (2013). Recent advances in robust optimization: An overview. *European Journal of Operational Research*.

Gao, N. (2012). *Essays on product return management and closed loop-supply chain network design.* Unpublished Ph.D., Iowa State University, United States -- Iowa.

Garner, J. W. (2002). Pulp & Paper Magazine : Energy Conservation Practices Offer Environmental and Cost Benefits. Retrieved May 2014, 2014, from http://www.risiinfo.com/magazines/October/2002/PP/pulp-paper/magazine/october/2002/Energy-Conservation-Practices-Offer-Environmental-and-Cost-Benefits.html

Ghaoui, L. E., Oks, M., and Oustry, F. (2003). Worst-case value-at-risk and robust portfolio optimization: A conic programming approach. *Operations Research, 51*(4), 543-556.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., and van Zelm, R. (2009). ReCiPe 2008. *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, 1*(First edition (version 1.08)).

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., and van Zelm, R. (2013). ReCiPe 2008. *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, 1*(First edition (version 1.08)).

Goedkoop, M., and Spriensma, R. (2001). The eco-indicator99: A damage oriented method for life cycle impact assessment: Methodology report.

Guide Jr, V. D. R., and Van Wassenhove, L. N. (2009). The evolution of closed-loop supply chain research. *Operations Research, 57*(1), 10-18.

Guide, V. D. R., Harrison, T. P., and Van Wassenhove, L. N. (2003). The challenge of closed-loop supply chains. *Interfaces, 33*(6), 3-6.

Guillén-Gosálbez, G., and Grossmann, I. E. (2009). Optimal design and planning of sustainable chemical supply chains under uncertainty. *AIChE Journal, 55*(1), 99-121.

Gülpınar, N., Pachamanova, D., and Çanakoğlu, E. (2013). Robust strategies for facility location under uncertainty. *European Journal of Operational Research, 225*(1), 21-35.

Gupta, A., and Evans, G. W. (2009). A goal programming model for the operation of closed-loop supply chains. *Engineering optimization, 41*(8), 713-735.

Harvey, W. (1975). Principles of operations research: Prentice Hall Publications.

Hassanzadeh Amin, S. (2012). *Design and Optimization of Closed-Loop Supply Chain Management.* Unpublished NR78499, University of Windsor (Canada), Canada.

Herrmann, J. W. (1999). *A genetic algorithm for minimax optimization problems*. Paper presented at the Evolutionary Computation, 1999. CEC 99. Proceedings of the 1999 Congress on.

Hinojosa, Y., Kalcsics, J., Nickel, S., Puerto, J., and Velten, S. (2008). Dynamic supply chain design with inventory. *Computers & Operations Research, 35*(2), 373-391.

Hong, I.-H., Assavapokee, T., Ammons, J., Boelkins, C., Gilliam, K., Oudit, D., Realff, M. J., et al. (2006). Planning the e-scrap reverse production system under uncertainty in the state of Georgia: A case study. *Electronics Packaging Manufacturing, IEEE Transactions on, 29*(3), 150-162.

Huang, D., Fabozzi, F. J., and Fukushima, M. (2007). Robust portfolio selection with uncertain exit time using worst-case VaR strategy. *Operations research letters, 35*(5), 627-635.

Hugo, A., and Pistikopoulos, E. (2005). Environmentally conscious long-range planning and design of supply chain networks. *Journal of Cleaner Production, 13*(15), 1471-1491.

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.

Kasah, T. (2014). LCA of a newsprint paper machine: a case study of capital equipment. *The International Journal of Life Cycle Assessment, 19*(2), 417-428.

Klibi, W., Martel, A., and Guitouni, A. (2010). The design of robust value-creating supply chain networks: a critical review. *European Journal of Operational Research, 203*(2), 283-293.

Klir, G. J., and Yuan, B. (1995). *Fuzzy sets and fuzzy logic* (Vol. 4): Prentice Hall New Jersey.

Klöpffer, W. (2014). Introducing Life Cycle Assessment and its Presentation in 'LCA Compendium'. In W. Klöpffer (Ed.), *LCA Compendium – The Complete World of Life Cycle Assessment* (pp. 262): Springer Netherlands.

Kopicki, R., Berg, M. J., and Legg, L. (1993). Reuse and recycling-reverse logistics opportunities.

Kouvelis, P., and Yu, G. (1997). *Robust discrete optimization and its applications* (Vol. 14): Springer.

Krikke, H., Bloemhof-Ruwaard, J., and van Wassenhove, L. N. (2001). *Design Principles for Closed Loop Supply Chains: Optimizing Economic, Logistics and Environmental Performance*: Erasmus Research Institute of Management, Erasmus Universiteit.

