Dedicated to my dearest loving parents

Low-Carbon Multi-Objective Location-Routing in Supply Chain Network Design

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Low-Carbon Multi-Objective Location-Routing in Supply Chain Network Design

Traditional supply chain modelling tends to focus on singular objectives, with a predominant focus on cost. Within this discipline location-routing problems are one of the most researched categories in recent years. This study extends this paradigm to consider the multi-objective of cost and environmental impact in the form of carbon emissions. The focus of this study is on the design of a low-cost low-carbon structure for the demand side of supply chain networks.

This research has developed two-layer and three-layer multi-objective 0-1 mixed-integer AHP-integrated location-routing models. Disparate multi-objective Genetic Algorithm, Particle Swarm, and Simulated Annealing-based optimisers are used to execute these developed models. The main execution platform used is modeFRONTIER®, a multi-objective optimisation and design environment.

The main contributions from this research are 1) the modelling extension to include low carbon emissions; costs; demand as an objective function component; and the inclusion of the decision makers' priority as a green constraint, 2) with regard to implementing these specific NP-hard models, a DoE-guided solution approach is used. Various heuristics/meta-heuristics are adopted and compared in terms of their efficiency, with the three-layer model being solved in two phases, 3) both sets of developed models are applied to the demand side of a dairy supply chain in Ireland.

Keywords: green supply chain network design, location-routing modelling, multi criteria decision making, heuristics/meta-heuristics, Irish dairy market

List of Abbreviations

AHP	Analytical Hierarchy Process
DC	Distribution Centre
DoE	Design of Experiment
FLP	Facility Location Problem
GrSCM	Green Supply Chain Management
LRP	Location-Routing Problem
MCDM	Multi Criteria Decision Making
MO-LRP	Multi-Objective Location-Routing Problem
MOGA-II	Multi-Objective Genetic Algorithm II
MOPSO	Multi-Objective Particle Swarm Optimiser
MOSA	Multi-Objective Simulated Annealing
NP-hard	Non-deterministic Polynomial-time hard
NSGA-II	Non-dominated Sorting Genetic Algorithm II
SC	Supply Chain
SCM	Supply Chain Management
SCN	Supply Chain Network
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
VRP	Vehicle-Routing Problem

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CHAPTER ONE

Introduction

1.1. Introduction

An essential aspect of modern business is Supply Chain Management (SCM) (Schroeder et al. 2013). SCM is a cross-functioning approach to the management of a network of activities, entities, processes, and businesses, from initial suppliers to the end consumers in any Supply Chain (SC). SCM can be defined as managing an integrated system or network which synchronises a series of inter-related business processes in order to: (a) acquire raw materials, (b) add value to the raw materials by transforming them into finished/semi-finished goods, (c) distribute these products to Distribution Centres (DCs) or sell to retailers or directly to the customers, (d) facilitate the flow of raw materials/finished goods, cash and information among the various partners which include suppliers, manufacturers, retailers, distributors and third-party logistics providers (Amoozad-khalili et al. 2010). Considering the components of a SC and the players of any supply chain, a broad span of disciplines is used to manage a SC efficiently (Ganeshan et al. 2000).

In traditional SCs, managers tended to focus on operations, viz. providing the customer with a finished product at the right place, with the correct quality and in the shortest time, reducing delay times and costs throughout the chain. However, improving environmental performance and in turn reducing the impact of environmental destruction was generally not considered as being very important. As the necessity to protect and optimise the usage of limited natural resources becomes ever more apparent, and with increasing pressure from both internal and external factors, increasing numbers of SCs are attempting to exercise environmentally friendly practices with an ultimate goal of ultimately becoming classified as ‘green’.

Managing industrial pollution has been a critical issue since the early days of the industrial revolution. But it was only at the end of 1980s that clean technologies were being introduced and programs were being implemented in an attempt to reduce the impact of company’s on natural resources (Noci 1997). At the beginning of the 1990s operations procedures began to change and eco-auditing frameworks were introduced.

In parallel and what contributed to these movements was the quality revolution in the 1980s and the supply chain revolution in the 1990s. These two major revolutions began to get businesses to become a little more concerned about environmental issues (Srivastava 2007; Fortes 2009).

Green SCs strive to be environmentally friendly and attempt to reduce the consumption of resources and energy while minimising environmental pollution. This is generally achieved through the design of environmentally friendly processes throughout the SC (Wang et al. 2007). Some of the strongest drivers that move companies towards green exercises are: governments, customers, competitive advantages and society.

In order to consider the environmental issues of the businesses, the influence and the relationships between SCM and the natural environment are added as the green component to SCM (Sirvastava, 2007). Green SCM (GrSCM) is an emerging field stranding out of the traditional supply chain perspective (Fortes 2009). GrSCM is a consistent practice which affects the performance of management at all levels in an organisation (Diabat and Govindan 2010) with the boundaries of GrSCM studies very much based on the goal of the researcher (Srivastava, 2007).

In order to make a SC more efficient many decisions have to be made related to the flow of material, information, and other resources (Chopra 2003). Five major decisions related to SC strategy or design, SC planning or tactical level decisions, and SC operations have to be made (Farahani and Hekmatfar 2009). These decisions are production, inventory, location, transportation and information. Among these decisions facility location has a critical strategic role. Decisions related to establishing a facility (e.g. warehouse, manufacturing plants, distribution centres) or developing a facility are costly, difficult to reverse, time-sensitive, and have long term effects (Owen and Daskin 1998). Such decisions are made through models evolved in the field of operations management and optimisation. The decision-making models that attempt to integrate different functionalities of the SC are considered as supply chain decision models (Min and Zhou 2002). These models deal with the multi-functional problems of location-routing, production-distribution, location-inventory, inventory control-transportation, and supplier selection-inventory control (Min and Zhou 2002).

A general view on sustainable development is that it connects economy, society and environment in order to satisfy the global needs of people for their better quality of life now and into the future (DEFRA 2011). Sustainable distribution strategy espouses an approach that seeks to achieve mutually reinforcing benefits for the economy, environment and society (Ilbery and Maye 2005). This leads to carbon trading mechanism such as defined in the Kyoto protocol. The Kyoto protocol encourages firms to reduce carbon emissions throughout their operations (Diabat and Simchi-Levi 2009).

Effective logistics and technologies are critical success factors for distribution systems in supply chain networks (Tarantilis et al. 2005). Traditionally, the critical success factors for an effective distribution system include meeting the requirements of the demand side of a supply chain through delivery of good quality products in appropriate quantities to the right place using the optimal path at the right time with optimal costs (Aghazadeh 2004).

The distribution of products to DCs or retailers, on the demand side of a SC network, using outbound transport has a significant impact on the environment. Issues related to sustainability of production and greening supply chains are of increasing importance in modern society and business. However, there is little evidence reported wherein the distribution routes are closely examined from both sustainability and a cost perspective. Hence, an effective blueprint for a modern competitive logistics system calls for the inclusion of the elements in a green-SC network so as to operate the demand side of the SC network on optimised carbon emissions, low operating costs and optimal traversed path.

Driven by sustainability issues, the economy and societal aspects of the SC, this research formulates both a two and three-layer green location routing model for the demand side of a SC. The proposed green logistics systems involves five inter-dependent decisions, viz., (i) allocation of customers to facilities, (ii) routing the vehicles to serve customers, (iii) optimisation of carbon emissions from the vehicles used for transporting product(s), (iv) determination of optimal costs of serving routes, and (v) locating optimal distance for the distribution. In this regard two integrated multi-objective location-routing models are designed by integrating 0-1 mixed-integer programming with Analytic Hierarchy Process (AHP) (Saaty 1977).

This introductory chapter is organised as follows. Section 1.2 presents a background on the research. Section 1.3 discussed the scope of the research. Section 1.4 highlights research aims and objectives. Section 1.5 lays out the significance of the research study. And section 1.6 presents the structure of the dissertation.

1.2. Background to the Research

Increased consciousness amongst consumers, firms and governmental organisations towards the escalated deterioration of the environment caused by human actions has boosted the momentum on GrSCM. Firms are now held responsible for their environmental and social performances (Seuring and Müller 2008). Considering this responsibility, one of the success parameters of enterprises depends on the efficacy of the location-routing decisions (Lopes et al. 2008). Therefore, an efficient design of an effective low-carbon location-routing system is now a strategic objective for many businesses.

The Kyoto protocol identifies six greenhouse gases. According to the United Nations Framework Convention on Climate Change (UNFCCC 2012), CO_2 is considered as the principal greenhouse gas in the "*carbon market*". Often the quantity of emitted greenhouse gases is expressed as CO_2 equivalent (CO_2e) in carbon footprint. The "*total amount of CO_2e emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product*" is considered as the carbon footprint (Wiedmann and Minx 2008). More precisely, CO_2e gases emitted across a SC for a single unit of a product is referred to as the carbon footprint (Reclay Holding GmbH 2012). Therefore, it is recommended to measure the total amount of CO_2e and propose the possible ways to minimise the carbon footprint in an SC thereby enhancing the efficiency of present day's green-SC network. In this research the term "low-carbon" is referred to as an alternative of carbon footprint.

Location-routing is considered to be one of the major concerns in SC logistics with substantial implications on a low-carbon SC as there is a significant contribution of the product distribution cost attributable to the total SC cost. In modern SC networks, the design of an efficient logistics system should operate on reduced carbon emissions in addition to low operating costs in today's competitive environment. Therefore the low-carbon operation of a SC is one today's most important strategic challenges.

A traditional location-routing model can be found in Berger (1997), which has been improved by, Daskin et al. (2005). This research considers the models proposed by Berger (1997) and Daskin et al. (2005) and contributes to the literature in the field of low-carbon capacitated two-layer and three-layer Location-Routing Problems (LRPs).

1.3. Scope of the Research

GrSCM is an emerging environmental practice for competitive businesses that assists growth in the economy through sustainable development by way of optimising transportation of products, information and capital along a value chain (Kumar et al. 2012; Zhu and Sarkis 2007). Green operation of SC logistics on reduced carbon emission and costs is one of todays' current strategic challenges (Srivastava 2007). Transportation activities are identified as one of the significant sources of air pollution and greenhouse gas emissions within a SC (Wang et al. 2011; Wu and Dunn 1995). An efficient and effective design of outbound logistics is one of the critical success factors for a sustainable distribution of products to multiple retailers and consumers through multiple DCs in SC networks (Lopes et al. 2008; Tarantilis et al. 2005). Therefore, low-carbon location-routing is one of the major concerns in SC. However, low-carbon operations in the SC logistics research and practices are still in the phase of infancy (Srivastava 2007; Vachon 2007; Seuring and Müller 2008).

The scope of this research is confined within the demand side of the two-layer and three-layer SC-networks (i.e., physical distribution system). Further the scope of this research is limited within the formulation of two multi-objective Analytic Hierarchy Process (AHP) integrated multi-objective 0-1 mixed integer programming models in order to address the LRPs for the two-layer (Figure 1.1) and three-layer (Figure 1.2) physical distribution systems. AHP is integrated with the MO-LRPs to add a green element in the modelling phase. The scope of this research is extended to a Design of Experiment (DoE)-guided meta-heuristic-based solution approach and the analysis of the final results using Pareto frontiers and a multi-attribute decision-making tool, TOPSIS. DoE is involved in the solution approach to ensure robustness while TOPSIS is used after solving the model for ranking results. Scenario analysis of the green location-routing for assisting the decision-makers ends the scope of this research.

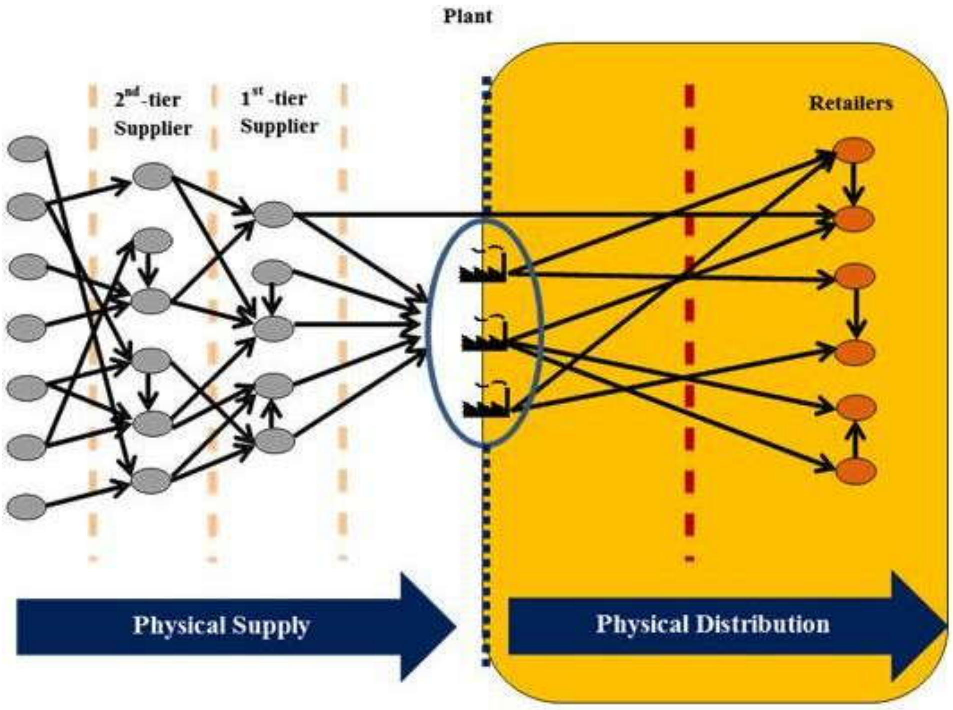


Figure 1.1 The two-layer demand side supply-chain (adopted from: Bowersox et al. 2013)

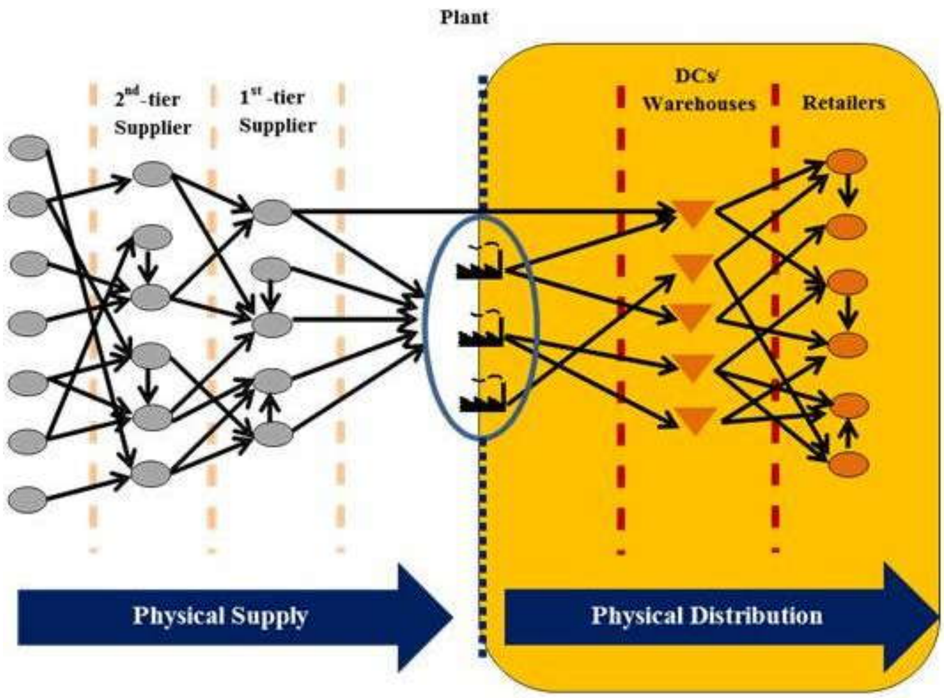


Figure 1.2 The three-layer demand side supply chain (adopted from: Bowersox et al. 2013)

1.4. Research Aims and Objectives

This PhD research study mainly aims to include the eco-friendly concerns in location-routing decisions in the context of supply chain network design. This main aim is planned to be pursued by focusing on improving Berger's (1997) two-layer LRP and Perl's (1983) three-layer LRP. As location-routing models are quantitative NP-hard models, the main purpose of this PhD thesis is three-fold. First: developing a low-carbon location-routing model for two and three-layer supply chain networks, considering DMs' priorities regarding choice of vehicles. Second: finding an effective solution approach to implement the developed models. And third, Offering tailored solutions to DM's based on their priorities.

1.4.1. Developing low-carbon location-routing models

Berger's (1997) two-layer LRP and Perl's (1983) three-layer LRP are the considered as the basis for developing low-carbon models. One of the main outcomes of this study is improving these two well-established LRPs to include low-carbon elements in them. The low-carbon elements appear as new objective function and new constraint in the developed LRPs. The objective function is focused on minimising the CO2 emission form transportation within the SCN while the constraint introduces the DMs' priorities to the model. Hence the developed models are multi-objective 0-1 mixed integer LRPs integrated with a MCDM technique that can represent the DMs' priorities efficiently .

1.4.2. Finding an effective solution approach to implement the developed models

Literature states that, two and three-layer LRPs are computationally NP-hard. One of the known characteristics of NP-hard models is that traditional techniques do not yield an optimal set of solutions. It is an established fact that the application of meta-heuristic approach generates an optimal solution space in a better manner from such NP-hard formulations. This research aims to explore the solution approaches and implement an effective approach that suits the developed models and its characteristics. Survey of literature shows that a variety of heuristics/meta-heuristics are used to solve these types of models. This study aims to solve these models using more than one heuristics/meta-heuristics and compare their performance. Furthermore, a proper implementation platform has to be recognised that can effectively solve the developed models.

1.4.3. Offering targeted and tailored low-carbon low-cost scenarios to DM's considering their priorities

> As the LRPs are NP-hard, the solution approach provides a large number of non-dominated optimal solutions distributed along the Pareto front. In order to further analyse the outcome of the solution approach, MCDM techniques are considered in order to rank and prioritise the optimal solutions based on the priorities of DMs' regarding the importance of cost and CO_2 emission.

In order to address the aims and objectives of the research, low-carbon multi-objective location-routing models are considered to be developed. These models are meant for designing two-layer and three-layer supply chain networks. In designing these models DMs' priorities regarding choice of vehicles are considered. In the next step, an effective solution approach to solve the developed models will be implemented. Finally, tailored solutions will be offered to DM's based on their priorities.

1.5. Significance of the Research Study

Low-carbon distribution strategy through logistics espouses an approach that seeks to achieve mutually reinforcing benefits for the economy, environment and society (Ilbery and Maye 2005). The Kyoto protocol encourages businesses to significantly reduce their carbon emissions from their operations (Diabat and Simchi-Levi 2009). Businesses are responsible for the environmental and social performance of their suppliers within an SC (Seuring and Müller 2008). As the transportation activities within the physical distribution network of a SC via roadways leave harmful effects on human health and environment, they are required to be investigated thoroughly. Minimisation of the traversed distance and overall costs and optimal utilisation of the vehicles during transportation of the products are the solutions for physical distribution in a SCN to operate on a reduced gas emission.

Traditional supply chain network modelling tends to focus on singular objectives, with a predominant focus on costs. Within this discipline location-routing problems are one of the most researched categories in recent years. The study reveals that low-carbon LRPs are not researched. Multi-objective modelling considering CO_2 emission from transportation as an objective is missing in literature. This research tries to extend this paradigm and develop low-carbon low-cost multi-objective LRPs to contribute to the literature in LR.

Study shows that Decision Maker's priorities are widely ignored in mathematical modelling; LRPs are not an exemption. This research considers the DM's priorities in the mathematical model by using MCDM techniques. As the focus of the study is on low-carbon LRPs, then the use of MCDM techniques in developing components of LRPs are considered. The main aim is to develop a constraint for the MO-LRPs that guide the model toward choosing a choice of transportation with lower level of CO2 emission based on the priorities of the DMs.

LRPs are NP-hard models with no exact solution to them but a space of solutions. Literature shows that a number of solutions approached have been introduced to solve LRP models. This study explores the solution approaches and looks for a more efficient one that suits the developed MO-LRPs in this study. The MO-LRPs are generic implied to a case of an Irish dairy supply chain network in east of Ireland.

1.6. Structure of the Dissertation

This dissertation comprises of seven inter-linked chapters. Chapter one introduces the elements of supply chain management and green location-routing for supply chain network design. Chapter two critically reviews the relevant literature in order to locate the research gaps. The following two chapters (three and four) are dedicated to the formulation of the two-layer and three-layer multi-objective integrated location-routing models, their solution approaches and analysis procedures. In these two chapters numerical and statistical experimentation of the proposed models and solution approaches has been conducted on the case of a two and three layer Irish dairy supply chain network. Findings from this numerical experimentation are discussed in Chapter five. Chapter six concludes the research outlining its significance. Scope for future research is also presented in Chapter six. Figure 1.3 provides an overview on the structure of this dissertation.

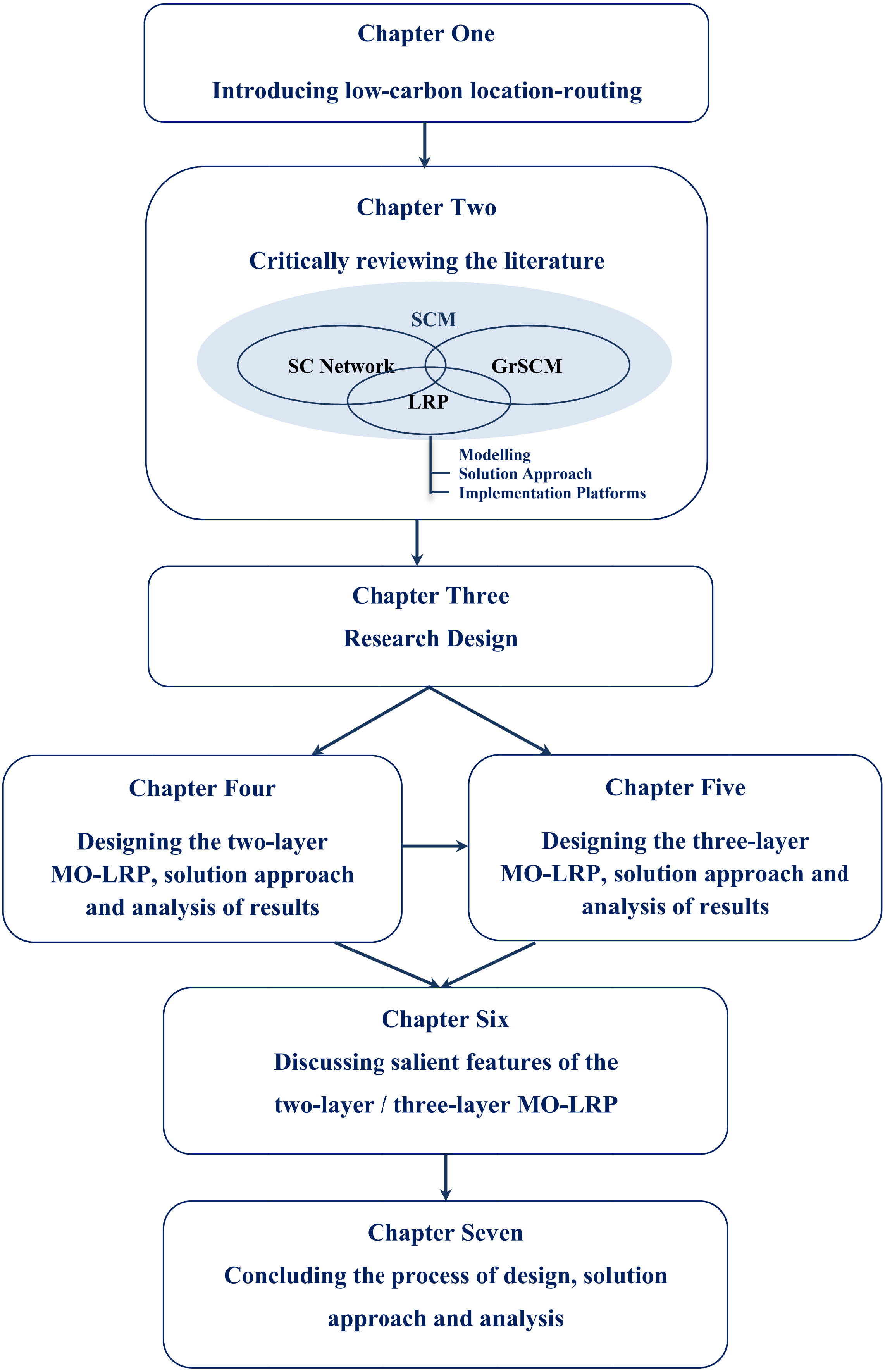


Figure 1.3 The organisation of the dissertation

CHAPTER TWO

Survey of Literature

2.1. Introduction

The initial concept of Supply Chain (SC) and Supply Chain Management (SCM) first appeared in business literature in 1961, when Forrester (1961) suggested that '*the success of industrial companies hinged on the interactions between flows of information, materials, manpower and capital equipment*'. An essential aspect of modern business is now SCM (Schroeder et al. 2013). Traditionally SCM has been seen as a melting pot of various disciplines, with influences from logistics and transportation, operations management and material and distribution management, marketing, as well as purchasing and information technology (Giunipero et al. 2005; Jain et al. 2009). Ideally, the all-encompassing philosophy of SCM should embrace each of these functions to produce an overall SC strategy that ultimately enhances firm performance (Croom et al. 2000).

The origin of the supply chain concept has been inspired by many fields including (i) the quality revolution, (ii) notions of materials management and integrated logistics, (iii) a growing interest in industrial markets and networks, (iv) the notion of increased focus, and (v) influential industry-specific studies. Researchers thus found themselves inundated with terminologies such as 'supply chains', 'demand pipelines', 'value streams', 'support chains', and many others (Chen and Paulraj 2004). Min and Mentzer (2004) and Mentzer et al. (2001) suggest that SCM should be investigated in the context of managed SCs that are organized through the collective efforts of supply chain members and thus are distinguished from SCs. SC has been defined many times in a variety of ways by researchers (Porter 1985; Christopher 1992; La Londe and Masters 1994; Mentzer et al 2001; Ganeshan 2002; Heizer and Render 2010; Amoozad-khalili et al. 2010). Zheng and Katzumi (2010) define SCM: *a) as a set of approaches utilized to effectively integrate suppliers, manufacturers, logistics, and customers for improving the long term performance of individual companies and supply chain as a whole, b) as an actor-oriented approach, focusing on how to organize and manage flow of materials from 'point of origin' to 'end user' as the point of departure, c) as a relation-oriented approach focusing on relationship between the actors in the supply chain, and how co-*

operation and mutual interests can lead to improvement, and d) by using a process-oriented approach as the integration key business process from end-user to original suppliers that provide products and services and information that add value to customers and other stakeholders. A schematic presentation of a traditional SC is depicted in Figure 2.1.

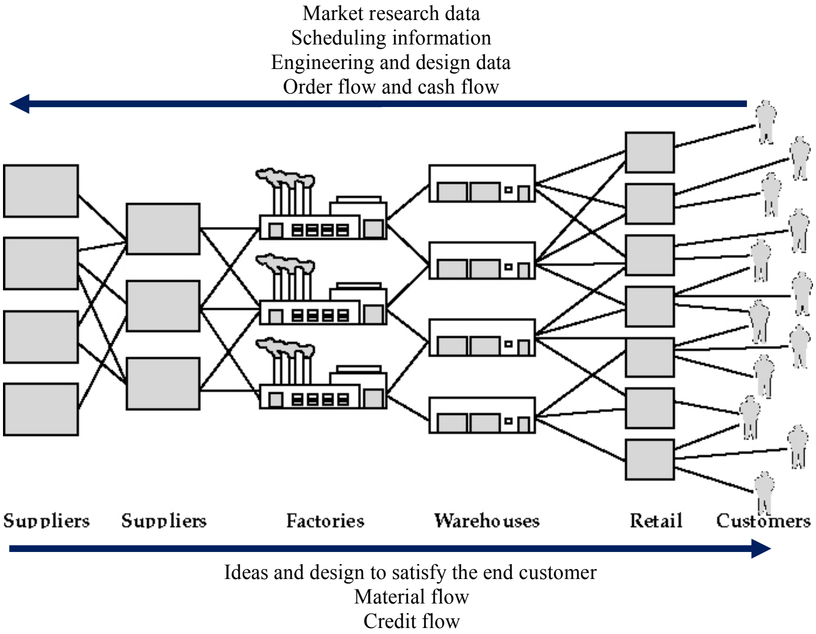


Figure 2.1 A traditional SC (Adapted from: Schroeder et al. 2013; Heizer and Render 2010)

With a 'network perception' of SCM, Christopher (2011) defines SCM as a 'network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer'. Aitken et al. (2005) and Jain et al. (2009) share the same perspective on SCM. Min and Zhou (2002), reviewing analytical modelling literature in SC, characterise a supply chain by a forward flow of goods and a backward flow of information. Figure 2.2 presents this approach.

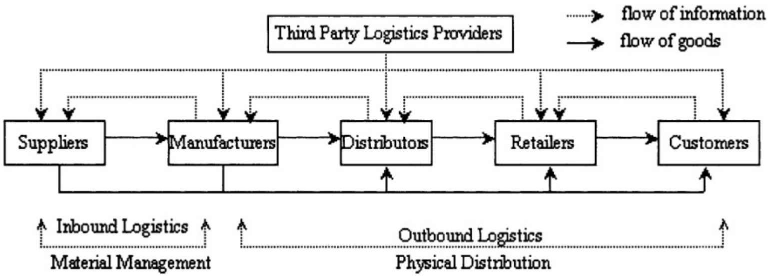


Figure 2.2 The supply chain process (Min and Zhou 2002)

Simchi-Levi et al. (2003), in an effort to discuss the design and management of SCs, introduces a number of ‘key issues in SCM: (i) distribution/logistics network configuration, (ii) inventory control, (iii) supply contracts, (iv) distribution strategies, (v) supply chain integration and strategic parenting, (vi) outsourcing and procurement strategies, (vii) product design, (viii) information technology and design-support systems and (ix) customer value. These main key issues can be categorised on three levels, viz. strategic (the number, location, and capacity of warehouses and manufacturing plants, flow of material through the logistics network), tactical (purchasing and production decisions, inventory policies, transportation strategies) and operational (scheduling, lead time quotations; routing, truck loading) level (Simchi-Levi et al. 2003).

In today’s fiercely competitive business environment, companies are confronted with new elements. Sundarakani et al. (2010) argues companies that are trying to design and operate a modern SC networks traditionally focusing on the efficiency of the network and value creation for customers. The value has been created by increasing the benefit of the product for the customers by lowering the costs of the product, improving delivery services and delivery time, and improving quality (Christopher and Gattorna 2005; Ulaga and Eggert 2006; Melnyk et al. 2009). Recently, customers have attached value to some less obvious factors, such as low-risk supply chains and security (Wagner and Bode 2008; Melnyk et al. 2009), more visibility across supply chain (Balan et al. 2009), socially responsible supply chains and responsiveness (Boyd et al. 2007; Melnyk et al. 2010), resilience and innovation (Melnyk et al. 2010), and green SCs and sustainability (Quariguasi Frota Neto et al. 2008).

In recent years, Green SCM (GrSCM) has begun to emerge as an important field with direct lineage with the traditional supply chain perspective (Fortes 2009). ‘*Adding the green component to supply chain management involves addressing the influence and relationships between supply chain management and the natural environment*’ (Sirvastava 2007). GrSCM is a practice that affects the performance of management at all levels of any organisation. Toke et al. (2010) consider four major functions within a green supply chain and from this they attempt to develop an understanding of ‘what a green supply chain is’ based on discussions around their relationships (Figure 2.3).

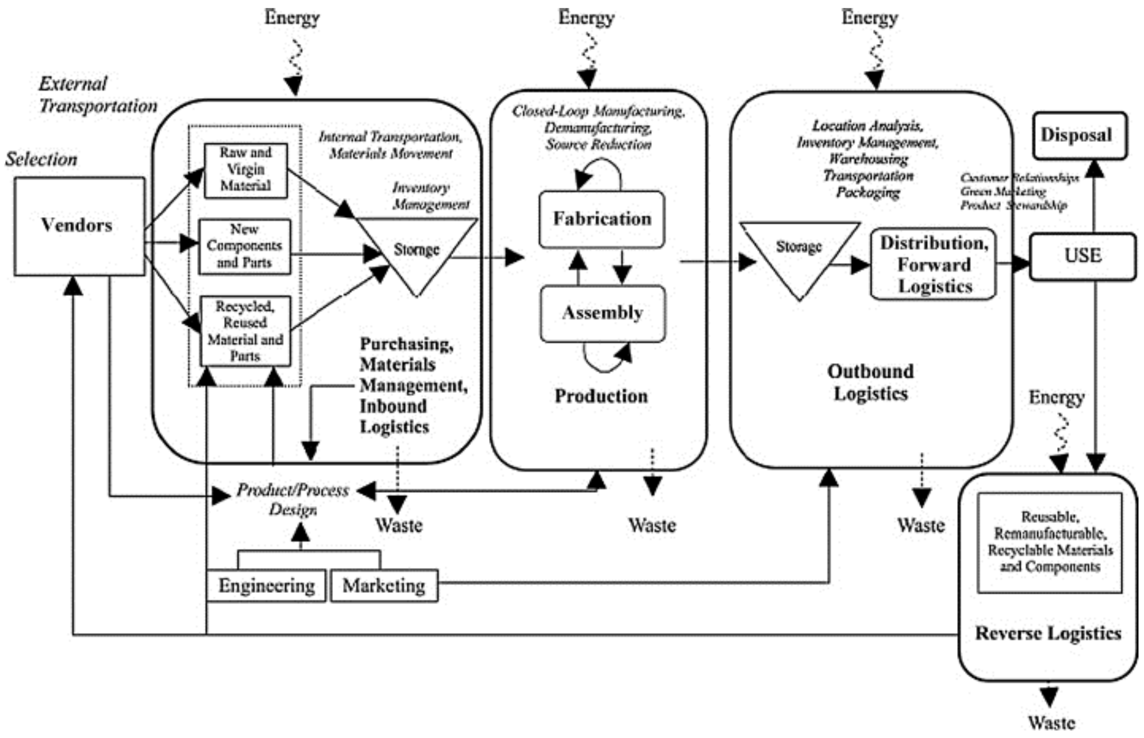


Figure 2.3 Operational functions and environmental practices within the green supply chain (Toke et al. 2010)

The four major functions discussed (Figure 2.3), are purchasing and in-bound logistics, production, distribution (i.e., outbound logistics and marketing), and reverse logistics. Outbound logistics is one of the major areas of green practices in the SC. It deals with location analysis, inventory management, warehousing, transportation, and packaging. These functions contribute greatly to the amount of greenhouse gasses in the environment.

GrSCM as defined by Green et al. (1996) is: '*Green supply refers to the way in which innovations in supply chain management and industrial purchasing can be considered in the context of the environment*'. GrSCM is an '*integrating environmental thinking into supply chain management, including product design, material sourcing and selection, manufacturing processes, delivery from the final product to the consumers as well as end-of-life management of the product after its useful life*' (Srivastava 2007). As these two selected definitions show, the definition of GrSCM has moved for focusing on just one aspect of the system (organisation) to considering the whole system elements in making decisions. Definitions of GrSCM by different authors show that there is a range of focus and purpose on green SC and its management (Toke et al. 2010). Literature identifies a variety of driver for implementing GrSCM practices (Noci 1997;

Guide and Srivastava 1998; Walton et al. 1998; Gunger and Gupta, 1999; Rao and Holt 2005; Srivastava 2007; Lee 2008; Walker et al. 2008; Fortes 2009; Diabat and Govindan 2010).

Many different aspects and facets of green SCs are found in the literature. In a comprehensive literature review, Fortes (2009) categorises the ‘key themes’ in GrSCM in the past twenty years as: green design, green operations, waste management, and green manufacturing. Sarkis (2003) offers a classification of environmentally conscious business practices which includes five major practices or elements: reduction (reduce), reuse, remanufacture, recycle, and disposal alternatives. Srivastava (2007) reviews all aspects and facets of GrSCM in literature and categorises them based on two main streams, viz. context and methodology/approach. In the context based category the problem in SC design is classified into two main themes: ‘green design’ and ‘green operations’ with sub-categories/sub-themes under each main theme. Figure 2.4 shows this context-base classification.

Green manufacturing and re-manufacturing, competition and its effects on remanufacturers, product design, logistics, purchasing, reverse logistics, integrating reverse logistics and re-manufacturing in supply chain design (Srivastava 2007; Fortes 2009; Sarkis et al. 2011) with environmental focus are all issues covered by green operations. In the green operations arena, the focus of this research in on green SC network design.

In order to design an efficient SC network many decisions are to be made. Amongst these strategic decisions, network design decisions are pointed out (Farahani and Hekmatfar 2009). In this strategic level one of the major design decisions is facility location related decision. Once the structure of the SC is determined the next set of decisions focuses on decisions such as logistics and distribution decisions. Riopel et al. (2010) discuss the network of logistics decisions by focusing on the precedence relationship between 48 logistics decisions. Table C.1 shows these logistics decisions and the precedence relationships between these decisions and also the type of information that might be needed to make any one of these decisions.

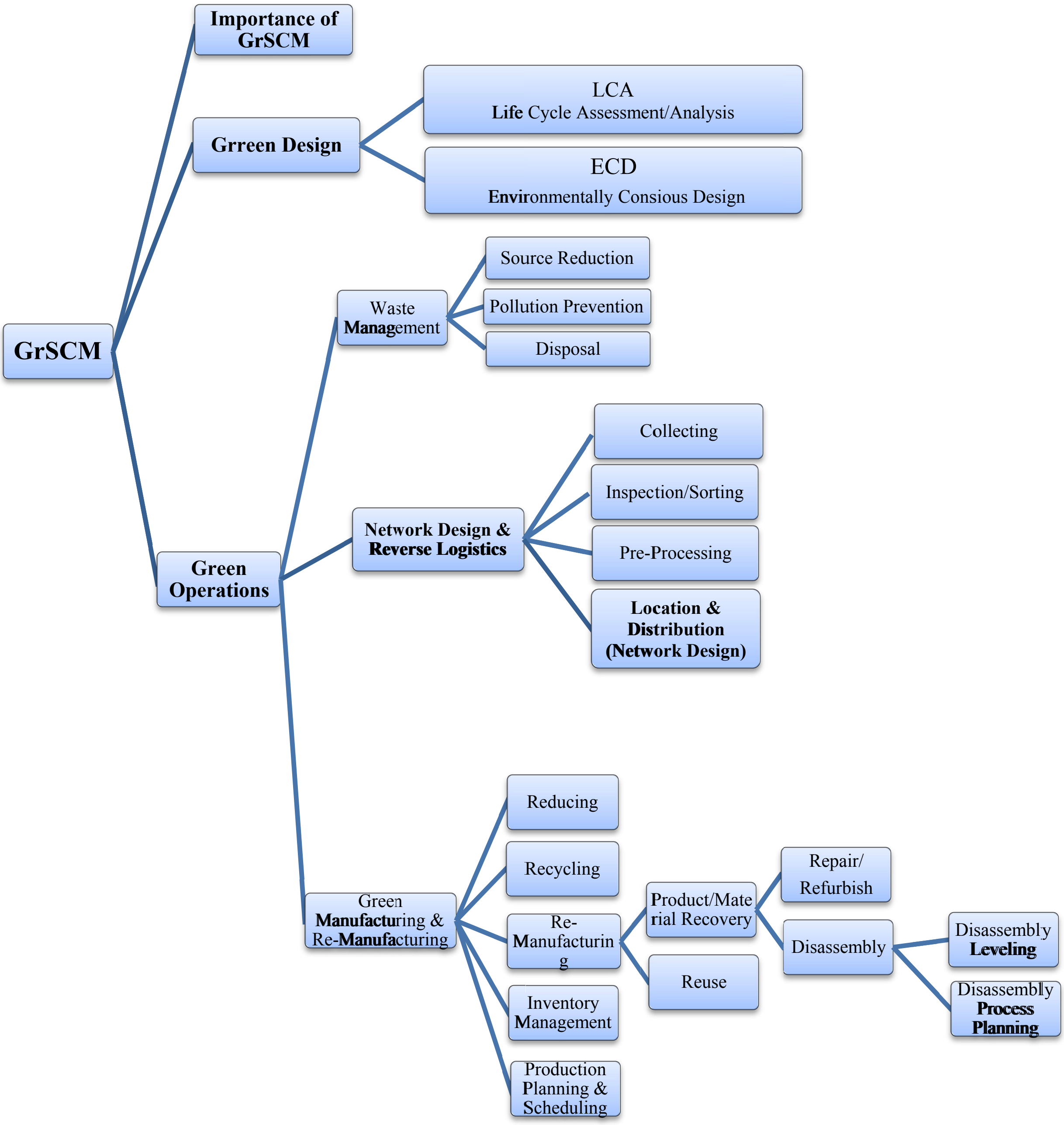


Figure 2.4 Classification based on problem context in supply chain design (Adapted from Srivastava 2007)

This chapter reviews the related literature. This chapter is organised as follows. Section 2.2 deals with supply chain network design. Under this section logistic decisions and green logistic decisions are discussed. Section 2.3 discusses facility location problems. The sub-section of Section 2.3 illustrates classifications and mathematical modelling. Section 2.4 reports literature on integrated location-routing problem. Sub-sections of Section 2.4 elucidate mathematical formulation of LRP, applications of LRPs and solutions methods of LRPs. The next section deals with implementation platforms for LRPs. Under this section modeFRONTIER® platform is introduced. Finally in Section 2.6 the research gaps found from the critical survey of the literature are pointed out.

2.2. Supply Chain Network Design

In order to manage a SC successfully many decisions related to the flow of material, information, and other resources have to be made (Chopra and Meindl 2003). According to Farahani and Hekmatfar (2009) five major decisions related to SC strategy (and design), SC planning (and tactical level decisions), and SC operations have to be made. These decisions are: (i) production (what, how, and when to produce), (ii) inventory (how much to make and how much to store), (iii) location (where best to do each activity), (iv) transportation (how and when to move products), and (v) information (the basis for making these decisions). Among these decisions, facility location has a critical strategic role. Decisions related to establishing a new facility (e.g., warehouse, manufacturing plants, distribution centres (DCs)) or developing a facility are costly, difficult to reverse, time-sensitive, and have long term effects. For instance inventory, transportation, and information decisions can be changed based on the changes in the market more quickly and easily (Owen and Daskin 1998; Melo et al. 2009; Farahani and Hekmatfar 2009; Snyder 2006; Daskin et al. 2010). In a SC network, design decisions broadly cover the location of production/processing factory, warehouses/DCs and transportation-related facilities and the allocation of roles to each facility through the SC (Farahani and Hekmatfar 2009; Daskin et al. 2010). Literature reveals that these issues are categorised into two main areas, viz. logistics decisions and facility location decisions.

2.2.1. Logistics decisions

The field of logistics, in the context of business, has changed substantially during the past few decades. Riopel et al. (2010) report that in the 1960s, business logistics was only really dealing with two functions of logistics, viz. materials management and distribution. In the 1970s, there was a move to 'focus on the interdependence of these functions' and it gained a more integrated view. Logistics professionals have begun to focus attention on 'integrating the activities of the supply chain' since the 1990s. The paradigm shift in the area of logistics started from physical distribution and has evolved into SCM. This evolution of logistics, demands a more comprehensive and global vision of logistics and logistics decision making. Riopel et al. (2010) report that the decision-making environment has become more and more complex when new approaches, new strategies and new models are developed, markets are changed and globalised, SCs are more and more global, information technology keeps developing and evolving, customer demands are ever changing and with more focus on customer satisfaction. All these require a new approach to logistics and affect logistic decision making. Logistics in SCM has a primary and important role in arranging the flow of products and services to link focal firms to both the supply and market network (Bowersox et al. 2013).

In particular, the Council of Logistics Management (CLM) defined logistics in 2003 as:

'*that part of the supply chain process that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services, and related information between the point or origin and the consumption in order to meet customers' requirements'*.

A logistics system consists of the following components (Rushton et al. 2006), viz. (i) storage, warehousing and material handling, (ii) packaging and unitization, (iii) inventory, (iv) transport, and (vi) information and control.

Logistics decisions range from long-term strategic decisions to short-term tactical/operational decisions (Riopel et al. 2010; Farahani and Hekmatfar, 2009). As Seifi et al. (2011) mentions, there are diverse categorisations of logistics decisions and they all consist of these three strategic decisions: (i) customer service, (ii) logistics network design, and (iii) outsourcing versus vertical integration. Riopel et al. (2009) categorises logistics decisions into three levels, viz. (i) strategic planning level, (ii) network level (physical facility network, and communication and information network) and (iii) operations level (demand forecasting, inventory management, production, procurement and supply management, transportation, product packaging, material handling, warehousing, order processing). Strategic level decisions are discussed by many researchers in literature. Wanke and Zinn (2004) report that logistics managers are dealing with three strategic level decisions: (i) make to order vs. make to stock; (ii) push vs. pull inventory deployment logic; and (iii) inventory centralisation vs. decentralisation. Riopel et al. (2010) (Appendix A.1) discuss that strategic planning level decisions are involved with: definition of customer service and the associated metrics, customer service objectives, degree of vertical integration and outsourcing within a SC. Further, strategic planning level decisions involve ‘a variety of additional decisions that affect logistics, such as determining organization’s overall economic objectives and strategy, determining the range of products and services offered, determining the geographical scope of production, distribution, and marketing’ (Riopel et al. 2010).

Physical location decisions are strategic decisions which are affecting many other logistics decisions in any system. A physical facility network design decision includes types of facilities, number of each type of facility, size of facility, facility location, activities and services from each facility, utilisation of new or existing facilities, and links between facilities (Riopel et al. 2010). Prior to the network design decision, customer service objectives, and degree of vertical integration and outsourcing must be determined.

2.2.2. Green logistics decisions

In recent years, eco-conscious and eco-friendly logistics have grown exponentially as a competitive element of logistics (Lee et al. 2008). Considering the environmental burdens of manufacturing, the elements of modern day SC networks tend to operate on low carbon emissions. This becomes possible when the usage of energy-efficient vehicles, waste reduction, recycling, along with the deployment of optimisation techniques is considered. Greening a logistics system may occur in four phases: (i) green inbound logistics, (ii) operations and manufacturing, (iii) marketing/outbound logistics, and (iv) reverse logistics (Sarkis 2003).

Significant control on the emissions from the distribution of products through transportation is a pre-requisite as it is one of the major sources for environmental concern in transportation. There is an increasing concern regarding the growth of GNP in the industrialised world (Aronsson and Brodin, 2006). Therefore, substantial efforts are being made by the European Union (EU) to decrease the total emissions from the transportation sector (European Commission 2001). However, plenty of scope is still available to optimise the carbon emissions from the SC logistics.

One of the benefits of the Kyoto protocol carbon trading mechanism is that it encourages firms to minimise carbon emissions throughout their operations (Diabat and Simchi-Levi 2009). The Kyoto protocol identifies six greenhouse gases, viz., Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFC), Perfluorocarbons (PFC), Sulphur hexafluoride (SF_6). According to the United Nations Framework Convention on Climate Change (UNFCCC 2012), CO_2 is considered as the principal greenhouse gas in the ‘carbon market’. Often the quantity of emitted greenhouse gases is expressed as CO_2 equivalent (CO_2e) in carbon footprints. The ‘total amount of CO_2e emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product’ is considered as the carbon footprint (Wiedmann and Minx 2008). More precisely, CO_2e gases emitted across a SC for a single unit of a product is referred to as the carbon footprint (Reclay Holding GmbH 2012). Therefore, it is recommended to measure the total amount of CO_2e and propose possible ways to minimise the carbon footprint in a SC in order to enhance the efficiency of today’s green-SC network. In this research the term ‘low-carbon’ is referred to as an alternative of ‘carbon footprint’.

There are plenty of recommended low-carbon SC principles in businesses. Recommended principles are: the in-depth discernment of the impact of the carbon footprint in manufacturing locations and raw material sources, alternative sourcing options, operating speed of SCs, reduction of the use of packaging, proportionate increase in reverse logistics and re-design of distribution channels etc. In a SC network, logistics service providers are required to contribute by increasing SC efficiency and simultaneously reducing associated costs and carbon emissions. Transportation activities are one of the significant sources of air pollution and greenhouse gas emissions within a SC (Wang et al. 2011). These activities leave harmful effects on human health and the environment. Therefore, transportation activities of products from plants to customers via roadways are required to be investigated thoroughly. Minimisation of the traversed distance and maximum utilisation of the vehicles during transportation are possible solutions to minimise gas emissions. Considering the principles of a low-carbon SC and the effect of transportation activities on society and the environment, this research is focused on optimising the efficiency of SC carbon management through location-routing models, which are a variant of facility location problems.

2.3. Facility Location Problems

Facility location is a well-established area of research and within the operations research (OR) domain (Melo et al. 2009). Facility location models and techniques have begun to appear gradually in a SC context (Chopra and Meindl 2007) and have become one of its most important applications. In the literature, facility location is also much discussed and studied in the context of logistic decisions (e.g. Lanagevin and Riopel 2010).

Location theory formulation started in 1909 when Alfred Weber tried to position a single warehouse to minimise the total distance between the warehouse and several customers. Following this in 1964 Hakimi tried to locate switching centres in a communication network and police stations in a highway system (Owen and Daskin, 1998). Since the mid-1960s the study of location theory, specifically the mathematical science of facility location (ReVelle and Eiselt, 2005), has attracted much research attention and as a result many models have been developed.

Location analysis has been defined by ReVelle and Eiselt (2005) as: ‘modelling, formulation, and solution of a class of problems that can be best described as sitting facilities in some given space’. ReVelle et al. (2008) suggest that ‘even though the context in which Facility Location models are situated may differ, their main features are always the same: *a space* including a *metric*, *customers* whose locations in the given space are known, and *facilities* whose locations have to be determined according to some objective function’. These four components characterise the location problems (ReVelle and Eiselt 2005):

‘*(1) Customers: who are presumed to be already located at points or on routes, (2) Facilities that will be located, (3) A Space in which customers and facilities are located, and (4) A Metric that indicates distances or times between customers and facilities’.*

2.3.1. Classifications and mathematical modelling

Categories and taxonomies of facility location models are found in Francis and White (1974), Bradndeau and Chiu (1989), Daskin (1995), Owen and Daskin (1998), ReVelle et al. (2008), Jia et al. (2007), Daskin (2008), Klose and Drexl (2005), and Eiselt and Marianov (2011).

In literature, categories and taxonomies of facility location models under different contexts of OR, logistics, and SCM are overlapped. Riopel et al. (2010) and Langevin and

Riopel (2010) discuss the physical facility network in the context of logistics decisions considering several inter-dependent key decisions, viz. the type and the number of different facilities (warehouses, DCs and terminals), size and the location of each facility, the products and services provided from each facility and whether to use new or existing facilities or open a new one.

Riopel et al. (2010) categorise mathematical facility location models as followed:

(i) the fixed charge facility location problem. Extensions of this model consider: a) facility capabilities and single sourcing requirements, b) multiple echelons in the supply chain, and c) multiple products,
(ii) integrated location/routing models,
(iii) integrated location /inventory models,
(iv) planning under uncertainty,
(v) location models with facility failures.