Kuo, T. C. (2011). The study of production and inventory policy of manufacturing/remanufacturing environment in a closed-loop supply chain. *International Journal of Sustainable Engineering, 4*(4), 323-329.

Laporte, G., Mesa, J. A., and Perea, F. (2010). A game theoretic framework for the robust railway transit network design problem. *Transportation Research Part B: Methodological, 44*(4), 447-459.

Laviolette, M., Seaman, J. W., Barrett, J. D., and Woodall, W. H. (1995). A probabilistic and statistical view of fuzzy methods. *Technometrics, 37*(3), 249-261.

Lebreton, B. (2006). *Strategic closed-loop supply chain management* (Vol. 586): Springer.

Lebreton, B. (2007). Strategic Network Planning in Closed-Loop Supply Chains. *Strategic Closed-Loop Supply Chain Management*, 67-96.

Leiden, C. V. M. (2001). Part 3: Scientific Background. In: Guinée et al., eds., Life Cycle Assessment: An Operational Guide to the ISO Standards, A Report for the Ministries of Housing, Spatial Planning and the Environment, Economic Affairs, Transport, Public Works and Water Management, Agriculture, Nature Management and Fisheries, CML, Leiden University, The Netherlands.

letsrecycle. (2001). Recovered paper chiefs agree to look at price mechanisms. Retrieved 9 June 2014, from http://www.letsrecycle.com/news/latest-news/general/recovered-paper-chiefs-agree-to-look-at-price-mechanisms

letsrecycle. (2002a). Paper industry resolves PRN dispute and calls for higher landfill costs. Retrieved 9 June 2014, from http://www.letsrecycle.com/news/latest-news/paper-industry-resolves-prn-dispute-and-calls-for-higher-landfill-costs/

letsrecycle. (2002b). Three-year time bomb for unsorted comingled kerbside schemes. Retrieved 9 June 2014, from http://www.letsrecycle.com/news/latest-news/paper/three-year-time-bomb-for-unsorted-comingled-kerbside-schemes

Leung, S. C., Tsang, S. O., Ng, W., and Wu, Y. (2007). A robust optimization model for multi-site production planning problem in an uncertain environment. *European Journal of Operational Research, 181*(1), 224-238.

Li, C., and Liu, S. (2013). A robust optimization approach to reduce the bullwhip effect of supply chains with vendor order placement lead time delays in an uncertain environment. *Applied Mathematical Modelling, 37*(3), 707-718.

Li, Y., Huang, G. H., Nie, X., and Nie, S. (2008). A two-stage fuzzy robust integer programming approach for capacity planning of environmental management systems. *European Journal of Operational Research, 189*(2), 399-420.

Linton, J. D., Klassen, R., and Jayaraman, V. (2007). Sustainable supply chains: An introduction. *Journal of Operations Management, 25*(6), 1075-1082.

Liu, G., and Wu, J. (2011, 15-17 July 2011). *Research trends of network design for closed-loop supply chain.* Paper presented at the Software Engineering and Service Science (ICSESS), 2011 IEEE 2nd International Conference on.

Marler, R. T., and Arora, J. S. (2004). Survey of multi-objective optimization methods for engineering. *Structural and multidisciplinary optimization, 26*(6), 369-395.

Mavrotas, G. (2009). Effective implementation of the epsilon-constraint method in multi-objective mathematical programming problems. *Applied Mathematics and Computation, 213*(2), 455-465.

Melvyn, S. (2004). *Robust optimization.* PhD. Thesis, Massachusetts Institute of Technology.

Minoux, M. (2009). On robust maximum flow with polyhedral uncertainty sets. *Optimization Letters, 3*(3), 367-376.

Mirzapour Al-E-Hashem, S., Malekly, H., and Aryanezhad, M. (2011). A multi-objective robust optimization model for multi-product multi-site aggregate production planning in a supply chain under uncertainty. *International Journal of Production Economics, 134*(1), 28-42.

Mudchanatongsuk, S., Ordóñez, F., and Liu, J. (2008). Robust solutions for network design under transportation cost and demand uncertainty. *Journal of the Operational Research Society, 59*(5), 652-662.

Mulvey, J. M., Vanderbei, R. J., and Zenios, S. A. (1995). Robust optimization of large-scale systems. *Operations Research, 43*(2), 264-281.