Daskin et al. (2010) and Alizadeh-Shabdiz (2009) classify and review facility location models into three main groups. This research uses the above-mentioned classification system. Based on integrated location-routing models (ii) in this classification system, two-layer and three-layer models are proposed. This classification system is as follows.

- **Classical/traditional models**: This category consists of classical facility location problems which forms the basis of most location models. In this type of location problem a set of customer locations with known demand and a set of candidate facility locations are given. The problem is finding the location of facilities and the movement (shipment) pattern between the facilities and the customers in order to minimise the combination of facility location and movement (shipment) costs subject to the constraint that all customer demand be met (Daskin et al. 2010). Sub-models of this group of models are:

i. fixed charge facility location problem,
ii. uncapacitated facility location model (with single sourcing),
iii. capacitated facility location model,
iv. locating plants and distribution centres (with multiple commodity).

Fixed charge facility location problem is discussed below.

Fixed charge facility location problem: Fixed charge facility location problem is the basis of most of location models used in SC design. In this type of model, there is a set of data available: (a) a set of customer locations with known demand, (b) a set of candidate facility locations, if the model maker decided to locate a facility in a known site then a fixed cost is implied and (c) a known unit delivery/transportation cost between each candidate site and each customer. The problem here is to find the optimum locations of the facilities in order to minimise the costs of transportation and facilities, subject to the requirement of meeting all customer demands. The mathematical formulations of the other three facility location models, viz. uncapacitated facility location model (with single sourcing), capacitated facility location model, and locating plants and distribution centres (with multiple commodity), are included in Appendix A.2.

- **Integrated decision making models**: A study of the literature reveals many studies, and a variety of models for the purpose of attempting to integrate any two of the important decisions regarding SC design (Daskin et al. 2005; Hassanzadeh et al. 2009). These efforts in integration and combining elements of SC design are categorised as:

  i. Integrated location-routing models (LR)
  ii. Integrated inventory-routing models (IR)
  iii. Integrated location-inventory Models (LI)

LR is the main concern of this research. This group of combined facility location models is discussed in more details in the following section.

- **Other models:** The following models do not fall into classical or integrated categories and are classified as 'other models':

  i. model with routing cost estimation,
  ii. model with capacitated DCs (distribution centres),
  iii. model with multiple levels of capacity,
  iv. model with service considerations,
  v. profit maximising model with demand choice flexibility,
  vi. model with multiple commodities,
  vii. model with unreliable supply,
  viii. model with facility failures,
  ix. planning under uncertainty.

2.4. Integrated Location-Routing Problem

The introductory concept of a Location-Routing Problem (LRP) was first reported in the 1960s and early 1970s (Maranzana 1964; Webb 1968; Lawrence and Pengilly 1969; Higgins 1972; and Christofides and Eilon 1969). In the late 1970s and 1980s studies on LRP, as an integrated combined problem, began to appear separately (Jacobsen and Madsen 1978; Or and Pierskalla 1979; Laporte and Norbert 1981).

Integrated LRPs combine three important components of a SC design: facility location, customer allocation to facilities, and vehicle routing (Daskin et al. 2010). These problems merge two different problems in nature, viz., facility location and vehicle routing. Literature discusses LRPs under both categories. Facility location decisions are strategic decisions by nature, while vehicle routing decisions are not.

In the early attempts LRP is mostly discussed as a part of Vehicle-Routing Problems (VPR). VRPs are complex themselves and LRPs are considered a component of the VRPs. Laporte et al. (1988), in one of the early reviews on different types of LRP models and solution techniques, define VRP and LRP as follows:

‘The VRP is commonly defined as the problem of designing optimal delivery or collection routes from one or several depots to a set of geographically scattered customers, under a variety of side conditions. LRPs are VPRs in which the optimal depot locations and route design must be decided simultaneously.’

Min et al. (1998) tried to offer a comprehensive categorisation of LRP studies by using a two way classification: (i) classifying LRP with regard to its problem perspective and (ii) classifying LRP problem with regard to its solution method. Table 2.1 presents these classifications.

Table 2.1 Classification of LRPs (Min et al. 1998)

Classification of LRP with regard to problem perspective	Classification of LRP with regard to solution method
I. Hierarchical level a. Single stage b. Two stages II. Nature of demand/supply a. Deterministic b. Stochastic III. Number of facilities a. Single facility b. Multiple facility IV. Size of vehicle fleets a. Single vehicle	I. Exact algorithm a. Direct tree search / Branch & bound b. Dynamic programming c. Integer programming d. Non-Linear programming II. Heuristic a. Location-allocation-first, route-second b. Route-first, location-allocation-second c. Savings / insertion d. Improvement / exchange

b. Multiple vehicles V. Vehicle capacity a. Uncapacitated b. Capacitated VI. Facility capacity a. Uncapacitated b. Capacitated VII. Facility layer a. Primary b. Secondary VIII. Planning horizon a. Single period (static) b. Multiple periods (dynamics) IX. Time window a. Unspecified time with no deadline b. Soft time windows with loose deadlines c. Hard time windows with strict deadlines X. Objective function a. Single objective b. Multiple objectives XI. Types of model data a. Hypothetical b. Real-world	

Then Min et al. (1998) states the LRP as: '*In general, the combined location-routing model solves the joint problem of determining the optimal number, capacity, and location of facilities (domiciles) serving more than one customer/supplier, and finding the optimal set of vehicle schedules and routes*'.

There is a main difference between the LRP and the classical location-allocation. The classical location allocation problem ignores tours when locating facilities. This eventually leads to more distribution costs (Salhi and Rand 1989; Min et al. 1998). Min et al. (1998) and Daskin (1995) consider two types of trips between facilities and customers, viz. direct trips and tour trips. Based on these two types of trips between facilities and customers, Hassanzadeh et al. (2009) in an effort to define LRP, describes the different types of serving customers (Figure 2.5):

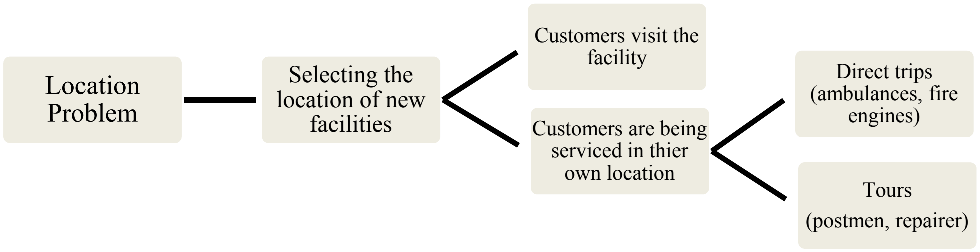


Figure 2.5 Different types of servicing a customer (adopted form Hassanzadeh, 2009)

Hassanzadeh et al. (2009) define the LRP as: '*a feasible set of potential facility sites and locations and expected demands of each customer which are given. Each customer is to be assigned to a facility which will supply its demand. The shipments of customer demand are carried out by vehicles which are dispatched from the facilities, and operate on routes that include multiple customers. The location of distribution facilities and the distribution of products from these facilities to customers are two key components of a distribution system.*'

Nagy and Salhi (2007) look at the LRP as an approach for modelling and solving locational problems as the LRP is not a single well defined problem from their point of view. In a state-of-the-art survey on location-routing, Nagy and Salhi (2007) classify literature at the time based on a classification system that includes a number of criteria. They state that '*classifying location-routing problems is at least as difficult a task as that of classifying location problems, with added complexity provided by the variability in the underlying vehicle routing problems*'.

Literature reports mathematical formulation of the integrated LRPs in two-layer (Berger 1997; Hassanzadeh et al. 2009) and three-layer (Perl 1983; Perl and Daskin, 1985) stages or echelons. In the literature an example of a four-layer LRP is also presented (Hamidi et al. 2012). The number of layers represents the main players on the demand side of the supply chain considered in these models. Figure 2.6 presents a general representation of a SC. It consists of the supply side, the demand side, and the connections between the supply and the demand sides with the focal company. Most SC network design models are focused on the demand side and physical distribution of products.

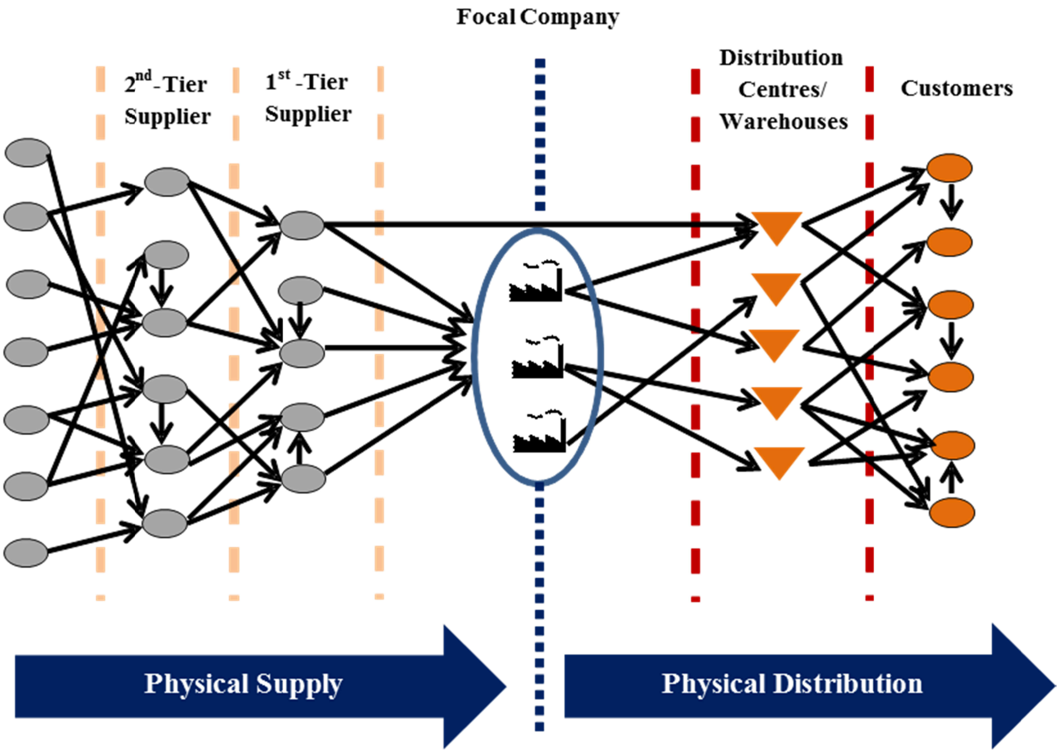


Figure 2.6 A general representation of a SC (Bowersox et al. 2013)

The two-layer LRP considers two players on the demand side of the SC. These two-layers can be the plant(s) and DC(s), or plant(s) and customer(s) (Hassanzadeh et al. 2009). The mathematical formulations of a two-layer LRP developed by Berger (1997) and a three-layer LRP developed by Perl (1983) are presented in Appendix A.3.

2.4.1. Applications of LRPs

A full review of the literature reveals implementation of location-routing in various sectors. A summary of LRP application in literature since its inception is provided in Table 2.2.

Table 2.2 A summary of LRP applications (updated based on Nagy and Salhi 2007; Hassanzadeh et al. 2009)

Author	**Application Area**
Watson-Gandy & Dohrn (1973)	Food & drink distribution
Bednar & Strohmeier (1979)	Consumer goods distribution
Or & Pierskalla (1979)	Blood bank location
Jacobson & Madsen (1980)	Newspaper distribution
Nambiar et al. (1981)	Rubber plant location
Madsen (1983)	Newspaper Distribution
Perl & Daskin (1984,1985)	Goods distribution
Labe & Laporte (1986)	Post-box location
Nambiar et al. (1989)	Rubber plant location
Semet & Taillard (1993)	Grocery distribution
Kulcar (1996)	Waste collection

Murty & Djang (1999)	Military equipment location
Burns et al. (2000)	Parcel delivery
Chan et al. (2001)	Medical evacuation
Lin et al. (2002)	Bill delivery
Lee et al. (2003)	Optical network design
Wasner & Zapfel (2004)	Parcel delivery
Cappanera et al. (2004)	Obnoxious facility LR
Billionnet et al. (2005)	Telecom network design
Gunnarsson et al. (2006)	Shipping industry
Alumur and Kara (2007)	Disposal of hazardous material
Rönnqvist et al. (2007)	Forest harvesting
Apaydin and Gonullu (2008)	Waste collection
Aksen and Altinkemer (2008)	Distribution logistics
Wang et al. (2011)	Environmental impact of SC
Stenger et al. (2012)	Small package shippers
Validi et al. (2012)	Green distribution system
Erdoğan and Miller-Hooks (2012)	Green vehicle-routing

The literature also reports green initiatives with respect to location routing, particularly in green reverse logistics (Fleischmann et al. 2001; Zhu et al. 2008; Neto et al. 2009). Trade-offs between the cost factors and the environmental impact of a supply chain is reported in Wang et al. (2007). A green VRP is reported that uses a mixed-integer linear programming approach (Erdoğan and Miller-Hooks 2012). A dairy manufacturer's supply chain distribution system is reported using a multi-objective programming approach (Validi et al. 2012). In the next section, solutions offered to facility location and integrated location-routing models are discussed.

2.4.2. Solution methods

LRP combines facility location and customer allocation to facilities with vehicle routing. These problems are hard to solve since they merge two different problems in nature: facility location and vehicle routing. Mathematically, such problems are considered as NP-hard problems (Karp 1972; Nagy and Salhi 2007; Marinakis and Marinaki 2008; Yu et al. 2010; Daskin et al. 2010; Perl and Daskin 1985; Hassanzadeh et al. 2009). Due to the computational complexity of such problems there is no unique solution to them. Therefore, a solution space is defined by the use of a solution approach and an optimiser. Within the specified solution space the optimum solution(s) considering the goal(s) of the problem and its constraints are found.

Hassanzadeh et al. (2009) categorises the solution methods into three groups, viz. exact, heuristic, and meta-heuristic. Brimberg and Hodgson (2011) argue that the classical location problems fall into a two-dimensional space and can be depicted in three ways, viz. continuous, discrete, network space. In network space, according to Brimberg and

Hodgson (2011), ‘demands are expressed at vertices of networks, facility locations (in the case of medians) are selected from network vertices, and distances are calculated over the shortest paths in the network’. Nagy and Salhi (2007) categorise the methods used for solving LRPs in four main groups (Figure 2.7).

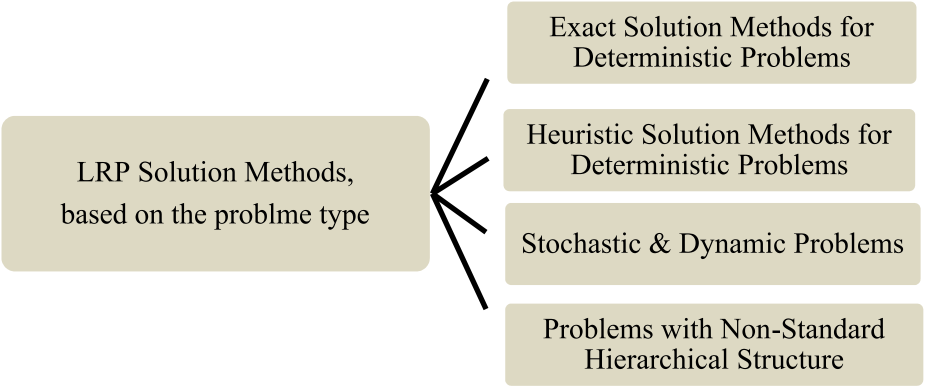


Figure 2.7 LRPs solution methods (adopted form Nagy and Salhi 2007)

Solution methods to facility location problem and its variants in the context of SC design are depicted in Table 2.3:

Table 2.3 Solution methods for supply chain design problems

References	Problem	Solution Method
Cooper (1963-1964)	Fixed charge FLP	
Teitz and Bart (1968)	Fixed charge FLP	Exchange or ‘swap’ algorithm
Maranzana (1964)	Uncapacitated fixed charge LP	Neighbourhood search improvement algorithm
Geoffrion and Garves (1974)	Fixed charge LP	Lagrangian relaxation algorithm
Galovo et al. (2002) and Daskin (1995)	Uncapacitated fixed charge LP	Lagrangian relaxation algorithm
Hansen and Mladenvic (1997)	Fixed charge FLP	Variable neighbourhood search algorithm
AL-Sultan and Al-Fawzan (1999)	Uncapacitated fixed charge LP	Tabu search
Jayaraman and Pirkul (2001)	Multi-Commodity, multi-plant, capacitated facility FLP (supply chain design problem)	Heuristic approach base on Lagrangian relaxation
Jang et al. (2002)	Design of SC network	Lagrangian heuristics
Sayrif et al. (2002)	Multi-source, single-product, multi-stage SC network design problem	Spanning tree-based GA approach
Shen et al. (2003)	Basic model	Column generation approach
Oszen et al. (2003)	Model with routing cost estimation	Lagrangian relaxation based solution algorithm
Jayaraman and Ross (2003)	Designing of distribution network and management in supply chain environment	Heuristic approach based on simulated annealing
Shen and Daskin (2005)	Model with service consideration	Weighting method

Shen and Daskin (2005)	Model with service consideration	Genetic algorithm
Shen (2000)	Model with multiple commodities	Lagrangian relaxation embedded in a branch and bound algorithm
Yeh (2005)	Multistage supply chain network problem (MSCN)	Hybrid heuristic algorithm
Amiri (2006)	Designing a distribution network in a supply chain system with allow for multiple levels of capacities	Lagrangian based solution algorithm
Yeh (2006)	Multistage supply chain network problem (MSCN)	Memetic algorithm (MA)
Shen (2006)	Profit maximising model with demand choice flexibility	Branch-and-price algorithm
Altiparmak et al. (2006)	Multi-objective SC network design problem	New solution procedure based on genetic algorithm
Romeijn et al. (2007)	Two-echelon SC design problem	Column generation
Shen (2007)	Model with unreliable supply	Algorithm based on the bisection search and the outer approximate algorithm
Synder et al. (2007)	Model with parameter uncertainty	Lagrangian relaxation based solution algorithm
Hinojosa et al. (2008)	Dynamic supply chain design with inventory	Lagrangian approach which relaxes the constraints connecting the distribution levels
Schütz et al. (2008)	Two-stage stochastic supply chain design problem	Sample average approximation in combination with dual decomposition
Altiparmak et al. (2009)	Design of a single-source, multi-product, multi-stage SC network	Solution procedure based on steady-state genetic algorithm (SSGA)
Bischoff et al. (2009)	Multi-dimensional mixed-integer optimization problem (multi-facility location–allocation problem with polyhedral barriers)	Heuristic methods (alternate location–allocation; alternate location-with-barriers allocation algorithm, & alternate location allocation-with-routes algorithm)
Li et al. (2009)	Capacitated plant location problem with multi-commodity flow	Lagrangian-based method including a Lagrangian relaxation, a Lagrangian heuristic and a sub-gradient optimisation + Tabu search to further improve upper bounds provided by the Lagrangian procedure
Liberatore et al. (2011)	Stochastic R-interdiction median problem with fortification (S-RIMF)	- Pre-processing techniques based on the computation of valid lower and upper bounds - Heuristic approach
Reddy et al. (2011)	Single echelon supply chain two stage distribution inventory optimisation	No solution offered!

Several optimisation algorithms are adopted by researchers in LRPs. A good number of these algorithms are heuristics/meta-heuristics. A detailed survey of the location-routing techniques is provided in (Madsen 1983; Min et al. 1998; Kenyon and Morton 2001;

Nagy and Salhi, 2007). A synopsis of the optimisation techniques is illustrated in Table 2.4.

Table 2.4 A synopsis of the reported optimisation techniques for LRPs

Optimisation techniques used	**Publications**
Self-organised optimisation using artificial neural network	Schwardt and Fischer (2009)
Honey bees mating optimisation	Marinakis et al. (2008)
Ant colony optimisation	Bell and McMullen (2004), Bin et al. (2009), Ting and Chen (2013)
Particle swarm optimisation	Yang and Zi-Xia (2009); Liu et al. (2012)
Tabu search	Gendreau et al. (1994), Melechovský et al. (2005), Albareda-Sambola et al. (2005), Caballero et al. (2007)
Simulated annealing	Lin et al. (2002), Yu et al. (2010), Stenger et al. (2012).
Greedy randomised adaptive search optimisation	Prins et al. (2006), Duhamel et al. (2010), Nguyen et al. (2012)
Variable neighbourhood search optimisation	Melechovský et al. (2005), Ghodsi and Amiri (2010), Derbel et al. (2011)
Genetic algorithms	Zhou and Liu (2007), Marinakis and Marinaki (2008), Jin et al. (2010), Karaoglan and Altiparmak (2010)
Branch and cut optimisation	Belenguer et al. (2011), Karaoglan et al. (2011)
Mixed-integer programming; Integer linear programming	Alumur and Kara (2007), Diabat and Simchi-Levi (2009); Laporte et al. (1989); Ambrosino and Scutella (2005)

NP-hard LRP is broken down into its components by heuristics/meta-heuristic methods. These components (Karp 1972) are solved and then the final solution to the problem is reached. These heuristic/meta-heuristic methods can follow location-allocation-routing algorithms or allocation-routing-location algorithms. Location-allocation-routing algorithms first locate the facilities, then allocated the customers to facilities and then define the connection routes. Instead, allocation-routing-location algorithms deal with allocation of facilities and routing simultaneously. Usually allocation-routing-location algorithm defines a set of routes and assumes that all facilities are open, allocates customers to facilities and drops the unselected facilities from the system and updates the location and routing decision (Karp 1972; Perl 1983; Wu et al. 2002). Heuristics and meta-heuristics tend to search the solution space more electively when compared to conventional approaches.

Considering the nature of the solution methods and optimisers, the next challenge in dealing with LRPs and any other form of SC network design model is finding a proper platform to solve the constructed model. Next section reviews the most used software packages and programs used as a solution platform for LRPs.

2.5. Implementation Platforms for LRPs

In the context of Facility Location, Tafazzoli and Mozafari (2009) have done a literature review on the 'classification of location models and location software tools'. They first tried to review the classification of facility location problems and then presented a software survey on FLPs. They categorised the software packages used for solving FLPs into general specialised software packages for solving specific problems. A brief review of some of the main software used for solving/modelling facility location problems are presented in Table 2.5.

Table 2.5 A brief review of the main solution software tools and programmes for facility location modelling (Tafazzoli and Mozafari 2009)

Software	Covering Methods/Models	Source
General software packages and programs		
LOLA	Network, and discrete FLPs including: median, centre, q-median, q-centre (q: the number of facilities in a multi facility problem or the number of objective functions in a multi-objective problem)	Hamacher et al. 1996
SITATION	p-median, set covering, maximal covering, p-centre, UFLP FLs; using branch & bound, Lagrangian relaxation, genetic algorithm, variable neighbourhood	Daskin, 2002 (accompanies Daskin text: Network and Discrete Location: models, algorithms, and applications)
S-Distance	focused on location-allocation analysis: p-median, p-centre, maximal covering, multi-objective; using greedy and randomised algorithms, local search heuristics, meta-heuristics, Lagrangian relaxation	Sirigos and Photis, 2005
More specifically focused software programs and tools (limited)		
Mathematical Programming 1. LINGO 2. LINDO 3. GAMS 4. CPLEX	These software programs need a different level of programming and coding to solve the mathematical model.	
Jure Mihelic (k-centre algorithms)	K-centre algorithms; a program for solving facility location problems with k-centres	Mihelic 2004
RLP	Solving restricted one facility location problem	Nickel and Hamacher, 1992

Advanced Interactive Multidimensional Modelling System (AIMMS), a software system designed for modelling and solving optimisation models has been tested as an option. The software is not compatible to the nature of the models and failed in reaching a feasible solution space.

For the purpose of this research a commercial solver capable of solving the two-layer and three-layer multi-objective 0-1 mixed integer AHP-integrated LRP is required. Furthermore, a commercial solver that offers a variety of optimisers of different natures is desirable. Conventional software packages and tools are not capable of providing a Pareto efficient optimum solution space for these two SC network design models using a variety of advance multi-objective heuristics/meta-heuristics. A multi-disciplinary and multi-objective software capable of handling complex optimisation problems is available for designing purposes. modeFRONTIER® is a multi-disciplinary and multi-objective optimisation and design environment developed by ESTECO SpA (ESTECO 2013). The complex algorithms within modeFRONTIER® can spot the optimal results, even conflicting with each other or belonging to different fields. modeFRONTIER® consists of Design of Experiments (DoE), optimisation algorithms, and robust design tools, capable of blending to create an efficient strategy to solve complicated multi-disciplinary problems. It is offering a wide range of evolutionary optimisers to manage continuous, discrete, and mixed variable problems.

After initial evaluation of available software solution platforms, it was concluded that modeFRONTIER® is the most suitable platform for solving complex NP-hard multi-objective LRPs as are being developed in this study based on its extended capabilities and multi optimiser availability. modeFRONTIER® is a commercial solver, which can be described as a design environment in contrast to a final stage software package. As such a development platform it allows significant scope and flexibility to the designer.

In modeFRONTIER®, MOGA-II, NSGA-II, MOSPOS, MOSA and HYBRID are selected to solve the two and three-layer MO-LRPs. MOGT works using a combination of Game Theory and a Simplex algorithm and uses only the first entry of DoE table, therefore this optimiser is not selected to solve the models in this study. SAnGeA is developed for unconstrained models. As the MO-LRPs are both constrainted in this study, it is deemed not suitable for these models. modeFRONTIER® is explained in more details in Appendix A.4.

2.5. Research Gaps

Survey of literature shows that there has been very little research into the environmental impacts of SC network design. This area of research has the potential to offer a considerable contribution to the environment in terms of GHG emission. Facility location and vehicle-routing are already well established areas of study in SC network design. However, the literature review reveals that more focus should take into account green considerations on the use of facility location and vehicle-rooting techniques and methods.

The main three objectives of this study are: (a) Developing low-carbon location-routing models, (b) Finding an effective solution approach to implement the developed models, and (c) Offering targeted and tailored low-carbon low-cost scenarios to DM's considering their priorities. In order to consider green elements in SC network design, this research is particularly focused on improvement of Berger's (1997) two-layer LRP and Perl's (1983) three-layer LRP. The critical survey of literature reveals the following gaps in location-routing modelling in the context of SC network design:

- **From modelling perspectives of LRPs**
    - Prior research fails to include cost of serving routes while optimising CO2 emission in SC network. Therefore this research optimises the total CO_2 emission caused from transportations throughout the SC network considering the cost of serving the routes. Existing LRPs do not include the capacity of DCs and the demand of retailers. The effect of the capacity of DCs and the demand of retailers on the total cost is studied in this research by adding these components to the developed models.
    - DM's priorities are not considered in designing prior LR models. This research considered the DM's priorities in the mathematical model by using MCDM tools and techniques. This will make the mathematical model capable of responding to the priorities of the DM with qualitative nature
- **From solution perspective on LRPs**
    - The developed models in this research are multi-objective. Besides, MCDM techniques are used to consider the DM's priorities. The combi-

    nation of these two characteristics makes the developed models quite different from any prior LRPs. Therefore, an effective implementation platform for low-carbon multi-objective LRPs is to be identified and deployed.

    - One of the shortfalls of evolutionary algorithms such as genetic algorithms is that they generate a considerable number of irrelevant solutions. By introducing DoE to the solution algorithms robust solution approach is achieved.

- **From analysis of results perspective**
    - Prior research to LRPs doesn't consider MCDM techniques to rank the results. This research considers MCDM techniques for ranking results obtained from evolutionary algorithms used for implementing the models.
    - Prior research fails to provide the decision-makers with various scenarios and analysis related to these scenarios. This research suggests multiple scenarios followed by analysis based on the scenarios and the solutions offered by each one of them.

2.6. Summary

This research is focused on low-carbon low-cost integrated location-routing and this chapter reviewed the highly inter-disciplinary relevant literature to this topic. The literature on Supply Chain Design, Facility Location Problems and Integrated Location-Routing Problems are reviewed. Logistics Decisions and Green Logistics Decisions are surveyed as sub-sections to SC design. The survey of available literature in these three main sections reveals that the environmental issues have been considerably neglected in Integrated Location-Routing modelling. The next observation from reviewing the available literature is that the decision-makers opinions are not considered in making LR decisions. There is possibility of considering DM's opinion and their priorities in the modelling phase and/or in the analysis of results phase. Implementation platforms and solution approaches available to LRPs are studied in this chapter. Literature shows that there is room for improvement in the solution approaches to LRPs.

The thorough survey of literature reveals that low-carbon low-cost LRPs have not been studied before. To the best of my knowledge there is no evidence of a multi-objective low-carbon LRP in literature. This is the exact area this PhD research is focused on. Next chapters of this dissertation explain two sets of multi-objective LRPs developed to minimise cost and carbon emissions simultaneously.

CHAPTER THREE

Research Design

3.1. Introduction

Chapter One presented an introduction to the study outlining its background, scope, aims and objectives and significance. Chapter Two presented a survey of the literature in the main context of SC network design. This chapter presents and overview of the adopted methodology to meet the aims and objectives of the research.

The chapter outlines as follows. The research method is introduced in section 3.2. Section 3.3 describes the modelling approach. Section 3.4 deals with solution approach while section 3.5 describes the data analysis approach. A summary on the chapter is presented in section 3.6.

3.2. Research Method

This research is focused on 'Integrated Location-Routing', one of the Facility Location integrated models in Supply Chain Network design. Facility Location is a well-established subject area in Operations Research. Thus, in order to explore and enquire the aims and objectives of this study mathematical optimisation is adopted. Mathematical optimisation involves three main steps in Operations Research: i) Modelling approach, ii) Solution approach and iii) Analysis approach. In the following section these main steps of the methodology for this research are briefly introduced.

3.3. Modelling Approach

One of the main aims of this research is to improve Berger's (1997) two-layer LRP and Perl's (1983) three-layer LRP. The improvement is focused on inclusion of the green elements into these models. The 'green' element in this research is defined as 'minimising CO2 emission from transportation within the two and three SCNs'. The focus is on developing and introducing two components to the two and three layer

LRPs: developing a new green objective function and developing a new green constraint.

Conventionally two and three layer LRPs are single-objective primarily focused on cost. The developed models are multi-objective with two objective functions. The traditional objective function exists which focuses on ‘costs’. The green objective function aims to minimise the ‘CO_2 emission from transportation’. These two objective functions work simultaneously in order to find an optimum solution space to the developed models.

The green constraint leads the model to find the best transportation option considering the DMs’ priorities. In the construction of this constraint the DMs’ priority regarding the importance and weight of ‘cost’ and ‘CO2 emission’ when it comes to transportation (i.e. types of trucks) is considered. Contribution of this constraint to the model is offering a transportation option tailored based on the DMs’ priorities and within the main framework of the model. MCMD techniques are considered to construct this constraint.

3.4. Solution Approach and Solution Platform

Literature reveals that two-layer LRPs are computationally NP-hard problems. There is no unique solution to these types of models but a feasible solution area. In different attempts a variety of heuristics/meta-heuristics in one or multi-phase algorithms have been implemented to solve LRPs.

Two-layer LRPs are solvable in a one phase solution approach while multi-phase solution approaches are implemented in order to solve three-layer LRPs. Typically the multi-phase solution algorithms break the problem into its main components (facility location, allocation of customers to facilities, vehicle routing). These algorithms follow a consecutively connected multi-phase approaches to solve the three-layer LRPs. The Perl (1983) three-layer LRP has been solved by him using a three phased heuristic. In another attempt, Wu et al. (2002) solves the Perl’s (1983) three-layer LRP in two phases.

One of the main aims of this study is to find or offer an effective solution approach for both the two-layer and the three-layer MO-LRPs. The two-layer MO-LRP is an extension of the Berger (1997) LRP and the three-layer MO-LRP is an extension of the Perl

(1983) and a variation of the two-layer MO-LRP. Implementation platforms, solution approaches and different optimisers are considered to be studied in this research to find or offer the best possible implementation platform, the most effective solution approach and the most efficient optimiser.

After reviewing available software solution platforms, modeFRONTIER® is recognised as the most suitable platform for solving complex NP-hard multi-objective LRPs as are being developed in this study. This commercial solver can be described as a design environment in contrast to a final stage software package. It allows significant scope and flexibility to the designer. In modeFRONTIER®, MOGA-II, NSGA-II, MOSPOS, MO-SA and HYBRID are selected to solve the two and three-layer MO-LRPs.

3.5. Supply Chain Cases and Data Analysis Approach

In order to elucidate the efficacy of the formulated generic mathematical models, a dairy supply chain network in east of Ireland is considered. Two case studies consisting of two-layer and three-layer dairy SC networks in east of Ireland are developed. The required data is collected and calculated according to their availability and their nature. The structure of these SC cases are validated by means of: (i) interviewing a consultant to few dairy companies in Ireland, (ii) interviewing experts from two major dairy companies in Ireland, (ii) using company profiles, technical reports from dairy companies, outcomes of researches on dairy SCs, and SC text books. There is a questionnaire designed to collect data from experts (Appendix B.1). Based on this validated real structure of the dairy supply chain network in Ireland, two-layer and three-layer SC cases are considered to test the models on. Carbon-emission related data is calculated based on the available recognised methodologies for calculating carbon emission from transportation. Due to unavailability of production fixed and variable cost-related data, they are assumed based on: i) interviewing a consultant to dairy SC companies in Ireland, and ii) the real available data regarding costs of dairy products in Ireland. Vehicle-routing costs are calculated using real data. After validating the structure of the SC networks, distance-related data are calculated using google map. And finally, DM’s priorities are collected by interviewing experts in the modelling phase to develop the green constraint. The process of collection and calculation of the required data is respected to the two-layer and the three-layer SC networks structures.

In LRPs, Analysis of the obtained results is of a great importance as there is a feasible solution area not a single optimum solution to them. The analysis process consists of checking all feasible solutions, ranking them and offering the best possible solutions to the DMs. DMs' opinions is considered in this process using MCDM tools and techniques.

3.6. Summary

This research is dealing with Integrated-Location Routing in Supply Chain (SC) network design. Two-layer and three-layer SC networks are considered in this study. The two-layer SC network consists of plants and retailers while the three-layer SC network includes plants, distribution centres and retailers. The main outcome of the research would be a generic low-cost low-carbon framework to design a network of facilities and offering a routing pattern to connect these facilities.

The main subject area of this research is an interdisciplinary field in supply chain covered by operations research. The effective method to conduct research in this subject area is mathematical optimisation. This is the approach that this PhD study has taken to pursue its aims and objectives. Multi-objective location-routing optimisation is adapted to design two and three-layer supply chain networks. The developed optimisation models are explained in details in the following chapters of this dissertation.

CHAPTER FOUR

Two-Layer Multi-Objective Integrated Location-Routing

4.1. Introduction

A conventional two-layer Location-Routing Problem (LRP) on the demand side of a SC is found in Berger (1997) and Daskin et al. (2005). A proposed low-carbon/green two-layer Multi-Objective-Location Routing Problem (MO-LRP) improves the conventional models of Berger (1997) and Daskin et al. (2005) and contributes to the literature in the field of low-carbon capacitated two-layer LRPs.

The demand side of a two-layer SC with two facilities and multiple retailers is illustrated in Fig. 4.1. This two-layer SC network consists of plants and retailers. The flow of materials is also indicated in Fig. 4.1. The physical distribution of a two-layer SC network is the subject of analysis in this chapter.

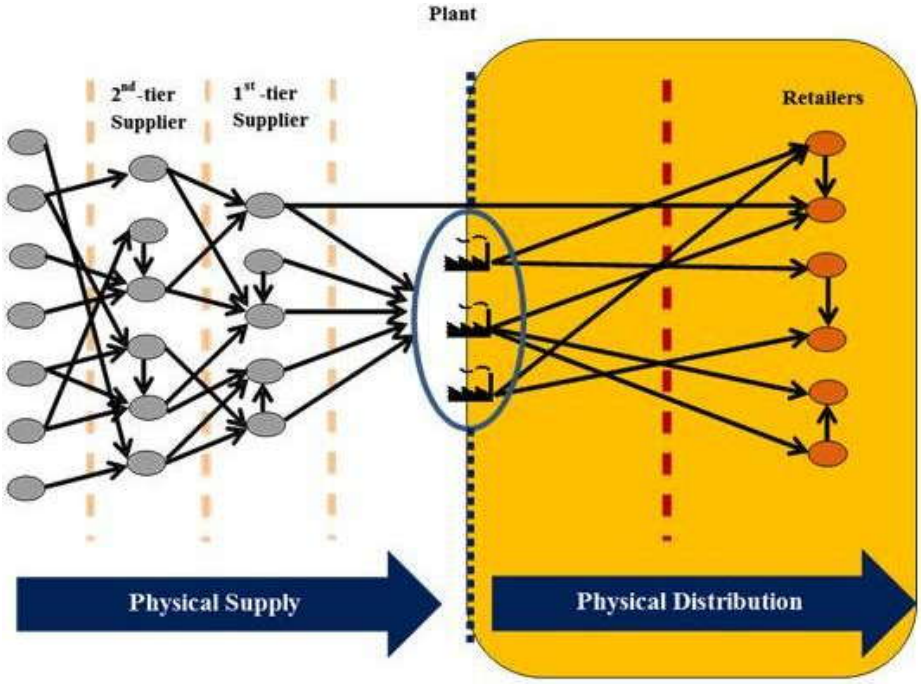


Figure 4.1 A two-layer SC with multiple retailers (Adapted from: Schroeder et al. 2013)

The main contribution of this chapter is three inter-linked aspects of the proposed variant of the two-layer MO-LRP, viz.:

(i) a green location-routing model is designed by integrating AHP with 0-1 mixed integer programming

(ii) a Design of Experiment (DoE) guided meta-heuristic-based robust solution approach under the modeFRONTIER® commercial solver is provided and

(iii) the decision-makers' (DMs') prioritisation and subsequent ranking of the realistic solutions are examined using Pareto frontiers, 'Technique for Order Preference by Similarity to Ideal Solution' (Hwang and Yoon 1981) (TOPSIS) and various scenarios of the green location-routing are featured.

This chapter is divided into three connected parts. Part-I presents the integrated green MO-LRP. Part-II elucidates the DoE-guided meta-heuristic-based robust solution approach under the modeFRONTIER® commercial solver followed by the deployment of a case of a two-layer supply chain. Part-III delineates the DMs' prioritisation and subsequent ranking of the realistic solutions using Pareto frontiers and TOPSIS. In this part various scenarios of the two-layer routing events are featured by determining alternative possible outcomes. This validates the robustness of the realistic solution sets.

The two-layer MO-LRP, its efficient solution approach and analysis of the realistic results contribute to the following aspects on the demand side of the SC in the following ways:

(i) a low-carbon two-layer MO-LRP optimisation model on the demand side of an SC is formulated. Green elements are embedded in an objective function and an AHP-integrated constraint.

(ii) the model allocates retailers to the facilities, i.e., plants.

(iii) the model optimally routes the vehicles to serve the demand-side of the SC.

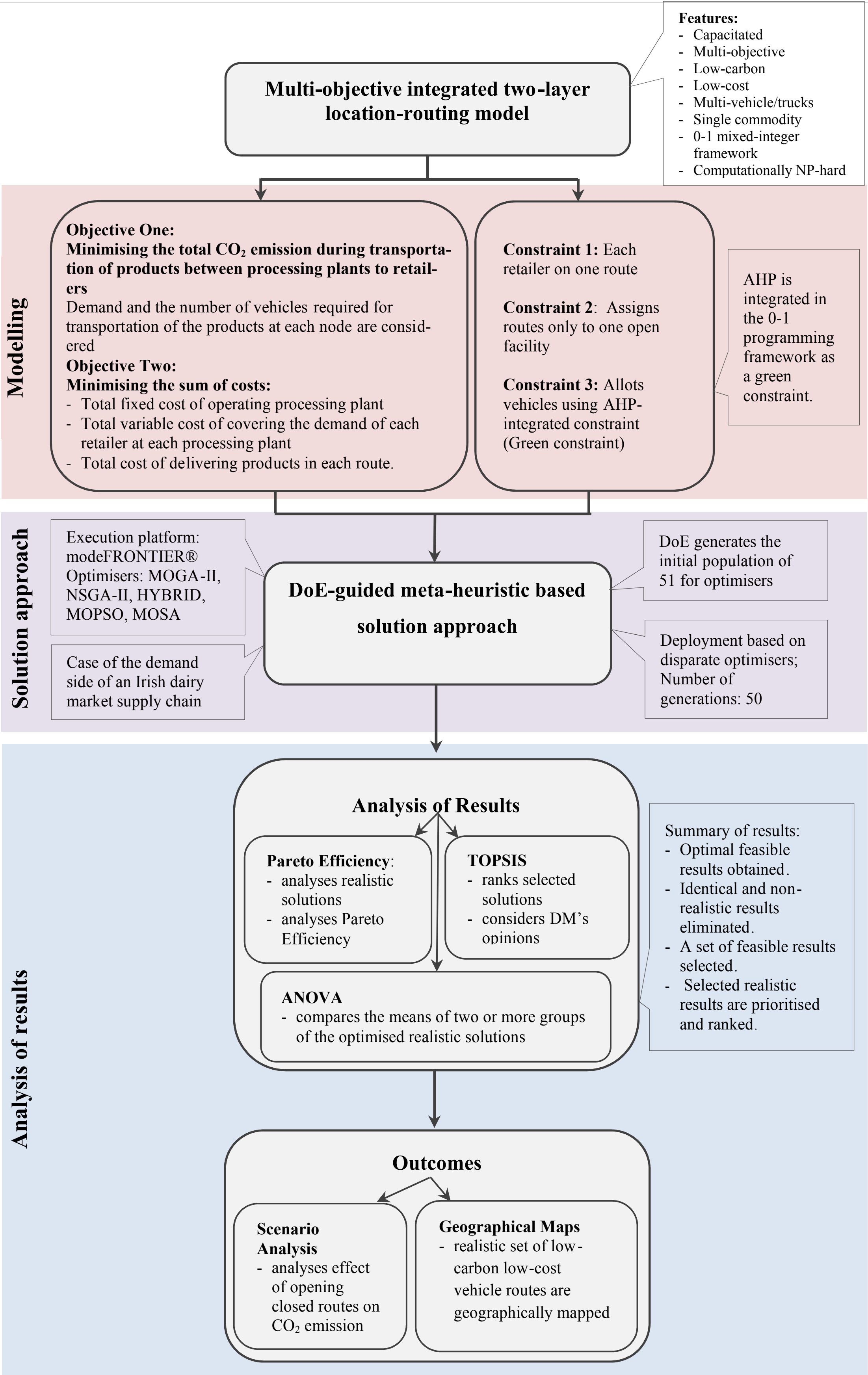
(iv) the total carbon emission and total cost are optimised. These criteria are conflicting in nature having incommensurable units of measurements.

(v) the optimisation model is found to be computationally NP-hard. The model is implemented using DoE-guided meta-heuristic disparate optimisers under the modeFRONTIER® commercial solver platform (ESTECO 2013).

(vi) sets of Pareto efficient realistic optimum results are found. The results are then prioritised and ranked by the DMs. TOPSIS assists in evaluating sets of selected results. An analysis reflecting the DMs' preferences is performed. This analysis reflects the changes in the controlling parameters with respect to the changes in the decision weights of TOPSIS.

(vii) a scenario analysis of the location-routing events is performed. The scenario analysis offers possible alternatives to DMs when the closed routes are forced to open. This shows the robustness of the realistic solution sets.

(viii) the set of low-carbon vehicle routes are geographically mapped.



Multi-objective integrated two-layer location-routing model

Features:
- Capacitated
- Multi-objective
- Low-carbon
- Low-cost
- Multi-vehicle/trucks
- Single commodity
- 0-1 mixed-integer framework
- Computationally NP-hard

Objective One:
Minimising the total CO_2 emission during transportation of products between processing plants to retailers
Demand and the number of vehicles required for transportation of the products at each node are considered

Objective Two:
Minimising the sum of costs:
- Total fixed cost of operating processing plant
- Total variable cost of covering the demand of each retailer at each processing plant
- Total cost of delivering products in each route.

Constraint 1: Each retailer on one route

Constraint 2: Assigns routes only to one open facility

Constraint 3: Allots vehicles using AHP-integrated constraint (Green constraint)

AHP is integrated in the 0-1 programming framework as a green constraint.

Execution platform: modeFRONTIER®
Optimisers: MOGA-II, NSGA-II, HYBRID, MOPSO, MOSA

Case of the demand side of an Irish dairy market supply chain

DoE-guided meta-heuristic based solution approach

DoE generates the initial population of 51 for optimisers

Deployment based on disparate optimisers; Number of generations: 50

Analysis of Results

Pareto Efficiency:
- analyses realistic solutions
- analyses Pareto Efficiency

TOPSIS
- ranks selected solutions
- considers DM's opinions

ANOVA
- compares the means of two or more groups of the optimised realistic solutions

Summary of results:
- Optimal feasible results obtained.
- Identical and non-realistic results eliminated.
- A set of feasible results selected.
- Selected realistic results are prioritised and ranked.

Outcomes

Scenario Analysis
- analyses effect of opening closed routes on CO_2 emission

Geographical Maps
- realistic set of low-carbon low-cost vehicle routes are geographically mapped

Figure 4.2 The formulation of the multi-objective two-layer location-routing model, its solution approach and analysis procedure

Part I: Modelling

4.2. Two-Layer Multi-Objective Integrated Location-Routing

The low-carbon MO-LRP is formulated by integrating AHP with a 0-1 programming approach. This model is developed to be generic and can be extended to any two-layer supply chain network. Realistically the model can be extended to any number of plants and retailers on the demand-side of a supply chain.

The integrated model is formulated considering a set of realistic assumptions. Similar vehicle capacities are considered. Transportation of the products between plants and retailers results in CO_2 emission. In summary, the following assumptions are considered while formulating the optimisation model:

Box 4.1 Assumptions

- Demand side of the SC is considered
- Multiple facilities, multiple retailers and a single product is considered
- Plants always remain open
- Locations of the plants and retailers are known
- Vehicle routes have known start and end points
- Total demand on each distribution route is less than or equal to the plant capacity
- A portion of the variable cost is dependent on the demand at retailer points
- Each distribution route is served by at least one vehicle
- Diesel operated refrigerated heavy duty vehicles / heavy goods vehicles are considered
- Fuel consumption of the vehicles is dependent on the total mass of the vehicles

Conventional location-routing problems are single-objective in nature with the principal aim of minimising total costs. The multi-objective mathematical programming model is formulated within a mixed integer programming framework. A detailed nomenclature of the optimisation model is elucidated in Table 4.1.

Table 4.1 Nomenclature

Sets and indices

I	Set of retailer locations indexed by i
J	Set of plants indexed by j
P_j	Set of feasible paths from plants to retailers, $j \in J$
K	Set of routes, indexed by k
M	Set of attributes in AHP decision matrix (CO_2 emission and costs) , indexed by m
N	Set of alternative vehicles in AHP decision matrix, , indexed by n

Decision variables

V_{jk}	Set of feasible paths form processing plant $j \in J$ to retailer $i \in I$
T_n	Trucks with different specifications; $n \in (1,2,3)$
X_j	Set of processing plants $j \in J$

Parameters

f_j	Fixed costs of locating at plant $j \in J$
v_j	Variable costs of serving retailers at each plant $j \in J$
a_j	Variable cost of providing a retailer with the products at a DC per unit, $j \in J$
r_j	Demand at retailer location, $j \in J$
c_{jk}	Cost of serving path, $k \in P_j$
p_{ji}	CO_2 emission from transportation in each path from plant $j \in J$ to retailer $i \in I$
z	Speed in different roads, km/hr
W_{mn}	Matrix of weights for each truck option
B_m	Right hand side matrix for green constraint
S_m	Values of p_{ji} and c_{jk} depending on the values of B_m

The model includes a 'green' objective function that aims to minimise the total CO_2 emission during the transportation of the products to the retailers. A low-carbon element is introduced to this integrated model as an objective function by way of integrating an AHP-based constraint. Based on the assumptions of the model, a multi-objective 0-1 mixed-integer two-layer location routing AHP-integrated model is developed as follows:

$$\text{minimise} \quad \sum_{j \in J} \sum_{i \in I} p_{ji} V_{jk} \quad , \qquad \forall k \in P_j \tag{4-1}$$

The first objective function of this model (4-1) is designed to minimise the total CO_2 emission related to transportation between plants and retailers. p_{ji} is calculated using the following formula (4-8) (The Department of Energy and Climate Change (DECC) 2008; Department for Environment, Food and Rural Affairs (DEFRA) 2008):

$$CO_2 \text{ emission from a diesel vehicle in kg} = \text{Litres of diesel burnt} \times 2.64 \ (kg) \tag{4-2}$$

The litres of diesel burnt by heavy duty vehicles/trucks are calculated using formula (4-3):

$$Litres\ of\ diesel\ burnt\ in\ each\ path\ = fuel\ efficiency\ (litre/km) \times Distance\ (km) \tag{4-3}$$

Fuel consumption (efficiency) is dependent on vehicle mass. Average fuel efficiency is considered as 0.35 $litre/km$ (DECC 2008; Nylund and Erkkilä 2005). As the geographical start and end points of the routes are known, distances can be measured between each plant and each retailer. V_{jk} defines all feasible routes from plants to retailers. V_{jk} is a 0-1 integer variable where 0 refers to the closed routes and 1 open routes.

The second objective function (4-10) minimises the total costs. The total costs include the sum of the fixed costs for operating the plants, variable costs for serving the retailers at each plant and vehicle-routing costs:

$$\text{minimise} \quad \sum_{j\in J} f_j X_j + \sum_{j\in J} v_j V_{jk} + \sum_{j\in J} c_{jk} V_{jk} \quad , \quad \forall k \in P_j \tag{4-4}$$

The following three costs are considered in this objective function (4-4):

- **Fixed costs**

Fixed costs of operating plants (f_j) are not dependent on the number of products produced or processed at each plant.

- **Variable costs**

Variable costs (v_j) are dependent on the number of products produced or processed to serve each retailers. Cost of serving retailers at each plant is considered (a_j) for each unit of product and it is dependent on the demand at retailer location (r_j). Open routes define a retailer to be served by a plant represented by V_{jk}. Equation (4-5) calculates the sum of variable costs at each plant:

$$v_j = (a_j . r_i) \tag{4-5}$$

In equation (4-5) the demand at a particular retailer location is considered while in conventional two-layer Location-Routing Problems (LRP) demand is not included.

- Vehicle-routing costs

In order to calculate vehicle-routing costs two main cost components are considered – total cost of fuel and the total wage of the driver on each route. Based on the assumptions of Box 3.1 equations (3-6), (3-7) and (3-8) are defined in order to calculate total vehicle-routing costs:

$$\textit{Cost of Serving Each Route}\ (€) = \textit{Fuel Cost}\ (€) + \textit{Driver's Wage}\ (€) \tag{4-6}$$

$$\textit{Total Fuel Cost}\ (€) = \textit{Diesel burnt}\ (\textit{litre}) \times \textit{Fuel Price}\ (€\ /\ \textit{litre}) \tag{4-7}$$

$$\textit{Total Driver's Wage}\ (€) = \textit{Driver's wage}\ (€\ /\ \textit{hr}) \times \frac{\textit{Distance}\ (\textit{km})}{z\ (\textit{km}\ /\ \textit{hr})} \tag{4-8}$$

The driver’s wage is paid on an hourly basis. On different roads and different countries velocity limits are considered in different ways. Therefore, in order to consider the effect of velocity on driver’s wage a variable (z) is introduced representing the average speed for each type of road.