Nagurney, A., and Qiang, Q. (2009). A relative total cost index for the evaluation of transportation network robustness in the presence of degradable links and alternative travel behavior. *International Transactions in Operational Research, 16*(1), 49-67.

Neto, J. Q. F., Walther, G., Bloemhof, J., Van Nunen, J., and Spengler, T. (2010). From closed-loop to sustainable supply chains: the WEEE case. *International Journal of Production Research, 48*(15), 4463-4481.

Nie, X., Huang, G., Li, Y., and Liu, L. (2007). IFRP: A hybrid interval-parameter fuzzy robust programming approach for waste management planning under uncertainty. *Journal of Environmental Management, 84*(1), 1-11.

Ochoa de Alda, J. A. (2008). Feasibility of recycling pulp and paper mill sludge in the paper and board industries. *Resources, Conservation and Recycling, 52*(7), 965-972.

Ordóñez, F., and Zhao, J. (2007). Robust capacity expansion of network flows. *Networks, 50*(2), 136-145.

Owsianiak, M., Laurent, A., Bjørn, A., and Hauschild, M. Z. (2014). IMPACT 2002+, ReCiPe 2008 and ILCD's recommended practice for characterization modelling in life cycle impact assessment: a case study-based comparison. *The International Journal of Life Cycle Assessment, 19*(5), 1007-1021.

Paksoya, T., Özceylana, E., and Weberb, G.-W. (2011). A multi objective model for optimization of a Green Supply Chain Network. *Global Journal of Technology & Optimization, 2*(1).

Pan, F., and Nagi, R. (2010). Robust supply chain design under uncertain demand in agile manufacturing. *Computers & Operations Research, 37*(4), 668-683.

Pati, R. K., Vrat, P., and Kumar, P. (2008). A goal programming model for paper recycling system. *Omega, 36*(3), 405-417.

Pazhani, S., Ramkumar, N., Narendran, T., and Ganesh, K. (2013). A bi-objective network design model for multi-period, multi-product closed-loop supply chain. *Journal of Industrial and Production Engineering, 30*(4), 264-280.

Peidro, D., Mula, J., Poler, R., and Lario, F.-C. (2009a). Quantitative models for supply chain planning under uncertainty: a review. *The International Journal of Advanced Manufacturing Technology, 43*(3-4), 400-420.

Peidro, D., Mula, J., Poler, R., and Verdegay, J.-L. (2009b). Fuzzy optimization for supply chain planning under supply, demand and process uncertainties. *Fuzzy Sets and Systems, 160*(18), 2640-2657.

Pennington, D., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., and Rebitzer, G. (2004). Life cycle assessment Part 2: Current impact assessment practice. *Environment international, 30*(5), 721-739.

Pihkola, H., Nors, M., Kujanpää, M., Helin, T., Kariniemi, M., Pajula, T., Dahlbo, H., et al. (2010). Carbon footprint and environmental impacts of print products from cradle to grave. *Results from the LEADER project (Part 1). Espoo*.

Pishvaee, M., Razmi, J., and Torabi, S. (2012). Robust possibilistic programming for socially responsible supply chain network design: A new approach. *Fuzzy Sets and Systems, 206*, 1-20.

Pishvaee, M., and Torabi, S. (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., 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 Razmi, J. (2011). Environmental supply chain network design using multi-objective fuzzy mathematical programming. *Applied Mathematical Modelling.*

Pohlen, T. L., and Farris, M. T. (1992). Reverse logistics in plastics recycling. *International Journal of Physical Distribution & Logistics Management, 22*(7), 35-47.

Poojari, C. A., Lucas, C., and Mitra, G. (2008). Robust solutions and risk measures for a supply chain planning problem under uncertainty. *Journal of the Operational Research Society, 59*(1), 2-12.

Ramezani, M., Bashiri, M., and Tavakkoli-Moghaddam, R. (2013a). A new multi-objective stochastic model for a forward/reverse logistic network design with responsiveness and quality level. *Applied Mathematical Modelling, 37*(1), 328-344.

Ramezani, M., Bashiri, M., and Tavakkoli-Moghaddam, R. (2013b). A robust design for a closed-loop supply chain network under an uncertain environment. *The*

International Journal of Advanced Manufacturing Technology, 66(5-8), 825-843.

Rangavajhala, S. (2007). *Decision Making in Design Under Uncertainty with Multiobjective Robust Design Optimization*: ProQuest.

Razmi, J., Zahedi-Anaraki, A., and Zakerinia, M. (2013). A bi-objective stochastic optimization model for reliable warehouse network redesign. *Mathematical and Computer Modelling, 58*(11), 1804-1813.