The two-layer MO-LRP has three operational constraints. Conventional LRPs have two constraints - (i) a constraint ensuring a demand node is on a particular route and (ii) a constraint assigning a route only to open facilities. The green MO-LRP covers both of these constraints and adds a green constraint suitably. The three constraints of the two-layer MO-LRP are illustrated in (4-9), (4-10) and (4-11).

Constraint 1: $$\sum_{j \in J} V_{jk} = 1 \quad , \quad \forall k \in P_j \tag{4-9}$$

The above constraint defines all open known operating routes from plants to retailers.

Constraint 2: $$\sum_{j \in J} V_{jk} - X_j \leq 0 \qquad , \qquad \forall k \in P_j \tag{4-10}$$

Constraint 2 assigns a route only to one open facility.

Constraint 3: $$S_m \Big(\sum_{m \in M} \sum_{n \in N} w_{mn} T_n \Big) \leq B_m \qquad , \qquad \forall i \text{ and } j \text{ on } V_{jk} \tag{4-11}$$

Constraint 3 infuses AHP into the 0-1 programming framework. This constraint determines the type of vehicle used for transportation of the products. This is the green constraint of the model involving the DMs’ priorities. The DMs are asked to evaluate the candidate-vehicles/trucks considering two criteria in order to select the best vehicles/trucks. The two criteria for decision-making are: CO_2 emissions and cost. The process of decision-making using this AHP-integrated constraint is illustrated in Figure 4.3:

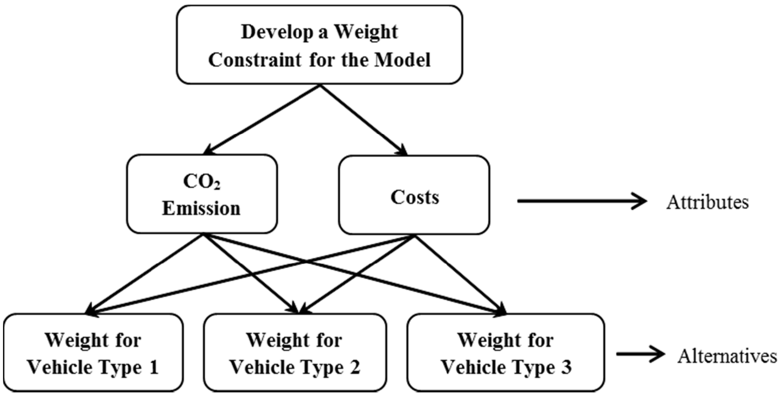


Figure 4.3 The process of developing a weight matrix in order to contract an AHP-integrated constraint

Three types of vehicles/trucks are considered for transportation of products. The characteristics of the trucks are considered as follows:

T_1 : Truck type 1 (Medium CO_2 emission / Medium cost)

T_2 :Truck type 2 (Low CO_2 emission / High cost)

T_3 :Truck type 3 (High CO_2 emission / Low cost)

The third constraint of the integrated MO-LRP introduces the flexibility in the DMs' consensus opinions in selecting the type of vehicles/trucks used for the distribution of the products in an environmental-friendly manner. DMs' priorities are converted by AHP into a weight matrix. The elements B_m and w_{mn} of the constraint use the results obtained from the decision-making approach through AHP. Figure 4.4 depicts how the vehicles/trucks, attributes of the decision-making and B_m (i.e., right hand side of the third constraint 4-11) contribute to the parameters of the objective functions (4-1) and (4-4).

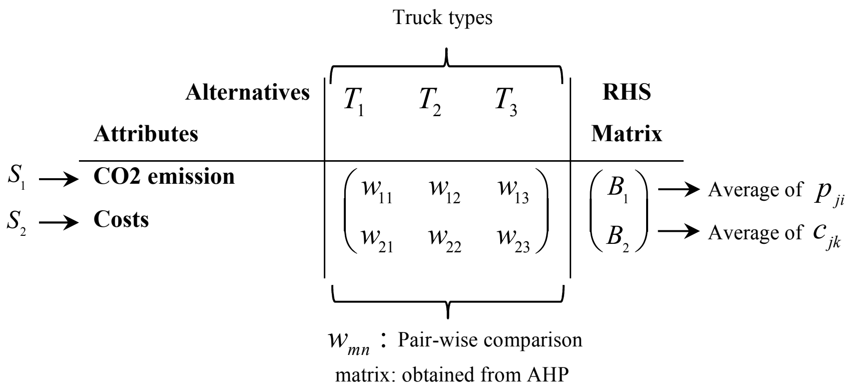


Figure 4.4 The integration of AHP to the objective functions

The standard integer (4-12 and 4-13) and non-negativity (4-14) constraints of the model are as follows:

Integer constraints:

$$V_{jk} = \begin{cases} 1, & \text{if path } k \in P_j \text{ is operating out of plant } j \in J \\ 0, & \text{if not} \end{cases} \tag{4-12}$$

$$T_n = \begin{cases} 1, & \text{if truck } n \in T_n \text{ is selected to transport the products} \\ 0, & \text{if not} \end{cases} \tag{4-13}$$

$$X_j = \begin{cases} 1, & \text{if plant j} \in J \text{ is open} \\ 0, & \text{if not} \end{cases} \tag{4-14}$$

Part II: Solution Approach

4.3. Solution Approach

Literature reports that LRPs are NP-hard combinatorial optimisation problems (Karp 1972; Nagy and Salhi 2007; Marinakis and Marinaki 2008; Yu et al. 2010). The two-layer MO-LRP is NP-hard as well. It is an improvement to Berger's (1997) NP-hard LRP and is a multi-objective combinatorial optimisation model. Such LRPs are very hard to solve as they combine two different conflicting-in-nature problems, viz. facility location and vehicle routing (Daskin et al. 2010). Conventional LRPs are single objective in nature with the main aim of minimising the total costs of operating facilities and transportation.

The multi-objective low-carbon two-layer AHP-integrated 0-1 mixed integer location-routing model, discussed in Part-I of this chapter, comprises of conflicting-in-nature objectives and constraints. In a Multi-Objective Problem (MOP) more than one objective function is optimised in order to find a set of Pareto optimal solutions (Coello et al. 2007). The two-layer MO-LRP features the characteristics of a MOP and LRP. Therefore, no exact solution exists for the two-layer MO-LRP. The technical details of the two-layer MO-LRP are presented in Table 4.2:

Table 4.2 Technical details of the two-layer MO-LRP

Scope	Vehicle routing decisions for routes connecting plants to retailers
Goals	Vehicle routing decision: - Routes connecting open plants to retailers
Objective functions	Objective function I: Minimise the total CO_2 emitted during the transportation of the products from plants to retailers Objective function II: Minimise the total cost of operating plants, cost of serving the retailers and cost of vehicle routing

Constraints	Constraint 1: Each demand node on one route Constraint 2: A route can be assigned only to one open facility Constraint 3: AHP integrated constraint (green constraint), considering the DM's priorities Integer constraints Non-negativity constraint
Outcomes	Low-carbon, low-cost routing patterns connecting open plants to retailers

The feasibility of the proposed two-layer MO-LRP is then examined by deploying the model in a SC network. The next section describes the details of the evaluation of the two-layer MO-LRP.

4.4. Validation of the two-layer MO-LRP – the case of an Irish dairy SC network

The two-layer MO-LRP is developed without considering the specifications of a particular supply chains. It is a generic model that can be applied to any SC. A set of data, as indicated in Box 4.2, is required to run the model and design a two-layer SC network.

Box 4.2 Required data set for the two-layer MO-LRP

a. Number of plants, number of retailers
b. Geographical location of plants and retailers in order to calculate the distances between each node in the SC
c. Fixed cost of operating plants
d. Variable cost of providing retailers with one unit of product at each plant
e. Vehicle routing-related costs:
   - Driver's wage
   - Cost of fuel per litre
f. Demand at each retailer location
g. Distance between plants and retailers, divided by the type of roads
h. CO_2 emission from transportation at each route from one vehicle
i. AHP related data:
   - DM's pair-wise matrix regarding the truck types based on CO_2 emission and costs
   - The limits (maximum allowed) for CO_2 emission and costs (RHS matrix)

In Ireland (according to latest EPA report of March 2012) the total GHG emission is 61.31 million tonnes. Agriculture is the largest contributor to the overall emission (30.5% of total) followed by energy (at 21.8%) and transport (at 18.9%). Ireland's

Kyoto limit in the period 2008-2012 was 62.84 million tonnes per annum and the combined emission in the period 2009-2010 was 5.48 million tonnes above this limits. CO_2, as a primary GHG gas, comes from both natural sources and human activities. The main human activity that emits CO_2 is the burning of fossil fuels for energy and transportation, followed by some industries that burn fossil fuel as well. As Irish dairy sector is one of the most important agricultural sectors in Ireland's economy this research is focused on the demand side of a dairy SC network in east of Ireland.

Main players of dairy market in Ireland have been recognised and a questionnaire has been prepared to gather information about the structure of demand side of SCs in Ireland. The questionnaire is presented in Appendix B.2. The structure of the two-layer SC case is validated by means of: (a) interviewing a consultant to few dairy companies in Ireland, (b) interviewing experts from two major dairy companies in Ireland, (c) using company profiles, technical reports from dairy companies, outcomes of researches on dairy SCs, and SC text books.

The two-layer MO-LRP consists of two main nodes in the demand side of the supply chain: plants and retailers. Plants are assumed 'open' therefore the facility location decision doesn't exist in this model. In order to solve the two-layer MO-LRP based on the data from the assumed case, a set of assumptions have been made. The details of the case of the two-layer dairy SC network in east of Ireland is explained in the following sections.

4.4.1 Number and geographical location of plants and retailers

Table 4.3 illustrates the number and the geographical location of the nodes of the supply chain network. A 'Node' refers to plants and retailers. Geographic locations of plants are the real locations of the two main processing plants owned by the dairy company the assumed case is built based on.

Table 4.3 Number and location of plants and retailers

Nodes	**Number of nodes**	**Geographical locations**
Plants	2	Drogheda, Ballitore
Consumers	22	Drogheda, Dundalk, Navan, Tullamore, Naas, Newbridge, Leixlip, Port Laoise, Bray, Arklow, Wicklow, Greystones, Clonmel, Waterford, Tramore, Kilkenny, Wexford, Ennoscorthy, Dublin City, Dun Laogharie/Rathdawn, Fingal, South Dublin

- Retailers are located in the east of Ireland in 15 counties within the 50 km radius from each processing plant. According to Irish Central Statistics Office (CSO) official statistics report (Population of each Province, County and City 2011), 22 population centres are considered within the 50 km radius from each processing plant based on having a population of >=10,000 inhabitants at the location.

4.4.2. Fixed and variable costs for the plants

Fixed and variable costs for plants are considered in the second objective function (4-10) and are presented in Table 4.4. The unit of product is considered to be a 2 litre container of milk.

Table 4.4 Fixed and variable costs for plants

Costs **Plants**	**Fixed costs (€)**	**Variable costs (€ / unit of product)**
Plant I	1,500	0.20
Plant II	2,000	0.24

4.4.3. Demand at retailer locations

Demand at retailer locations is considered to be 2/3 of the population for each population centre. Population information is adopted from CSO 2012 official reports. Demand information is for a delivery cycle time which is considered to be 2 to 3 days. Table 4.5 depicts the demand at each consumer location.

Table 4.5 Demand at retailer locations

Retailer Location	**Demand (unit)**
1. Drogheda	25,000
2. Dundalk	25,000
3. Navan	19,000
4. Tullamore	9,000
5. Naas	14,000
6. Newbridge	14,500
7. Leixlip	10,000
8. Port Laoise	9,000
9. Bray	21,000
10. Arklow	9,000
11. Wicklow	7,000

Retailer Location	**Demand (unit)**
12. Greystones	11,000
13. Clonmel	12,000
14. Waterford	35,000
15. Tramore	7,000
16. Kilkenny	16,000
17. Wexford	13,000
18. Ennoscorthy	7,000
19. Dublin City	350,000
20. Dun Laogharire /Rathdawn	138,000
21. Fingal	182,000
22. South Dublin	177,000

4.4.4. Distance between plants and retailers

Variety of speeds on different roads is considered in the model as a factor affecting the green objective function. The speed limits (Table 4.6) as defined in the 'Road Traffic Act 2004' are currently being enforced in Ireland. An average speed is assumed in this case study.

Table 4.6 Speed limits and average speeds

Type of road	Speed limit by Road Traffic Act 2004 (km/hr)	Averages speed (km/hr)
Motorway	120	100
National Primary & Secondary Routes (dual carriageways included)	100	80
Regional and Local Roads	80	50
Built Up Areas (Town & City)	50	30

Table A.2 in Appendix A depicts the distances between processing plants and retailers on different roads. Total distance between each processing plant and each retailer location is calculated in Table 4.7.

Table 4.7 CO_2 emission and costs of serving each route by heavy duty trucks

Plant ($j \in J$)	*I* **Drogheda**			*II* **Ballitore**		
Retailer ($i \in I$)	**Distance** km	**CO_2 Emission** kg	**Cost of serving route** €	**Distance** km	**CO_2 emission** kg	**Cost of serving route** €
1. Drogheda	2.0	1.85	1.84	117.0	108.11	77.70
2. Dundalk	36.4	33.63	23.68	146.0	134.90	96.59
3. Navan	25.8	23.84	19.75	105.0	97.02	68.30
4. Tullamore	110.0	101.64	74.72	62.5	57.75	47.84
5. Naas	75.4	69.67	57.72	29.1	26.89	22.28
6. Newbridge	103.0	95.17	67.00	24.5	22.64	18.75
7. Leixlip	47.5	43.89	36.36	61.1	56.46	39.75
8. Port Laoise	143.0	132.13	93.02	37.1	34.28	27.38
9. Bray	74.6	68.93	48.53	71.4	65.97	48.50
10. Arklow	128.0	118.27	85.29	57.6	53.22	44.09
11. Wicklow	121.0	111.80	78.71	48.0	44.35	36.74
12. Greystones	83.6	77.25	54.38	70.4	65.05	53.89
13. Clonmel	226.0	208.80	147.01	111.0	102.56	73.63
14. Waterford	219.0	202.36	142.46	105.00	97.02	68.30
15. Tramore	232.0	214.37	150.92	117.0	108.11	76.11
16. Kilkenny	178.0	164.47	115.79	63.4	58.58	41.24
17. Wexford	197.0	182.03	128.15	94.8	87.59	64.39
18. Ennoscorthy	184.0	170.02	124.98	72.4	66.90	52.64
19. Dublin City	52.4	48.42	34.09	59.8	55.25	40.62
20. Dun Laogharire/Rathdawn	62.9	58.12	40.92	66.7	61.63	45.31
21. Fingal	29.2	26.98	22.35	85.5	79.00	58.08
22. South Dublin	61.5	56.83	47.08	45.1	41.67	30.63

4.4.5. CO_2 emission and cost of serving each route

CO_2 emissions from transportation are calculated using formulae (4.12), (4.13) and (4.14) presented in Table 4.7. The average price of diesel in Ireland in April/May 2012 is 1.53 €/lit. The average wage of a heavy duty truck driver in April/May 2012 is €11.50/hr (sources: irishjobs.ie; payscale.com based on individual reports). The total cost of serving each route is calculated and presented in Table 4.7.

4.4.6. Green constraint data

The AHP constraint considers three types of vehicles/trucks as preferred by the DMs for the transportation of the products. Each type of truck considers different levels of CO_2 emission and costs. DMs have been asked to compare these truck types based on two attributes: CO_2 emission and cost. The outcome of this comparison is a pair-wise comparison matrix as shown in Table 3.8. Saaty's nine point scale (Saaty 1977; 1980) has been used to compare the truck types and a weight matrix is generated (Table 4.9):

Table 4.8 Vehicle comparison matrix

CO2 Emission

	T1	T2	T3
T1	1	¼	6
T2	4	1	1/8
T3	1/6	8	1

Costs

	T1	T2	T3
T1	1	4	1/3
T2	1/4	1	6
T3	3	1/6	1

Table 4.9 Weight matrix for vehicle types

Alternatives Attributes	T1	T2	T3	Sum
CO_2 Emission	0.33	0.24	0.43	1
Costs	0.32	0.43	0.25	1

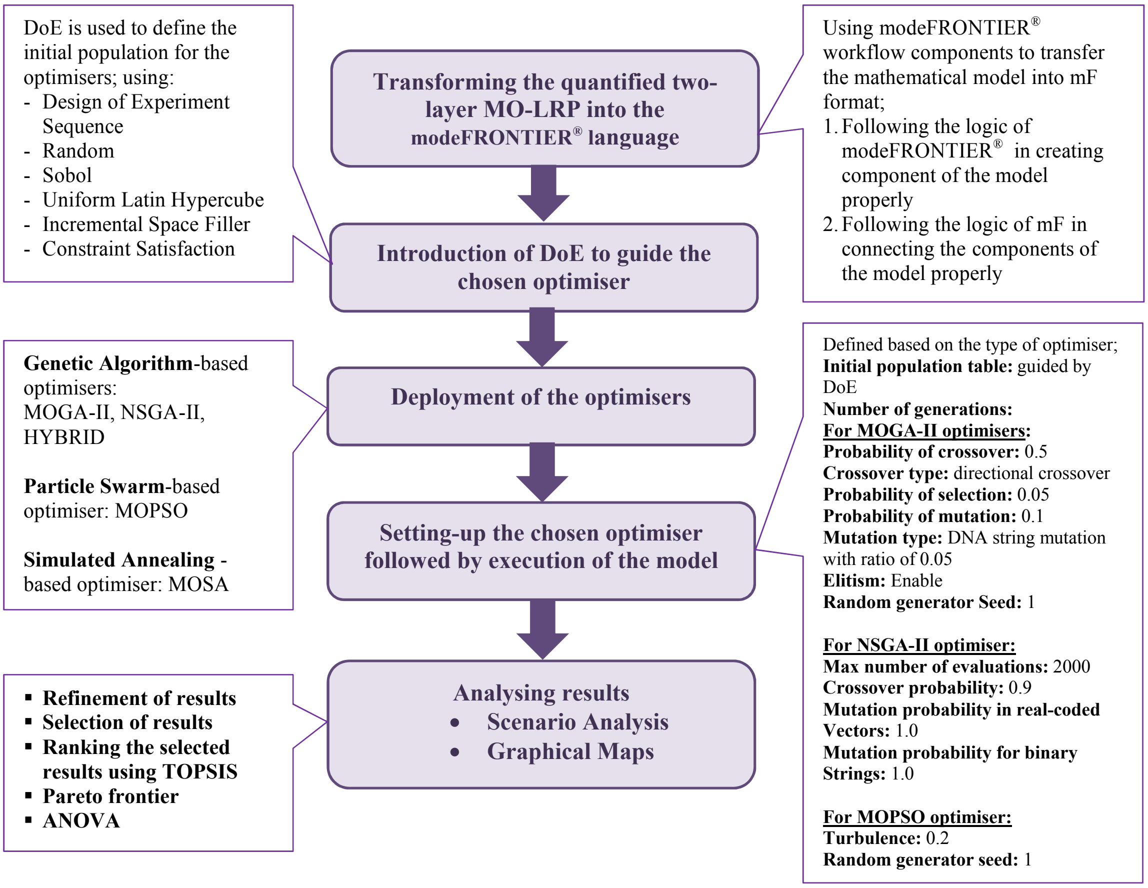
The RHS matrix for the AHP-integrated constraint is considered as an average of the maximum and minimum value for CO_2 emissions and cost as calculated in Table 4.7, as no limit is defined for CO_2 emissions from transportation in Ireland. Table 4.10 depicts the limits for CO_2 emission and costs in the AHP constraint:

Table 4.10 CO_2 emission and costs limit

Limits for 3 Type of Trucks	Min	Max	RHS Matrix
CO_2 Emission (kg)	2	215	108
Costs (€)	2	150	76

4.4. Solution Steps

modeFRONTIER® is a multi-disciplinary and multi-objective optimisation and design environment developed by Esteco SpA (ESTECO 2013). This study is the first case where LRPs are solved using this package. Extensive experimentation with the package reveals that the software is capable of handling LRPs by way of producing robust designs which have previously not been considered in the literature. However, the modeFRONTIER® package is not designed particularly to handle LRPs. Therefore, extensive customisation of the robust design optimisation solver using multi-objective metaheuristics has been made before implementing the two-layer MP-LRP. Design of Experiments (DoE) is coupled to the optimisers in such a manner that the solution of the two-layer MO-LRP is possible only if optimal feasible designs are obtained. A schematic description of the solution steps using modeFRONTIER® is presented in Figure 3.5:



DoE is used to define the initial population for the optimisers; using:
- Design of Experiment Sequence
- Random
- Sobol
- Uniform Latin Hypercube
- Incremental Space Filler
- Constraint Satisfaction

Using modeFRONTIER® workflow components to transfer the mathematical model into mF format;
1. Following the logic of modeFRONTIER® in creating component of the model properly
2. Following the logic of mF in connecting the components of the model properly

Genetic Algorithm-based optimisers: MOGA-II, NSGA-II, HYBRID

Particle Swarm-based optimiser: MOPSO

Simulated Annealing -based optimiser: MOSA

Defined based on the type of optimiser;
Initial population table: guided by DoE
Number of generations:
<u>For MOGA-II optimisers:</u>
Probability of crossover: 0.5
Crossover type: directional crossover
Probability of selection: 0.05
Probability of mutation: 0.1
Mutation type: DNA string mutation with ratio of 0.05
Elitism: Enable
Random generator Seed: 1

<u>For NSGA-II optimiser:</u>
Max number of evaluations: 2000
Crossover probability: 0.9
Mutation probability in real-coded Vectors: 1.0
Mutation probability for binary Strings: 1.0

<u>For MOPSO optimiser:</u>
Turbulence: 0.2
Random generator seed: 1

- **Refinement of results**
- **Selection of results**
- **Ranking the selected results using TOPSIS**
- **Pareto frontier**
- **ANOVA**

Figure 4.5 The process of implementing the two-layer MO-LRP using modeFRONTIER®

4.5.1. Transforming the two-layer MO-LRP into modeFRONTIER®

The two-layer MO-LRP is transformed using modeFRONTIER®'s input components and then connected properly to create a full logical imitation of the mathematical model in modeFRONTIER®. The workflow of the model in modeFRONTIER® is presented in Figure 4.6:

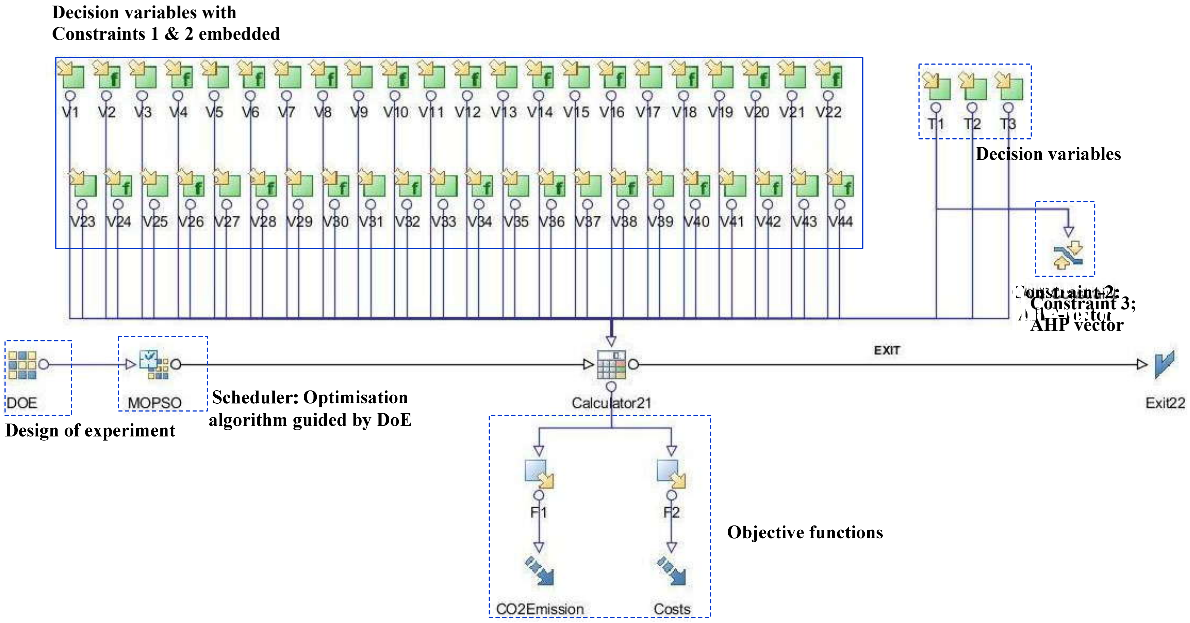


Figure 4.6 The two-layer MO-LRP design in modeFRONTIER®

Figure 4.6, presents the logical design for the two-layer MO-LRP model in modeFRONTIER® using the MOPSO optimiser. Graphically the design looks the same for all optimisers only the name of the optimiser is changed. The mathematical details of the developed model are all satisfied in this designed workflow using modeFRONTIER®.

4.5.2. Introducing DoE to the chosen optimiser

Logically in modeFRONTIER® the optimiser is connected to the main two-layer MO-LRP by the use of DoE. DoE generates the initial population sets for the optimisers to ensure the achievement of an optimum set of non-dominated solutions. The initial population table consists of 51 designs. The initial 51 DoE-guided designs consist of: (i) 10 'design of experiment sequence', (ii) 10 'random', (iii) 10 'sobol', (iv) 10 'uniform Latin hypercube', (v) 10 'incremental space filler' and (vi) 1 'constraint satisfaction' designs. The process of optimisation in modeFRONTIER® is DoE-guided by way of introducing the initial population table to the optimisers.

4.5.3. Deployment of optimisers

Five multi-objective evolutionary optimisers in modeFRONTIER® are initially selected to deploy the two-layer MO-LRP. The optimisers include three multi-objective Genetic Algorithm (GA)-based, one multi-objective Particle Swarm (PS)-based and one multi-objective Simulated Annealing (SA)-based. Based on extensive literature reviews in this area, it is believed that this is the first time that the modeFRONTIER® solver has been used to implement an LRP. Therefore, there is no report available on the performance of its multi-objective optimisers on LRPs. In this research disparate optimisers are used to compare the optimisers' performance on the two-layer MO-LRP. Results reveal that two of these optimisers, viz., HYBRID and MOSA, do not perform efficiently in solving the two-layer MO-LRP.

4.5.4. Setting-up the selected optimisers and executing the model

The chosen optimisers are set up separately. These optimisers have different requirements and distinctive specifications. Therefore they have disparate set up details. In order to compare the results obtained from these GA-based optimisers, the initial population and number of generations are kept the same in those optimisers. Table 4.11 presents the set up details for the GA-based optimisers:

Table 4.11 Set up details for GA-based optimisers in modeFRONTIER®

MOGA-II	NSGA-II
Number of generations: 50 Initial population: 51 Probability of crossover: 0.5 Type of crossover: Directional Probability of mutation: 0.1 Type of mutation: DNA String DNA string mutation ratio: 0.05 Elitism: Enabled Random generator seed: 1	Number of generations: 50 Initial population: 51 Crossover probability: 0.9 Mutation probability for real-coded vectors: 1.0 Mutation probability for binary strings: 1.0 Distribution index for real-coded crossover: 20.0 Distribution index for real-coded Mutation: 20.0

The set up specifications for MOPSO is presented in Table 4.12:

Table 4.12 Set up details for PS-based optimiser

MOPSO
Number of generations: 50 Initial population: 51 Turbulence: 0.2 Random generator seed: 1

The workflow and the mathematical model in modeFRONTIER® remain the same during implementation of the LRP. In order to compare the optimisers' performance, the initial population is kept the same in all generation-based optimisers. 50 generations with an initial population of 51, which generates 2,500 results. HYBRID in modeFRONTIER® works with number of iterations instead of generations. This optimiser is set at 2,500 evaluations with a DoE table that is identical to the other optimisers. Part-III of this chapter presents the categorised and analysed results.

Part III: Results and Analysis

4.6. Introduction

The two-layer MO-LRP is implemented and a set of results are obtained. Execution of the model using each optimiser offers 2,500 results. These results are further refined so as to obtain a realistic set of results from each optimiser. A set of best results, with regard to the two objective functions, have been selected from these realistic results to prioritise the process of decision-making and subsequent ranking. As both the objectives of the two-layer MO-LRP are minimum in nature, the selected results are picked from the best results belonging to the three lowest sets of feasible results obtained from modeFRONTIER® using each optimiser. After selecting a set of results, these results are ranked using TOPSIS considering a variety of DMs with different combinations of priorities. The process of analysing the results in obtaining the outcomes is shown in Figure 4.7. The results are presented and analysed in the next two sub-sections (i) a comparative analysis on the three multi-objective GA-based optimisers' performance, and (ii) the results of multi-objective PS-based optimisers.

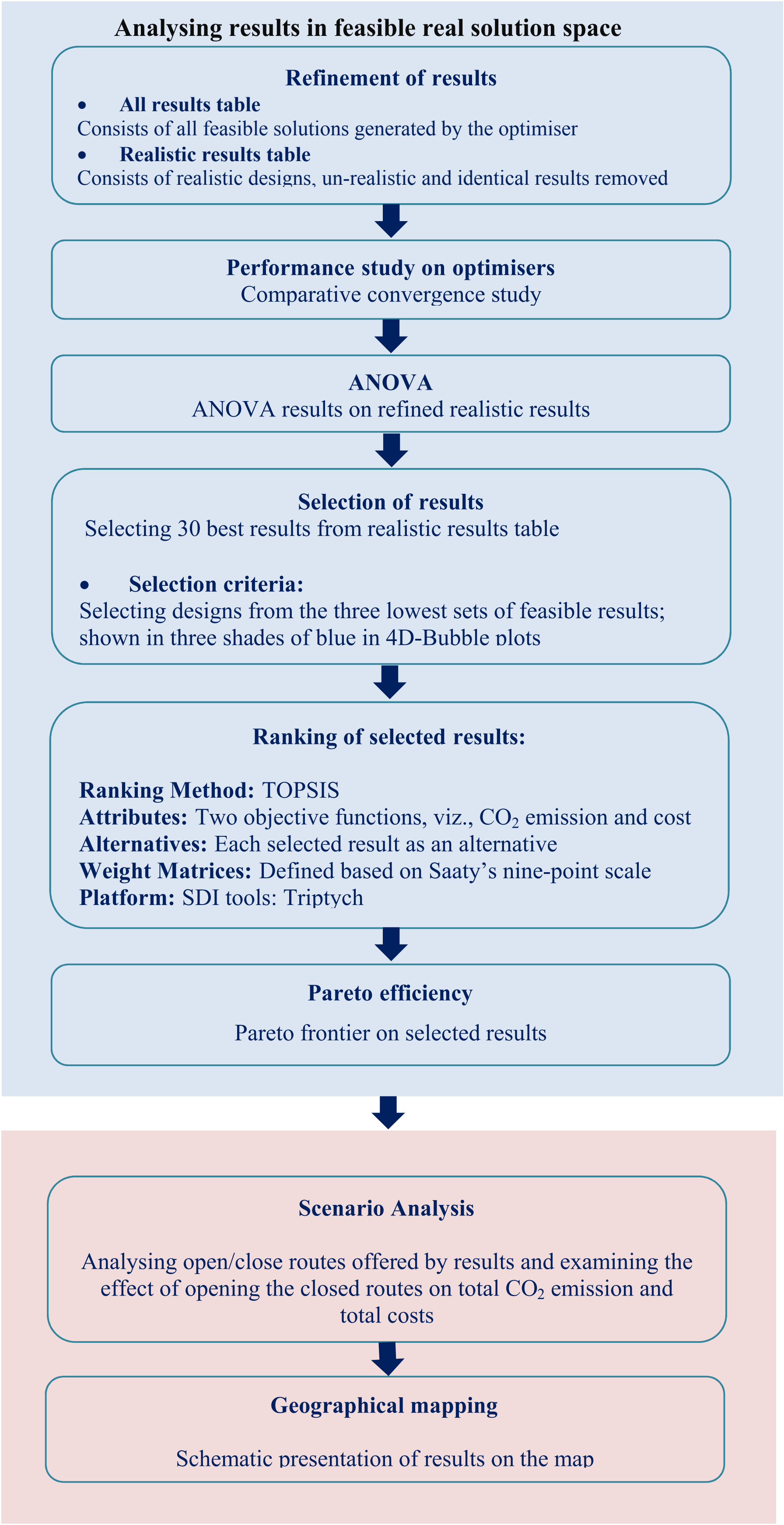


Figure 4.7 Process of analysing the results

4.7. Results of GA-based optimisers in the real feasible solution space

The results obtained from the two multi-objective GA-based optimisers used for the implementation of the two-layer MO-LRP are presented in this section. Firstly the results are analysed and then the outcomes are presented.

4.7.1. Analysis of results

In order to analyse the results obtained from the GA-based optimisers: (i) results are refined and a set of realistic results are identified, (ii) a performance study is conducted on each optimiser, (iii) Analysis of Variance (ANOVA) test is performed to compare means of multiple groups for the optimised data, (iv) a set of results are selected for further analysis, (v) selected results are ranked using TOPSIS, and finally (vi) Pareto efficiency is examined on the selected designs.

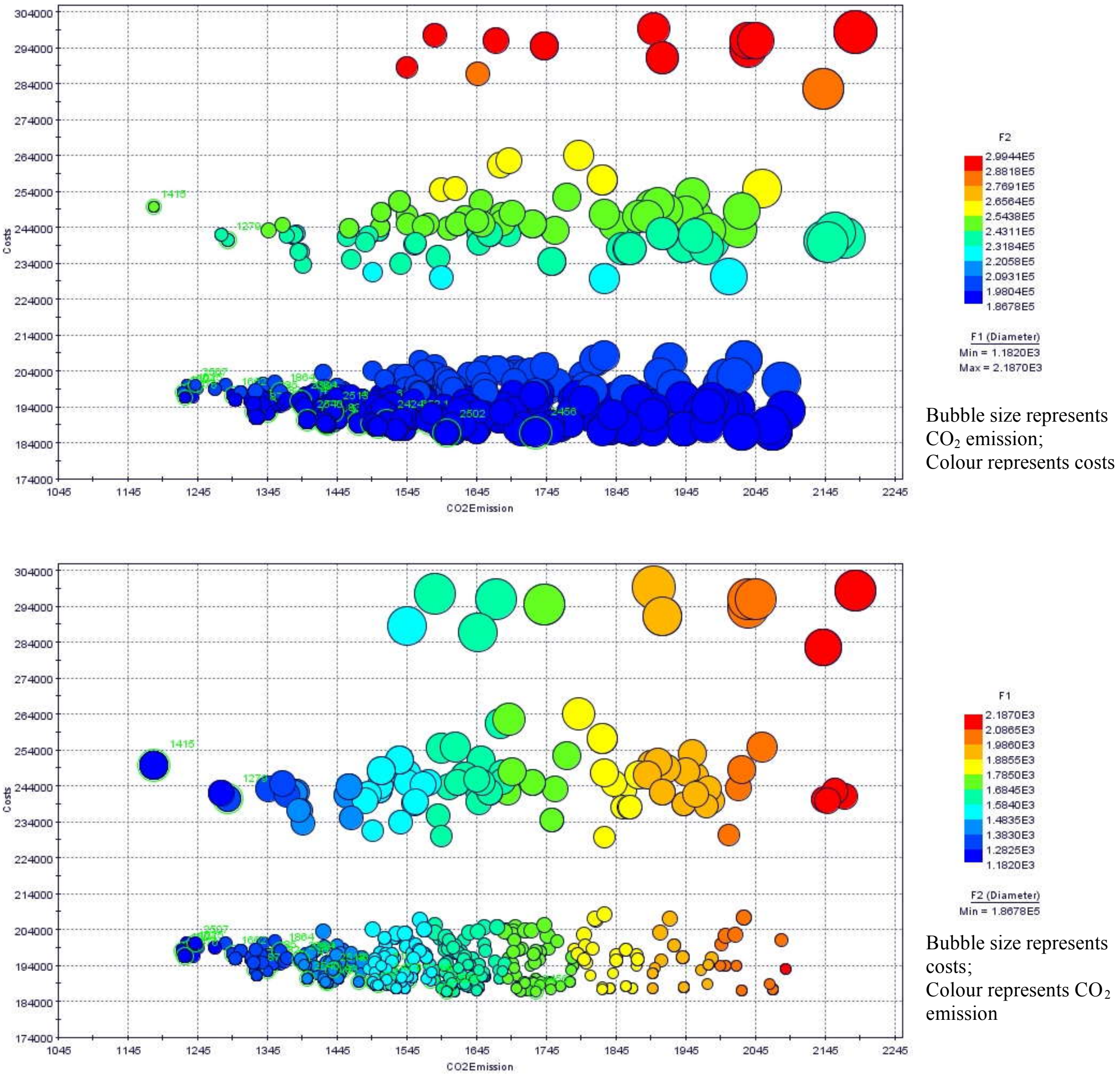
All results from the two optimisers are feasible and real. A statistical summary of these results is illustrated in Table 4.13. These results assist to analyse: a) the total result designs table consisting of all feasible real results obtained from the optimisers, b) the refined realistic results table consisting of realistic and non-identical results, and c) the selected results table consisting of selected results from the three lowest sets of feasible results from 4D-Bubble plots (Figures 4.8 and 4.9). 30 results have been selected for further analysis using each optimiser. These results are selected based on two criteria: costs and CO_2 emission. Using the bubble plots (Figures 4.8 and 4.9) and considering these two criteria these 30 results are selected. In the selection process different types of DMs have been considered as well.

Table 4.13 Statistical summary for multi-objective GA-based optimisers

Type of result designs on optimisers		Number of real feasible result designs (Alternatives)	CO_2 emission value (kg) (Objective Function I)		Costs value (€) (Objective Function II)	
			Min	*Max*	*Min*	*Max*
MOGA-II	Total results table	2,550	1,182	2,187	186,776	299,444
	Refined realistic results table	187	1,182	2,187	186,776	299,444
	Selected results table	30	1,182	1,729	186.776	249,716
NSGA-II	Total results table	2,550	1,171	2,352	185,948	299,444
	Refined realistic results table	543	1,171	2,187	185,948	299,444
	Selected results table	30	1,171	1,729	185,948	248,985

As presented in Table 4.13 the minimum value for total CO_2 emission is offered by NSGA-II. This does not necessarily yield a minimum value for the total costs. NSGA-II offers more refined realistic results as compared with MOGA-II.

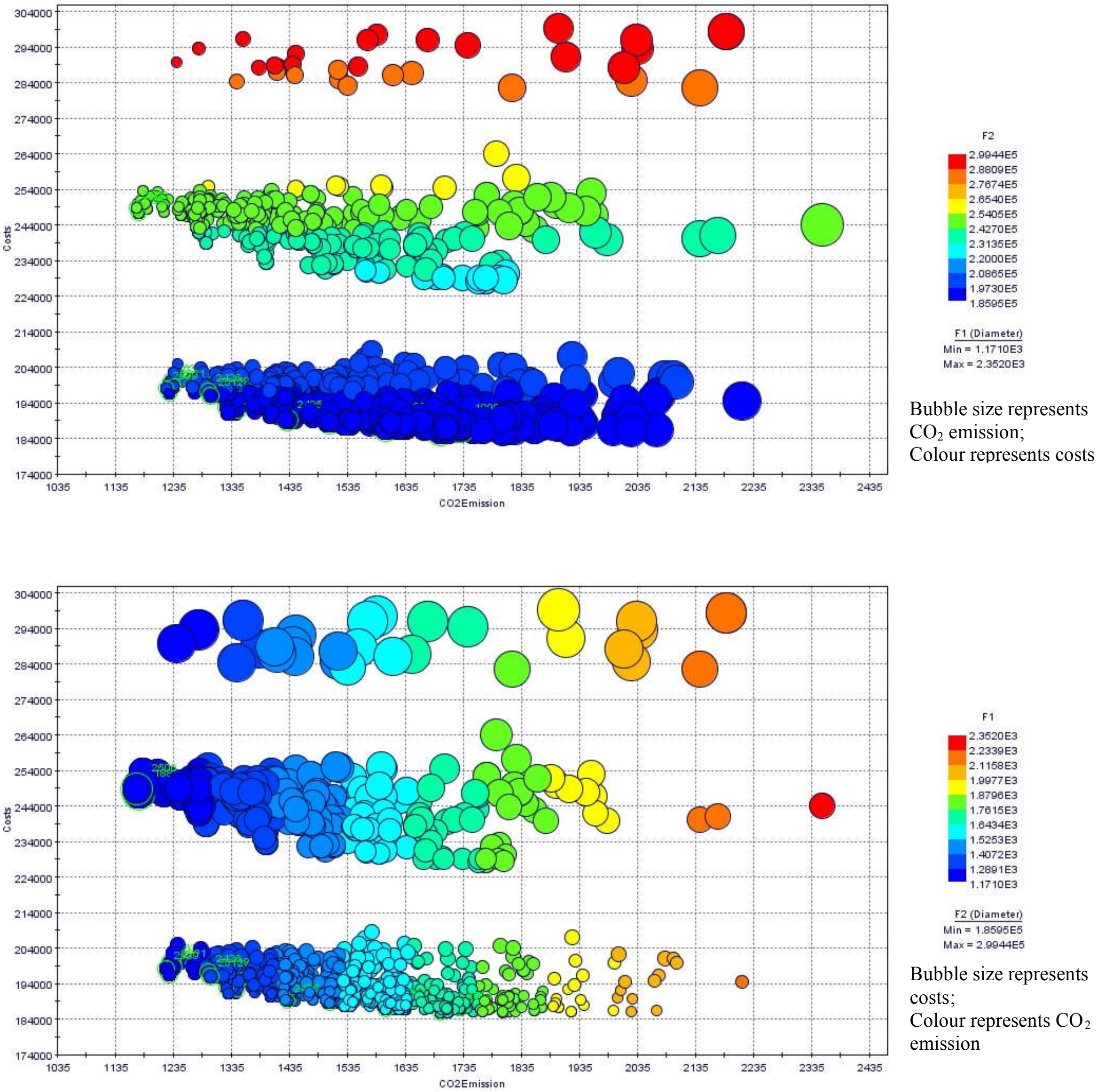
Guided by the DoE, MOGA-II and NSGA-II optimisers generate the feasible solution space. Figures 4.8 and 4.9 illustrate the feasible real solution space for MOGA-II and NSGA-II respectively. In these 4D plots, colour and diameter of bubbles are used to represent the values of both of the objective functions as explained in the plot legends. Colours range from dark blue to red signifying lowest to highest values of the objective functions respectively. Similarly, diameters of bubbles range from small to large indicating lowest to highest value of the objective functions respectively. Selected results are highlighted with green circles with reference to their IDs.



Bubble size represents CO_2 emission;
Colour represents costs

Bubble size represents costs;
Colour represents CO_2 emission

Figure 4.8 Feasible real solution space w.r.t. costs and CO_2 emission for MOGA-II optimiser



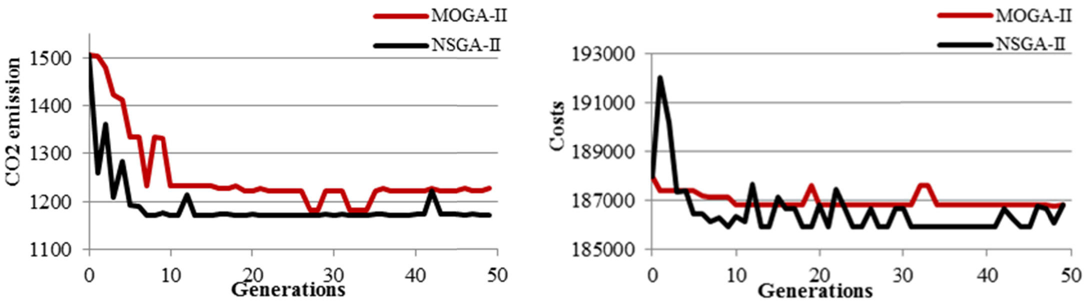
Bubble size represents CO$_2$ emission;
Colour represents costs

Bubble size represents costs;
Colour represents CO$_2$ emission

Figure 4.9 Feasible real solution space w.r.t. costs and CO$_2$ emission for NSGA-II optimiser

4.7.1.1. Performance of optimisers

The performance of the optimisers regarding their convergence is studied comparatively through plots presented in Figure 4.10, with respect to the objective functions:



a. Convergence w.r.t CO_2 emission b. Convergence w.r.t costs

Figure 4.10 Comparative convergence plots of the GA-based optimisers

It is evident from plot ‘a’ and plot ‘b’ of Figure 4.10 that the NSGA-II algorithm is converging in a comparatively better way than that of MOGA-II. History plots, Box Whiskers and Density plots (Appendix B.3) are considered for statistical analysis of the results.

4.7.1.2. ANOVA

One-way ANOVA is performed for both the total CO_2 emission and total costs of transportation to compare the means of multiple groups of the optimised data. ANOVA computes the p-value for the null hypothesis to detect if data from several groups have a common mean. Tables 4.14 and 4.15 present the ANOVA results for the two GA-based optimisers with respect to CO_2 emission and costs respectively. The ANOVA statistics are used to test the null-hypothesis (Walpole et al. 2006). For the two optimisers ANOVA computes the source of the variability, sum of squares (SS) due to each source, degrees of freedom (Df) associated with each source, mean squares (MS) for each source (SS/Df ratio), F-statistic (ratio of two MS) and p-value given by the cdf of F. It is noted that as the F-ratio increases, the p-value decreases. The ANOvA test presented in Tables 4.14 and 4.15 are calculated for refined realistic results. The insignificance in p-value could be a result of this selection of results. It is necessary to mention again that not all results are realistic and they have to be refined in order to find the realistic results.

Table 4.14 ANOVA for CO_2 emission on the refined realistic results

Optimiser	**Source of Variation**	**SS**	**Df**	**MS**	**F-ratio**	**p-value**
MOGA-II	Between groups	6.0825E6	8.1000E1	7.5093E4	3.1338E0	2.5970E-8
	Within groups	2.5160E6	1.0500E2	2.3962E4	—	—
	Total	8.5985E6	1.8600E2			
NSGA-II	Between groups	1.7674E6	4.0000E0	4.4185E5	1.6424E1	1.0559E-12
	Within groups	1.4419E7	5.3600E2	2.6902E4	—	—
	Total	1.6187E7	5.4000E2			

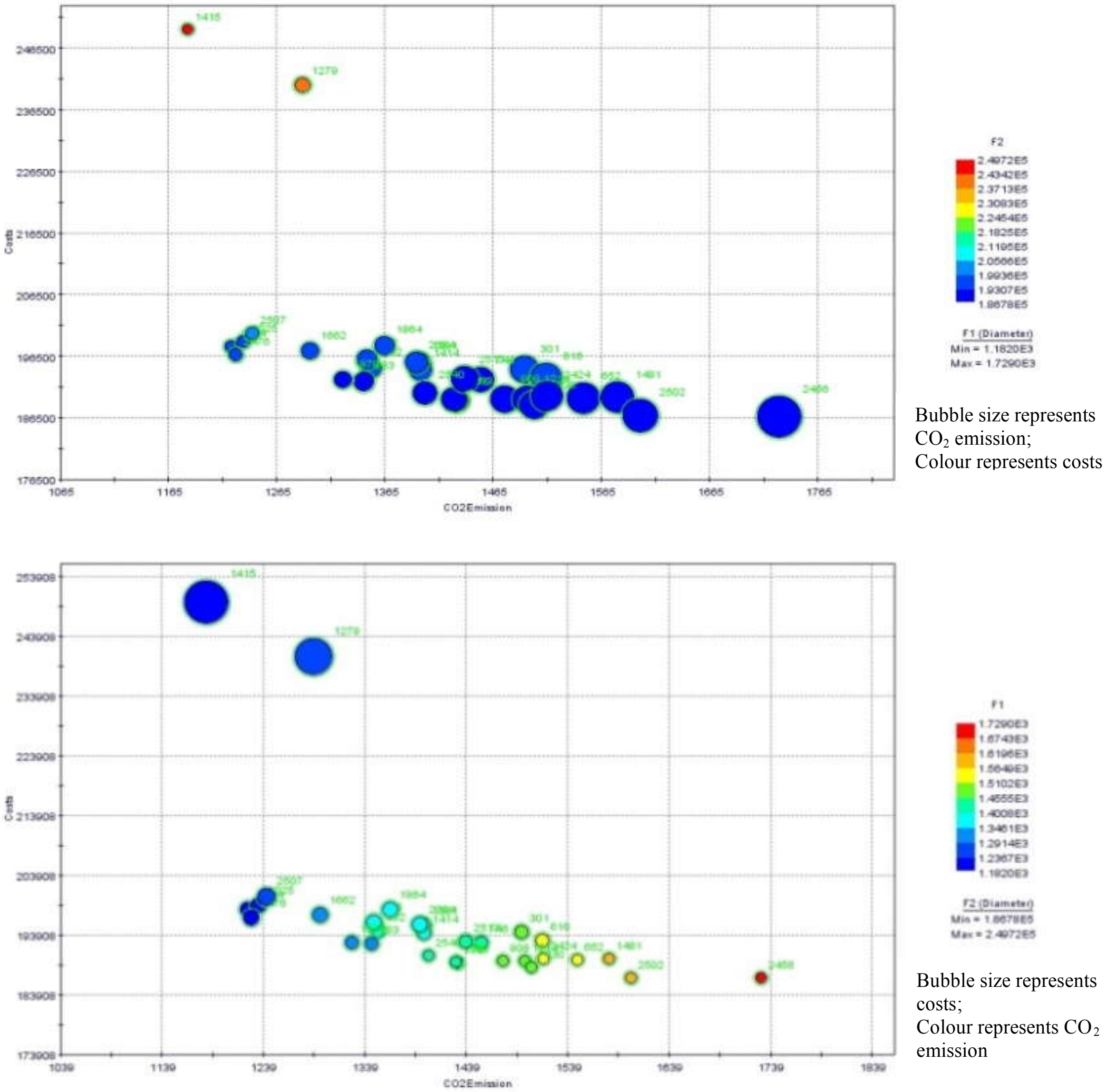
Table 4.15 ANOVA for costs on the refined realistic results

Optimiser	Source of Variation	SS	Df	MS	F-ratio	p-value
MOGA-II	Between groups	6.9805E10	8.1000E1	8.6180E8	2.0491E0	2.8399E-4
	Within groups	4.4160E10	1.0500E2	4.2057E8	—	—
	Total	1.1397E11	1.8600E2			
NSGA-II	Between groups	3.5138E10	4.0000E0	8.7845E9	1.2999E1	4.1364E-10
	Within groups	3.6222E11	5.3600E2	6.7579E8	—	—
	Total	3.9736E11	5.4000E2			

4.7.1.2. Selection of results

Un-realistic and identical results are eliminated from the feasible solutions space and the refined realistic results are considered for further analysis. Statistical summaries of the refined realistic results with respect to the two GA-based optimisers are presented in Table 4.13. Amongst the refined realistic results, a set of 30 results are selected for further analysis. The next paragraph illustrates the selection process.