Realff, M. J., Ammons, J. C., and Newton, D. J. (2004). Robust reverse production system design for carpet recycling. *IIE Transactions, 36*(8), 767-776.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., et al. (2004). Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment international, 30*(5), 701-720.

RISI. (2001). RISI:The leading information provider for the global forest products industry. from http://www.risiinfo.com/

Rogers, D. S., Tibben-Lembke, R. S., and Council, R. L. E. (1999). *Going backwards: reverse logistics trends and practices* (Vol. 2): Reverse Logistics Executive Council Pittsburgh, PA.

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.

Salema, M. I. G., Póvoa, A. P. B., and Novais, A. Q. (2009). A strategic and tactical model for closed-loop supply chains. *OR Spectrum, 31*(3), 573-599.

Sander, K., Tojo, N., and Vernon, J. (2007). The Producer Responsibility Principle of the WEEE Directive.

Sarimveis, H., Patrinos, P., Tarantilis, C. D., and Kiranoudis, C. T. (2008). Dynamic modeling and control of supply chain systems: A review. *Computers & Operations Research, 35*(11), 3530-3561.

Song, Q., Wang, Z., Li, J., and Zeng, X. (2012). Life cycle assessment of TV sets in China: A case study of the impacts of CRT monitors. *Waste management, 32*(10), 1926-1936.

Souza, G. C. (2012). Closed-Loop Supply Chains: A Critical Review, and Future Research*. *Decision Sciences*.

Soyster, A. L. (1973). Technical note—convex programming with set-inclusive constraints and applications to inexact linear programming. *Operations Research, 21*(5), 1154-1157.

Srivastava, S. K. (2007). Green supply-chain management: a state-of-the-art literature review. *International journal of management reviews, 9*(1), 53-80.

Srivastava, S. K. (2008). Network design for reverse logistics. *Omega, 36*(4), 535-548.

Stadler, W. (1988). Fundamentals of multicriteria optimization *Multicriteria Optimization in Engineering and in the Sciences* (pp. 1-25): Springer.

Stadler, W., and Dauer, J. (1993). Multicriteria optimization in engineering: A tutorial and survey. *Progress in Astronautics and Aeronautics, 150*, 209-209.

Stadtler, H. (2005). Supply chain management and advanced planning—basics, overview and challenges. *European Journal of Operational Research, 163*(3), 575-588.

Standardization, I. O. f. (1997). *Environmental management: Life cycle assessment: Principles and framework* (Vol. 14040): ISO Geneva, Switzerland.

Stindt, D., and Sahamie, R. (2012). Review of research on closed loop supply chain management in the process industry. *Flexible Services and Manufacturing Journal*, 1-26.

Tarapore, A. R. (2010). *Performance measures of closed-loop supply chains.* Mississippi State University.

Thierry, M., Salomon, M., Nunen, J., and Wassenhove, L. N. (1995). Strategic issues in product recovery management. *California management review, 37*(2), 114-135.

Wang, F., Lai, X., and Shi, N. (2011). A multi-objective optimization for green supply chain network design. *Decision Support Systems, 51*(2), 262-269.

Wang, H.-F., and Huang, Y.-S. (2013). A two-stage robust programming approach to demand-driven disassembly planning for a closed-loop supply chain system. *International Journal of Production Research, 51*(8), 2414-2432.

Wang, H. F., and Hsu, H. W. (2010). A closed-loop logistic model with a spanning-tree based genetic algorithm. *Computers & Operations Research, 37*(2), 376-389.

Winkler, H. (2011). Closed-loop production systems—A sustainable supply chain approach. *CIRP Journal of Manufacturing Science and Technology*, *4*(3), 243-246.

Wu, Y. (2006). Robust optimization applied to uncertain production loading problems with import quota limits under the global supply chain management environment. *International Journal of Production Research, 44*(5), 849-882.

Yeh, W.-C., and Chuang, M.-C. (2011). Using multi-objective genetic algorithm for partner selection in green supply chain problems. *Expert Systems with Applications, 38*(4), 4244-4253.

Yu, C.-S., and Li, H.-L. (2000). A robust optimization model for stochastic logistic problems. *International Journal of Production Economics*, *64*(1), 385-397.

Zadeh, L. A. (1965). Fuzzy sets. *Information and control, 8*(3), 338-353.

Zarandi, M. H. F., Sisakht, A. H., and Davari, S. (2011). Design of a closed-loop supply chain (CLSC) model using an interactive fuzzy goal programming. *The International Journal of Advanced Manufacturing Technology*, *56*(5), 809-821.