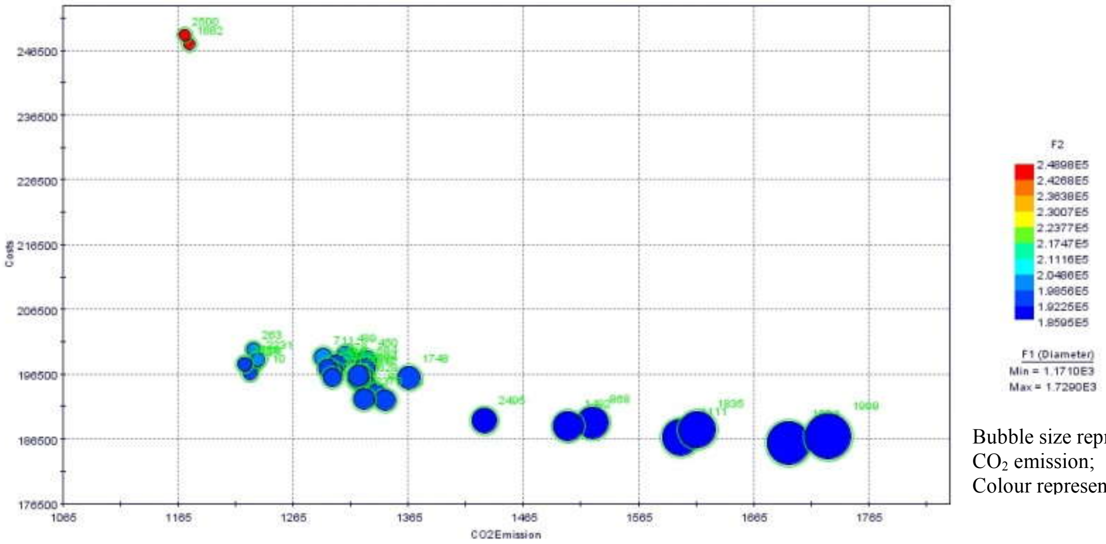
Selected results are chosen from the three lowest sets of objective function values as depicted in the plot legends. Figures 4.8 and 4.9 present values of the objective functions offered by the two optimisers with reference to colour and bubble diameter. The first three shades of blue in these plots represent the lowest three sets of values for the objective functions. Therefore the selcted results, with respect to the objcetive function values, are selected from these three sets of results. From Figures 4.8 and 4.9 it is found that the relationship between the two objective fucntions are not linear. Therefore, a low value for one objective fucntion may not necessarily yield a low value for the other objective function and vice versa. DMs' priorities are considered in the selection of the two-layer MO-LRP results. Therefore in each set of the selected results at least two results represent extreme decision-making events. Figures 4.11 and 4.12 exhibit the set of 30 selected result from MOGA-II and NSGA-II respectively:



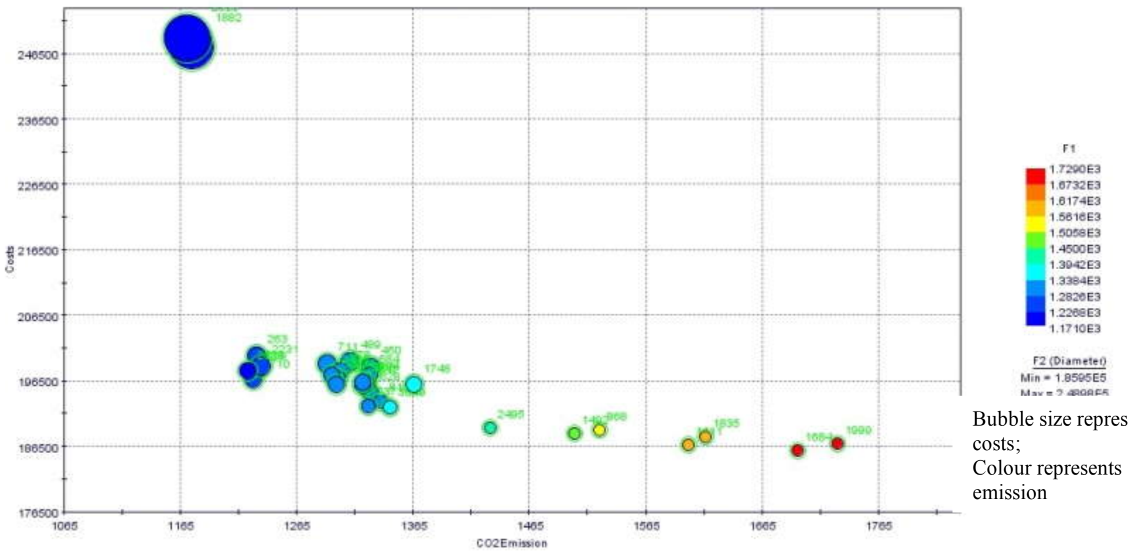
Bubble size represents CO_2 emission;
Colour represents costs

Bubble size represents costs;
Colour represents CO_2 emission

Figure 4.11 Selected results from feasible real solution space w.r.t. costs and CO_2 emission for MOGA-II optimiser



Bubble size represents
CO_2 emission;
Colour represents costs



Bubble size represents
costs;
Colour represents CO_2
emission

a. Bubble size represents costs; Colour represents CO_2 emission

Figure 4.12 Selected results from feasible real solution space w.r.t. costs and CO_2 emission for NSGA-II optimiser

The selected results of Figures 4.11 and 4.12 are ranked in order to prioritise the best optimised results. The ranking process is explained in the following section.

4.7.1.4 .Ranking the selected results

After selecting a set of 30 results, these selected results are ranked using TOPSIS in order to find the set of best results for differenet types of DMs. TOPSIS is a multi-criteria decision-making method originally developed by Hwang and Yoon (1981). It is a compensatory aggregation method that compares a set of alternatives by defining weights for each criterion, normalising scores for each criterion. The main concept behind TOPSIS is that the chosen alternative (here 'result') should have the shortest distance from the ideal solution and farthest distance from the negative ideal solution (Zavadskas et al. 2006; Yoon and Hwang 1995). TOPSIS allows trading-off between criteria so a weak result in one criterion could be negated by a good result in another criterion. This capacity provides a more realistic type of modelling comparing to non-compensatory methods (Asgharpour 1998).

Nine weight matrices are defined for TOPSIS. Each one of these weight matrices represents a type of DM and by selecting all nine weight matrices from Saaty's nine-point scale (1977; 1978) all DMs are covered. These weight matrices are:

$w_1 = (0.1 \quad 0.9)$, $w_3 = (0.3 \quad 0.7)$, $w_5 = (0.5 \quad 0.5)$, $w_7 = (0.7 \quad 0.3)$, $w_9 = (0.9 \quad 0.1)$ and $w_2 = (0.2 \quad 0.8)$, $w_4 = (0.4 \quad 0.6)$, $w_8 = (0.8 \quad 0.2)$.

Selected results offered by each optimiser are ranked using the above nine weight matrices, using SDI Tools – a commercial statistical tool. Ranking results show that the weight matrices can affect the ranking process by TOPSIS considering both objective functions. In order to illustrate the reflection of the DMs' priorities (i.e., weight matrices in TOPSIS) Figures 4.13-a and 4.13-b are presented.

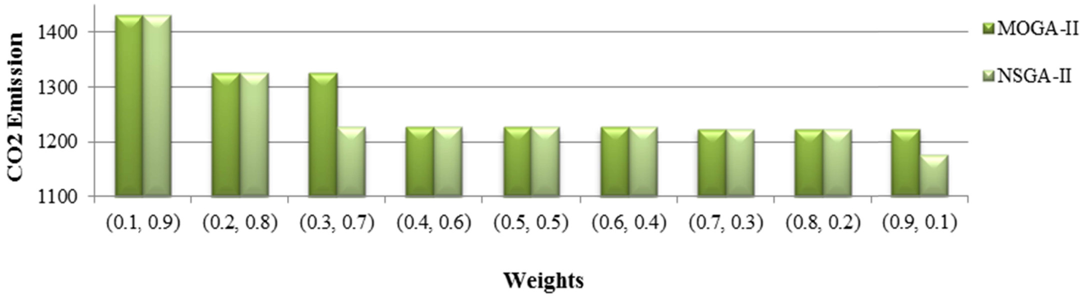


Figure 4.13-a Reflection of the DMs' priorities on TOPSIS ranking w.r.t. CO_2 emission

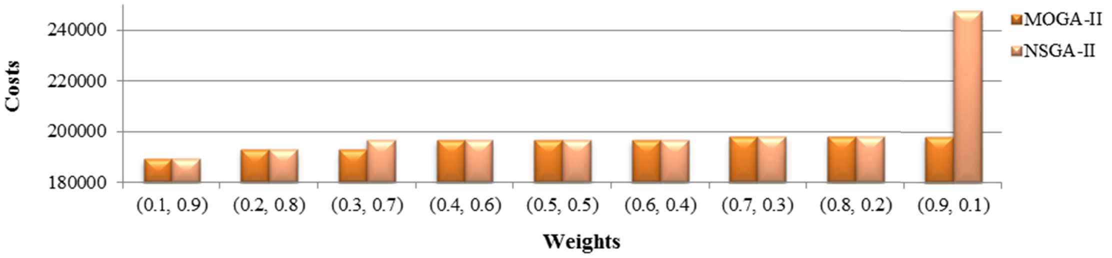


Figure 4.13-b Reflection of the DMs' priorities on TOPSIS ranking w.r.t. costs

Figures 4.13-a and 4.13-b demonstrate that TOPSIS offers results with considerable differences between the values of the two objective functions when weight matrices represent extreme decision-making events. The first three ranked results obtained from the three different weight matrices for MOGA-II and NSGA-II optimisers are presented in Table 4.16. Selected weight matrices (w_3, w_5, w_7) represent a vast majority of DMs.

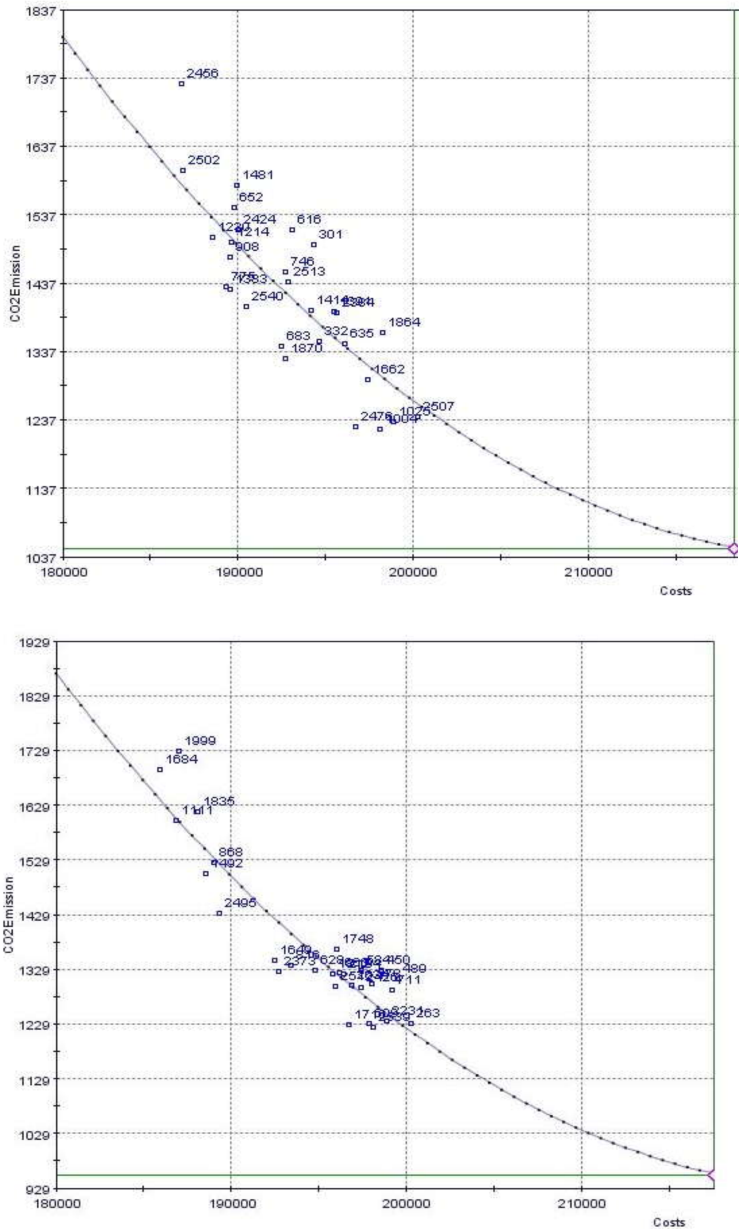
Table 4.16 First three ranked results w.r.t the GA-based optimisers using weight matrices w_3, w_5, w_7

	$W_3 = (0.3 \quad 0.7)$			$W_5 = (0.5 \quad 0.5)$			$W_7 = (0.7 \quad 0.3)$		
	Rank	**CO_2 emission**	**Costs**	**Rank**	**CO_2 emission**	**Costs**	**Rank**	**CO_2 emission**	**Costs**
MOGA-II	**1**	1326	192693	**1**	1227	196705	**1**	1223	198141
	2	1428	189523	**2**	1223	198141	**2**	1227	196705
	3	1402	190505	**3**	1234	198872	**3**	1234	198872
NSGA-II	**1**	1328	194778	**1**	1328	194778	**1**	1328	194778
	2	1695	185948	**2**	1227	196705	**2**	1227	196705
	3	1601	186844	**3**	1223	198141	**3**	1223	198141

As shown in Table 4.16, the lowest value for CO_2 emission (1227) has been ranked as first and second result by MOGA-II using w_5 and w_7. The same result appears in NSGA-II as third result using w_5 and w_7. The lowest value for costs (185948) has been ranked in second place by NSGA-II using w_3. It is evident from the results that NSGA-II has been more successful in minimising both the objective functions simultaneously.

4.7.1.5 .Pareto efficiency

Pareto efficiency is examined to evaluate the performance of optimisers and the selected result designs. 30 selected results obtained from MOGA-II and NSGA-II optimisers are separately examined with regard to their Pareto efficiency and the outcomes are presented in Figures 4.14(a) and 4.14(b) respectively.



b. MOGAII

a. NSGAII

Figure 4.14 Pareto frontier of selected results w.r.t. the GA-based optimisers

As is evident from Figure 4.14, selected results from all three GA-based optimisers follow the Pareto optimality and are strongly efficient. In the selection process of results, extreme decision-making events are considered. Therefore one or two extreme results exist in each selected results table that is outside of the Pareto frontier. Four out of 60 selected results (2 results from MOGA-II and 2 results from NSGA-II) are out of the Pareto Frontier. All these 4 results represent extreme decision-making events and are not affecting the Pareto efficiency of the selected results. None of these four results placed outside the Pareto frontier are ranked by TOPSIS as the first three ranked results.

4.7.2. Interpretation of Results

The resulting outcomes are categorised in two groups: scenario analysis and schematic presentation of the results on a map. The scenario analysis is a step towards building resilience in SCs by analysing the effect of opening a closed route on objective functions. In order to present the geographical location of the plants and retailers and the optimum vehicle-routing patterns, schematic presentation of the results on map are presented.

4.7.2.1. Scenario analysis

Once the selected results are ranked scenario analysis is conducted. Scenario analysis provides an analysis on closed routes for different results. Open routes have directly contributed to the total CO_2 emission and the total cost. Scenario analysis offers the contribution of each closed route to the total CO_2 emission and total cost if forcibly opened. After a DM selects a result, the scenario analysis related to that result will be offered. Once a particular TOPSIS weight matrix is selected by a DM the same matrix should be used for scenario analysis in order to identify the closed and open routes. Scenario analysis for MOGA-II and NSGA-II resulting from the weight matrix $W_5 = (0.5 \quad 0.5)$ is presented in Table 4.17.

Table 4.17 Scenario analysis for MOGA-II and NSGA-II on weight matrix $W_5 = (0.5 \quad 0.5)$

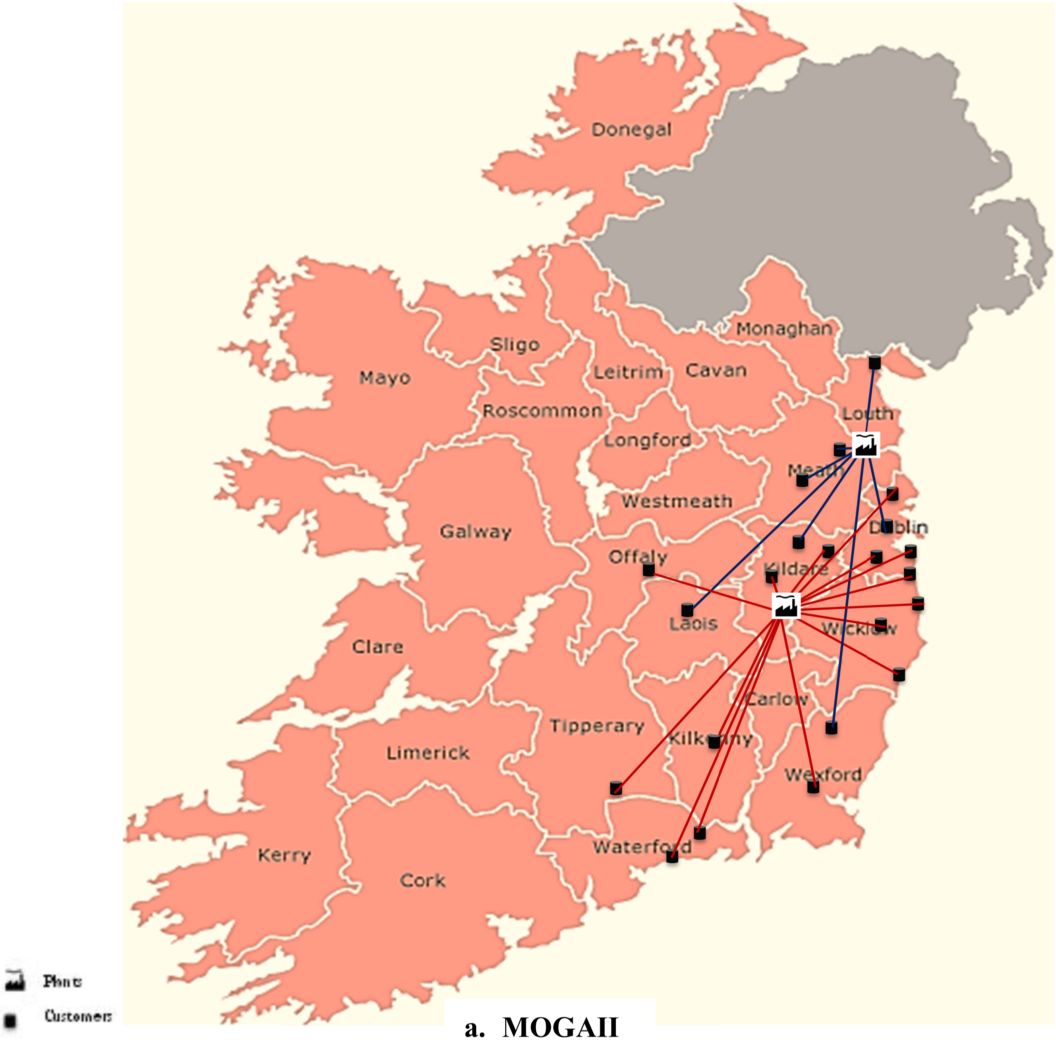
Closed Routes	MOGA-II		NSGA-II	
	Closed route (effect on CO_2 emission if open)	Closed route (effect on costs if open)	Closed route (effect on CO_2 emission if open)	Closed route (effect on costs if open)
V1II	108	5,108	108	5,108
V2I			34	3,834
V2II	135	1,935		
V3II	97	2,997	97	2,997
V4I	102	2,102	102	2,102
V5I	70	4,270	70	4,270
V6I	96	1,495	96	1,459
V7II	34	7,056	34	7,056
V8I	132	1,532	132	1,532
V9I	69	2,669	69	2,669
V10I	118	70,118	118	70,118
V11I	112	36,512	112	36,512
V12I	77	6,077	77	6,077
V13I	209	4,769	209	4,769
V14I	202	3,562	202	3,562
V15I	214	2,614	214	2,614
V16I	164	5,204	164	5,204

V17I	182	1,862	182	1,862
V18I			170	3,050
V18II	67	8,467		
V19II	55	3,895	55	3,895
V20I	58	3,178	58	3,178
V21I	27	84,027	27	84,027
V22I	57	43,737	57	43,737

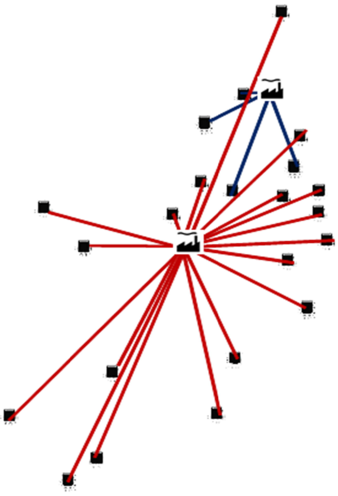
After conducting the scenario analysis, the first ranked results offered by TOPSIS using weight matrix w_5 are presented on the map as an output of the two-layer MO-LRP.

4.7.2.2. Schematic presentation of a result

Scenario analysis (Table 4.17) is an example of the guide available to the DMs to locate the feasible and realistic optimal vehicle routing patterns, with the trade-offs with respect to objective functions, if a closed route is forcibly opened. In order to present the results in a more tangible way, a schematic presentation of the results is presented on a geographical map, in this case for the first two ranked results. Figure 4.14 depicts a sample presentation of the vehicle routing patterns on the map of Ireland using the findings for MOGA-II and NSGA-II for the weight matrix w_5.



a. MOGAII



b. NSGAII

Figure 4.15 Presentation of first ranked result of MOGA-II and NSGA-II using weight matrix $w_5 = (0.5 \quad 0.5)$

4.8. Particle Swarm-Based Optimiser

The results obtained from the multi-objective PS-based optimiser during implementation of the two-layer MO-LRP are presented in this section.

4.8.1. Analysis of results

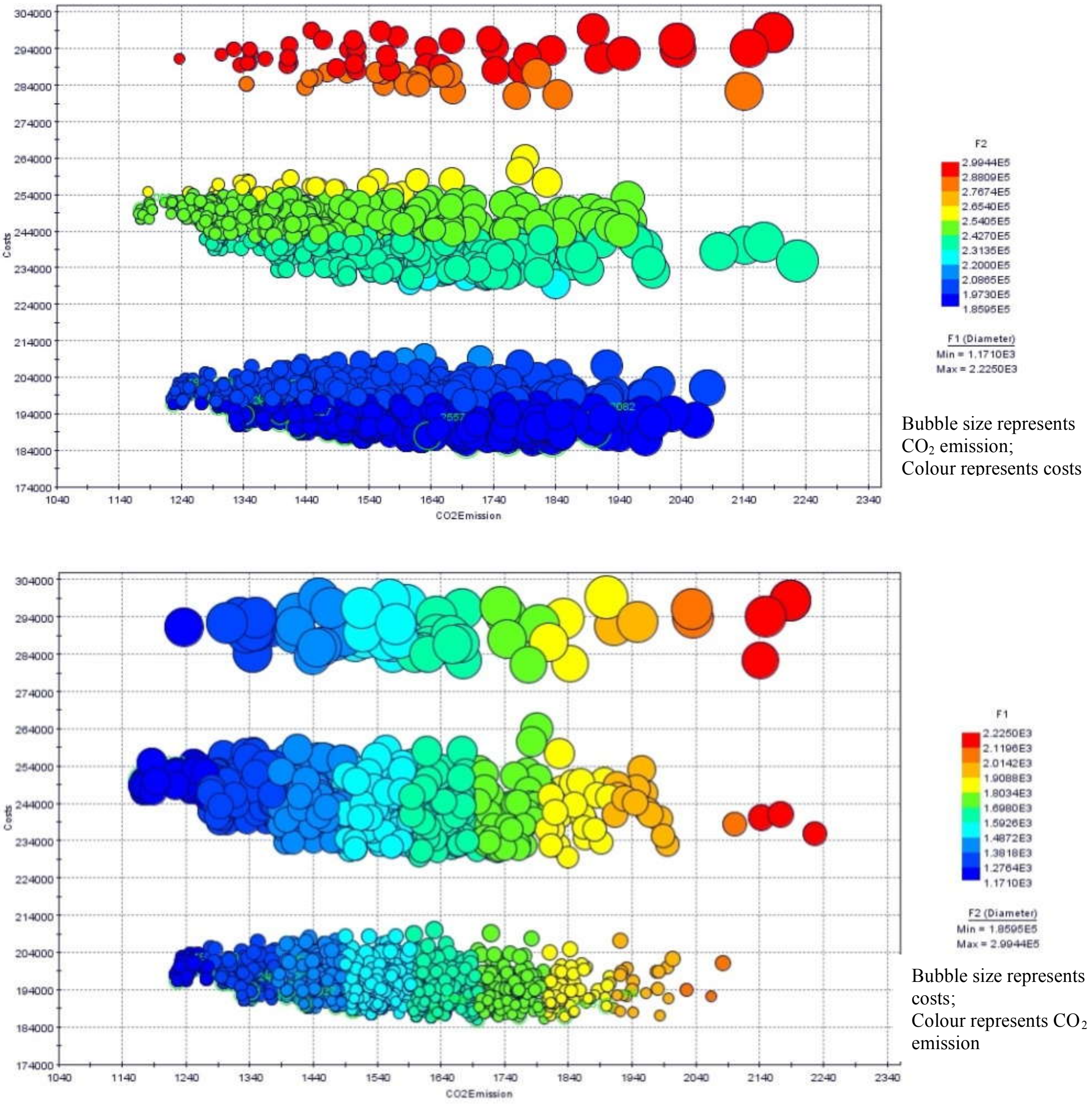
Results obtained from the MOSPO optimiser are all feasible and real. A statistical summary of these results is presented in Table 4.18. These results assist analysis of: a) all the results tables consisting of all feasible real results obtained from the optimiser, b) the refined realistic results table consisting of realistic and non-identical results, and c) the selected results table consisting of selected results from the three lowest sets of feasible results from the 4D-Bubble plots.

Table 4.18 Statistical summary for the MOPSO optimiser

Result		**Number of real feasible results** (Alternatives)	**CO$_2$ emission value** (kg) (Objective Function I)		**Costs value** (€) (Objective Function II)	
			Min	***Max***	***Min***	***Max***
MOPSO	All results table	2,600	1,171	2,225	185,948	299,444
	Refined realistic results table	1,065	1,174	2,225	185,948	299,444
	Selected results table	30	1,174	1,898	185,948	250,185

More than 40% of the results table population in MOPSO are realistic and out of these refined realistic results table, 30 are selected for further analysis.

Guided by the DoE, MOPSO generates the feasible space of solutions. Figure.16 illustrates the feasible real solution space for MOPSO. As discussed earlier, in Figures 4.16 colour and diameter of bubbles are used to represent the values of both of the objective functions as illustrated in the plot legends. Colours range from dark blue to red signifying lowest to highest value of the objective functions respectively. The diameter of the bubble ranges from small to large indicating lowest to highest values of the objective functions respectively.



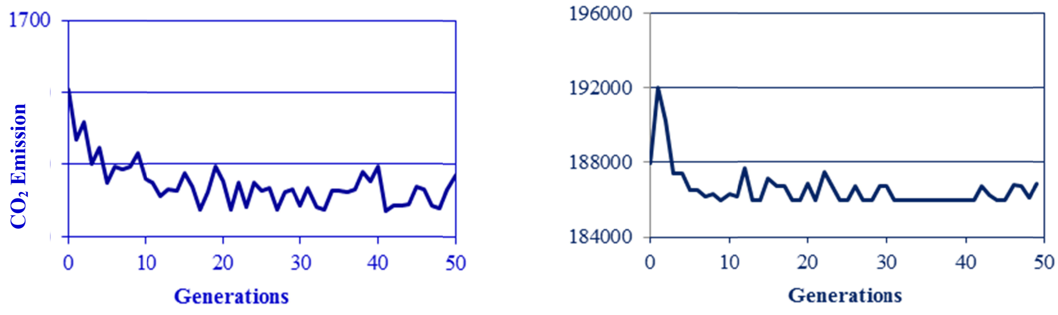
Bubble size represents CO_2 emission;
Colour represents costs

Bubble size represents costs;
Colour represents CO_2 emission

Figure 4.16 Feasible real solution space w.r.t. costs and CO_2 emission for the MOPSO optimiser

4.8.1.1. Performance study on MOPSO

The convergence of MOPSO is presented to examine its performance while solving the two-layer MO-LRP. Figure 3.16 presents the convergence of MOPSO with respect to the objective functions.



a. Convergence on CO_2 emission b. Convergence on costs

Figure 4.17 Convergence for the MOPSO optimiser w.r.t. the objective functions

MOPSO is converging in a steady manner as it is evident from Figure 4.17(a) and 4.17(b). History plots, Box Whiskers, and Density plots representing the convergence performance of the optimiser with reference to ID are presented in Appendix A.4 for further analysis.

4.8.1.2. ANOVA

One-way ANOVA is conducted for both the total CO_2 emission and total costs of transportation for comparing the means of two or more groups of the optimised data. Table 4.19 presents the ANOVA results for the MOPSO optimiser with respect to both the objective functions.

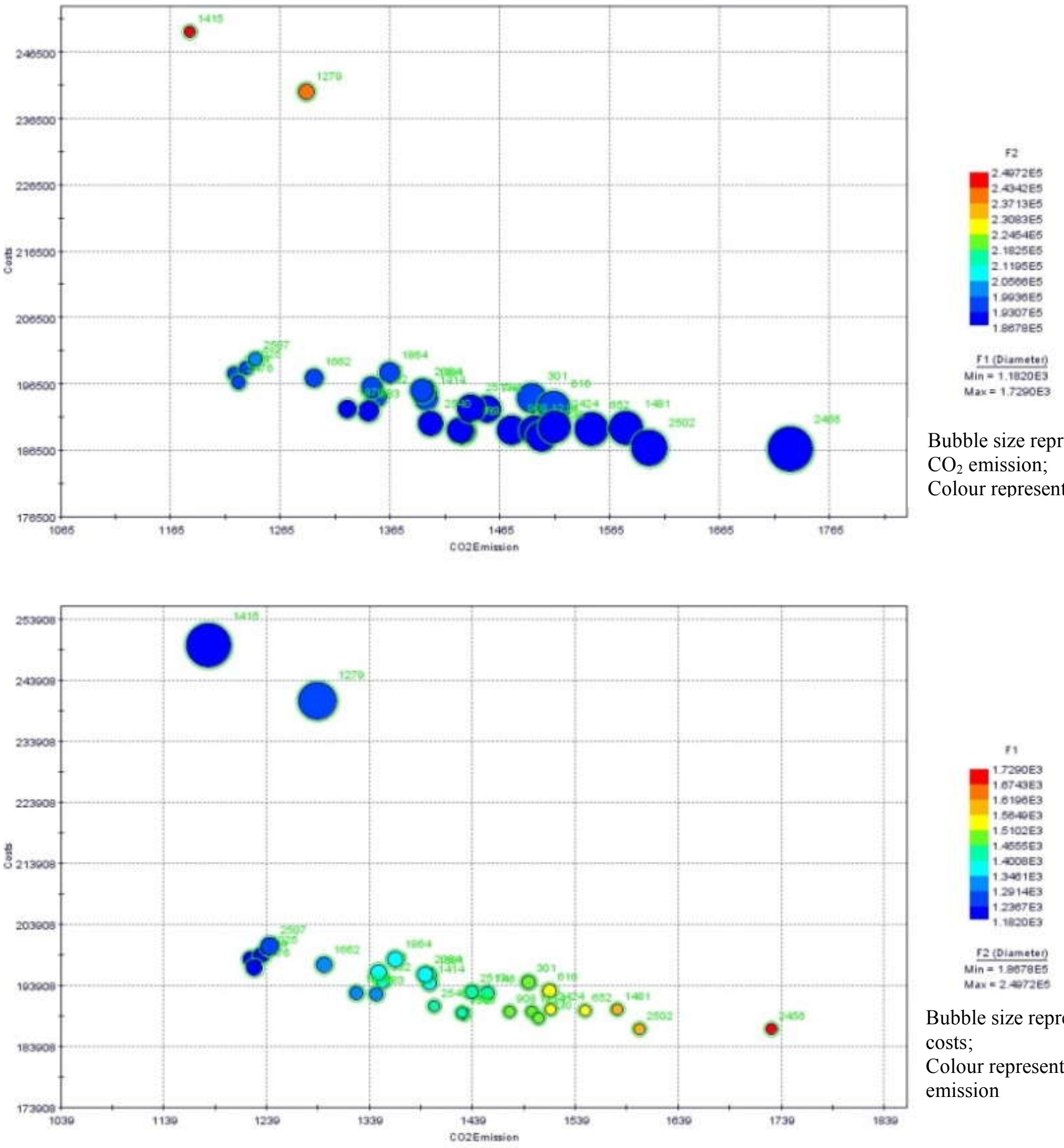
Table 4.19 ANOVA for the MOPSO optimiser

Objective function	**Source of variation**	**SS**	**Df**	**MS**	**F-ratio**	**p-value**
CO_2 emission	Between groups	1.2570E7	5.5000E1	2.2855E5	1.0303E1	0.0000E0
	within groups	5.6454E7	2.5450E3	2.2182E4	—	—
	Total	609024E7	2.6000E3			
Costs	Between groups	1.2298E11	5.5000E1	2.2359E9	3.5136E0	2.2204E16
	within groups	1.6196E126	2.545.E3	6.3637E8	—	—
	Total	1.7425E12	2.6000E3			

The p-value of the ANOVA table for the CO_2 emission (Table 4.19) using the MOPSO optimiser is zero suggesting significant differences ‘between the groups’. It signifies that at least one sample mean is considerably different than the other sample means.

4.8.1.3 .Selection of results

The refined realistic results table is presented in Table 3.18 that eliminates un-realistic and identical results. Amongst the refined realistic results, a set of 30 results is selected for further analysis. The selecting process is the same process explained and used for GA-based optimisers by way of selecting from the three lowest sets of objective function values. Figure 4.18 exhibit set of 30 selected results from MOPSO optimiser. Selected results are ranked using TOPSIS to obtain the best optimised results. The ranking process is explained in the following section.



Bubble size represents CO_2 emission;
Colour represents costs

Bubble size represents costs;
Colour represents CO_2 emission

Figure 4.18 Selected results in feasible real solution space w.r.t. costs and CO_2 emission for the MOPSO optimiser

4.8.1.4. Ranking selcted results

Selected results are ranked following the same ranking procedure adopted for the GA-based optimisers by defining nine weight matrices for TOPSIS. SDI Tools is used as the implementation platform for TOPSIS. Figures 4.19-a and 4.19-b present the reflection of DMs priorities (i.e., weight matrices in TOPSIS) using the first three ranked results using weight matrices in TOPSIS.

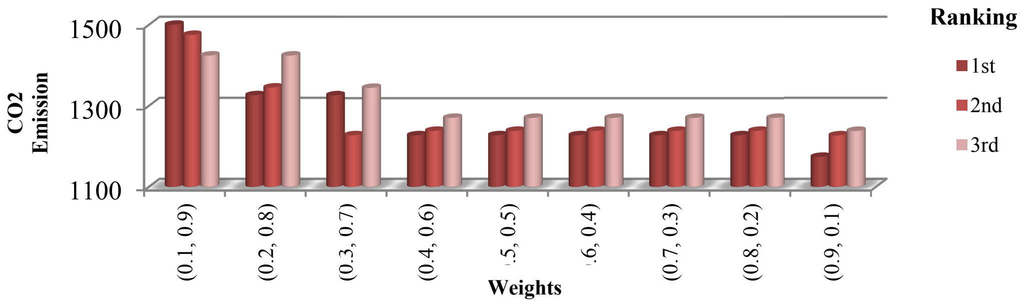


Figure 4.19-a Reflection of the DMs' priorities on TOPSIS ranking w.r.t. CO_2 emission

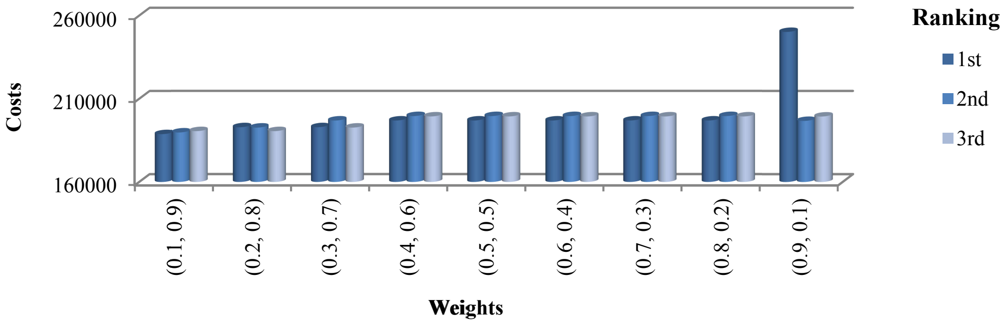


Figure 4.19-b Reflection of the DMs' priorities on TOPSIS ranking w.r.t. costs

Figure 4.19-a shows that the lowest and highest values for CO_2 emission (first objective function) are picked by w_9 and w_1 respectively. Both of these weight matrices represent extreme decision-making events. The same is correct with regard to costs as well. The first three results ranked by TOPSIS using weight matrices w_3, w_5 and w_7 are presented in Table 4.20.

Table 4.20 First three ranked results w.r.t the MOPSO optimiser using weight matrices w_3, w_5, w_7

	$w_3=(0.3\quad 0.7)$			$w_5=(0.5\quad 0.5)$			$w_7=(0.7\quad 0.3)$		
	Rank	**CO_2 emission**	**Costs**	**Rank**	**CO_2 emission**	**Costs**	**Rank**	**CO_2 emission**	**Costs**
MOPSO	**1**	**1326**	**192693**	**1**	**1227**	**196705**	**1**	**1227**	**196705**
	2	**1227**	**196705**	**2**	**1238**	**199357**	**2**	**1238**	**199357**
	3	**1345**	**192473**	**3**	**1270**	**199141**	**3**	**1270**	**199141**

4.8.1.5 .*Pareto efficiency*

Pareto efficiency is examined in order to evaluate the performance of the MOPSO optimiser. Figure 4.20 presents the Pareto frontier for the selected results obtained from the feasible real solution space for the MOPSO optimiser.

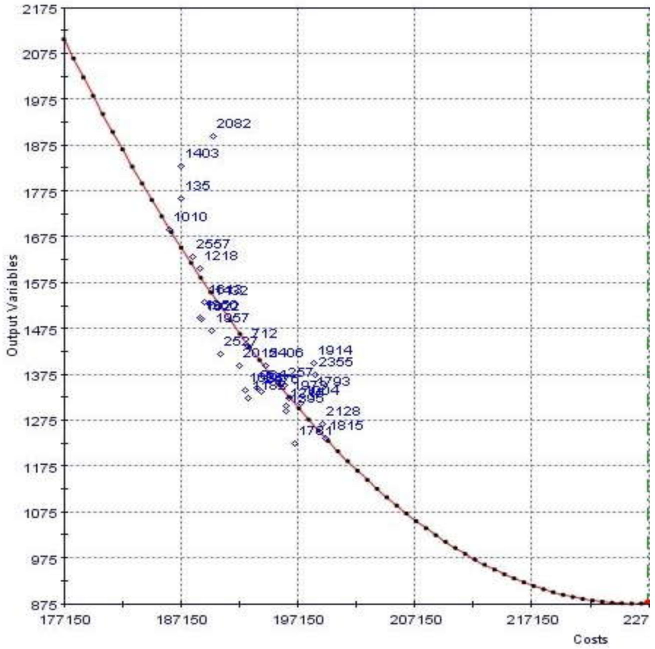


Figure 4.20 Pareto frontier w.r.t. selected results for the MOPSO optimiser

In Figure 4.20 the selected results from MOPSO optimiser follow the Pareto optimality and are strongly efficient. In the selection process of the results, extreme decision-making events are considered. Out of 30 selected results in MOPSO, 1 result is out of the Pareto frontier representing an extreme decision-making event. Therefore, this result does not affect the Pareto efficiency. The result placed outside of the Pareto Frontier is not ranked by TOPSIS.

4.8.2. Interpretation of Results

The two outcomes from the MOPSO optimiser include scenario analysis and schematic presentation of the results on map.

4.8.2.1. *Scenario Analysis*

In order to provide the details of open and close routes for different result IDs, a scenario analysis is presented on Table 4.21. The first ranked result using weight matrix w_5 obtained from MOPSO is selected for presenting the scenario analysis. DMs can observe the CO_2 emission and costs for the closed routes forced to open under certain circumstances and decide which route to open, if necessary.

Table 4.21 Scenario analysis for MOPSO on $w_5 = (0.5 \quad 0.5)$

Routes	Open(1)/ close(0) routes	Closed routes analysis (effect on CO_2 emission if open)	Closed routes analysis (effect on costs if open)
V1II	0	108	5,108
V2I	0	34	3,834
V2II	0	135	1,935
V3II	0	97	2,997
V4I	0	102	2,102
V5I	0	70	4,270
V6I	0	95	1,495
V7II	0	56	7,056
V8I	0	132	1,532
V9I	0	69	2,669
V10I	0	118	70,118
V11I	0	112	36,512
V12I	0	77	6,077
V13I	0	209	4,769
V14I	0	202	3,562
V15I	0	214	2,614
V16I	0	164	5,204
V17I	0	182	1,862
V18I	0	170	3,050
V19II	0	55	3,895
V20I	0	58	3,178
V21I	0	27	84,027
V22I	0	57	43,737

4.8.2.2. Schematic presentation of a result

The first ranked MOSPO result picked by TOPSIS suing weight matrix w_5 is presented geographically in Figure 4.21.

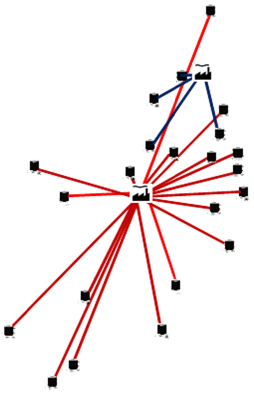


Figure 4.21 Schematic presentation of the a result for $W_5 = (0.5 \quad 0.5)$

4.9. Summary and Conclusions

This chapter elucidates the two-layer multi-objective AHP-integrated location-routing model, its solution approach, and the analysis process of the results obtained. The proposed MO-LRP considers plants and retailers as two players on the demand side of the supply chain network. A green objective function with the main aim of lowering the level of CO_2 emission caused from transportation is introduced to the model. An AHP-integrated constraint is developed in order to consider the priorities of the DMs in the model. Demand has been considered in this two-layer MO-LRP as a co-efficient in the objective function.

The execution platform is modeFRONTIER®, a multi-disciplinary commercial solver. Two different GA-based and a PS-based optimisers have been used to implement the model using modeFRONTIER®. The model has been validated using the case of an Irish dairy supply chain network based in east of Ireland. A questionnaire has been used to validate the structure of the SC and the data are generated based on a set of real logical assumptions. The model has been deployed to modeFRONTIER® using DoE-guided meta-heuristic optimisers. An identical initial population is defined for the meta-heuristics to ensure an experimental validation. The computation time for each attempt of solving the model has not been calculated separately, based on the procedure and the types of reports the calculation time varied between five minutes to 24+ hours. All optimisers have been set as similar as possible to make a comparative study feasible on the performance of the optimisers in solving the proposed model.

The proposed two-layer MO-LRP is mathematically NP-hard. Therefore, there is no unique solution to the two-layer MO-LRP but a set of optimum solutions. Results obtained from each optimiser have been analysed in details. With an initial population of 51, MOGA-II, NSGA-II and MOSPO are set on 50 generations. A number of 2,550 results, each from MOGA-II and NSGA-II optimisers, have been obtained while the MOPSO optimiser provides 2,600 results. The 'total results' have been refined by eliminating the un-realistic and identical results. Amongst these 'refined realistic results' a set of 30 results have been selected. These 'selected results' have been ranked by TOPSIS, using nine different weight matrices.

As there is no unique solution to the two-layer MO-LRP, a range of decision-making weights are considered in order to make sure all types of DMs with different priorities are taken into account to rank the results. A scenario analysis has been conducted on the first ranked results offered by TOPSIS using a moderate weight matrix. Scenario analysis offers the open and closed routes on the demand side of the two-layer MO-LRP. Furthermore, they analyse the effect of opening a ‘closed route forced to open’ under some circumstances, e.g. any kind of emergencies, natural disasters, etc. And finally, the first ranked results offered by TOPSIS using a moderate weight matrix has been geographically mapped to show the structure of the optimised two-layer supply chain network.

The comparative analysis on the GA-based optimisers (MOGA-II and NSGA-II) shows that NSGA-II has been converging in a steadier manner as compared with MOGA-II. The GA-based optimisers are strongly efficient on the Pareto fronts.

modeFRONTIER® proves to be efficient in implementing the NP-hard two-layer MO-LRP. The same commercial solver is used to execute the three-layer model which is much more complicated and larger in size comparing to the two-layer MO-LRP. The next chapter deals with a three-layer multi-objective AHP-integrated 0-1 mixed integer location-routing model for designing the demand side of a supply chain network. As proved to be more successful, convergent, and Pareto efficient, MOGA-II, NSGA-II, and MOSPSO have been used for implementing the three-layer model.

CHAPTER FIVE

Three-layer Multi-Objective Integrated Location-Routing

5.1. Introduction

The proposed three-layer low-carbon/green Multi-Objective-Location Routing Problem (MO-LRP) improves the conventional models of Perl (1983) and Perl and Daskin (1985) and contributes to the literature in the field of low-carbon capacitated three-layer LRPs. The three-layer MO-LRP is a variant of the two-layer MO-LRP presented in Chapter Three.

The green three-layer MO-LRP is a capacitated model on the demand side of the SC network. The three-layer model considers three main players on the demand side of the SC network, viz., plants, DCs and retailers with multiple routes connecting them. An example of the demand side of a three-layer SC network with multiple facilities and multiple retailers is presented in Figure 5.1. The physical distribution of the three-layer SC network is the concern of this chapter.

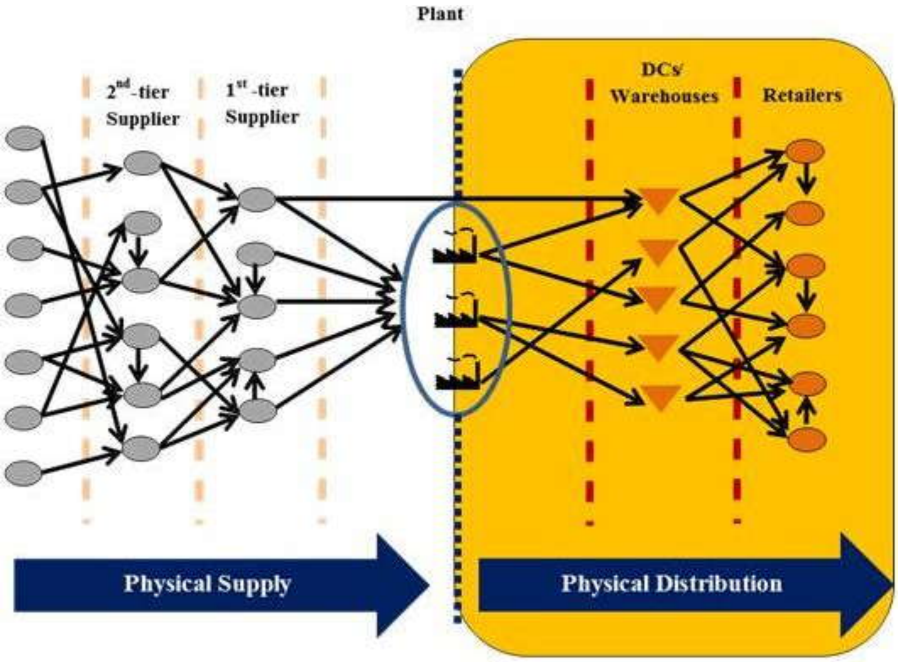


Figure 5.1 Three-layer SC with multiple consumers (Adapted from: Schroeder et al. 2013)

The main contribution of this chapter is three inter-linked aspects of the green three-layer MO-LRP, viz.:

(i) a green three-layer MO-LRP is designed by integrating AHP into the 0-1 mixed integer programming framework
(ii) a two phased Design of Experiment (DoE)-guided meta-heuristic-based robust solution approach under the modeFRONTIER® commercial solver is provided
(iii) the DMs' prioritisation and subsequent ranking of the realistic solutions are examined using Pareto frontiers, TOPSIS and various scenarios of the green location-routing are featured.

The implementation of the formulated three-layer MO-LRP is a challenging task as it is computationally NP-hard. In the case of NP-hard models conventional techniques do not yield an optimal set of solutions, instead a heuristic/meta-heuristic generates an optimal solution space. Due to the computational complexity in solving the entire model in a single run, the solution approach is divided into two inter-connected phases. Phase-I of the solution approach considers: (i) facility location decisions by opening/closing DCs, and (ii) vehicle routing decisions by offering routing patterns for connecting the three layers of the SC. Phase-II considers vehicle routing decisions on the demand side of the SC by setting the routing patterns with connections among the retailers. The three-layer MO-LRP is implemented using DoE-guided disparate meta-heuristic optimisers using the modeFRONTIER® commercial solver (ESTECO 2013).

The low-carbon three-layer MO-LRP, its efficient inter-linked two phased solution approach and analysis of the realistic results contribute to the demand side of the SC network in the following ways:

(i) a low-carbon three-layer MO-LRP on the demand side of a SC network is formulated. Green elements are embedded in an objective function and an AHP-integrated constraint.

(ii) the model optimally routes DCs to plants and allocates retailers to DCs, and retailers to retailers.

(iii) the total carbon emission and total cost are optimised. These criteria are conflicting-in-nature having incommensurable units of measurements.

(iv) an inter-linked two phased solution approach for the computationally NP-hard three-layer MO-LRP is proposed. The model is implemented using DoE-guided disparate meta-heuristic optimisers using the modeFRONTIER® commercial solver platform (ESTECO 2013).

(v) sets of Pareto efficient realistic optimum results are found. The results are then prioritised and ranked by the DMs. TOPSIS assists in evaluating sets of selected results. An analysis reflecting the DMs' preferences is performed. This analysis reflects the changes in the controlling parameters with respect to the changes in the decision weights of TOPSIS.

(vi) a scenario analysis of the location-routing events is obtained to guide the DMs in order to locate the feasible and realistic optimal routing patterns by trading-off the objective functions.

(vii) the routing patterns are schematically presented on map.

This chapter is organised in three parts (Figure 5.2). Part I presents the three-layer MO-LRP. Part II delineates the two phased DoE-guided meta-heuristic-based robust solution approach using the modeFRONTIER® commercial solver followed by the deployment of a case of a three-layer supply chain network. Part III elucidates the DM's prioritisation and subsequent ranking of the realistic solutions using Pareto frontiers and TOPSIS. In this section various scenarios of the green location-routing events are featured by determining alternative possible outcomes.

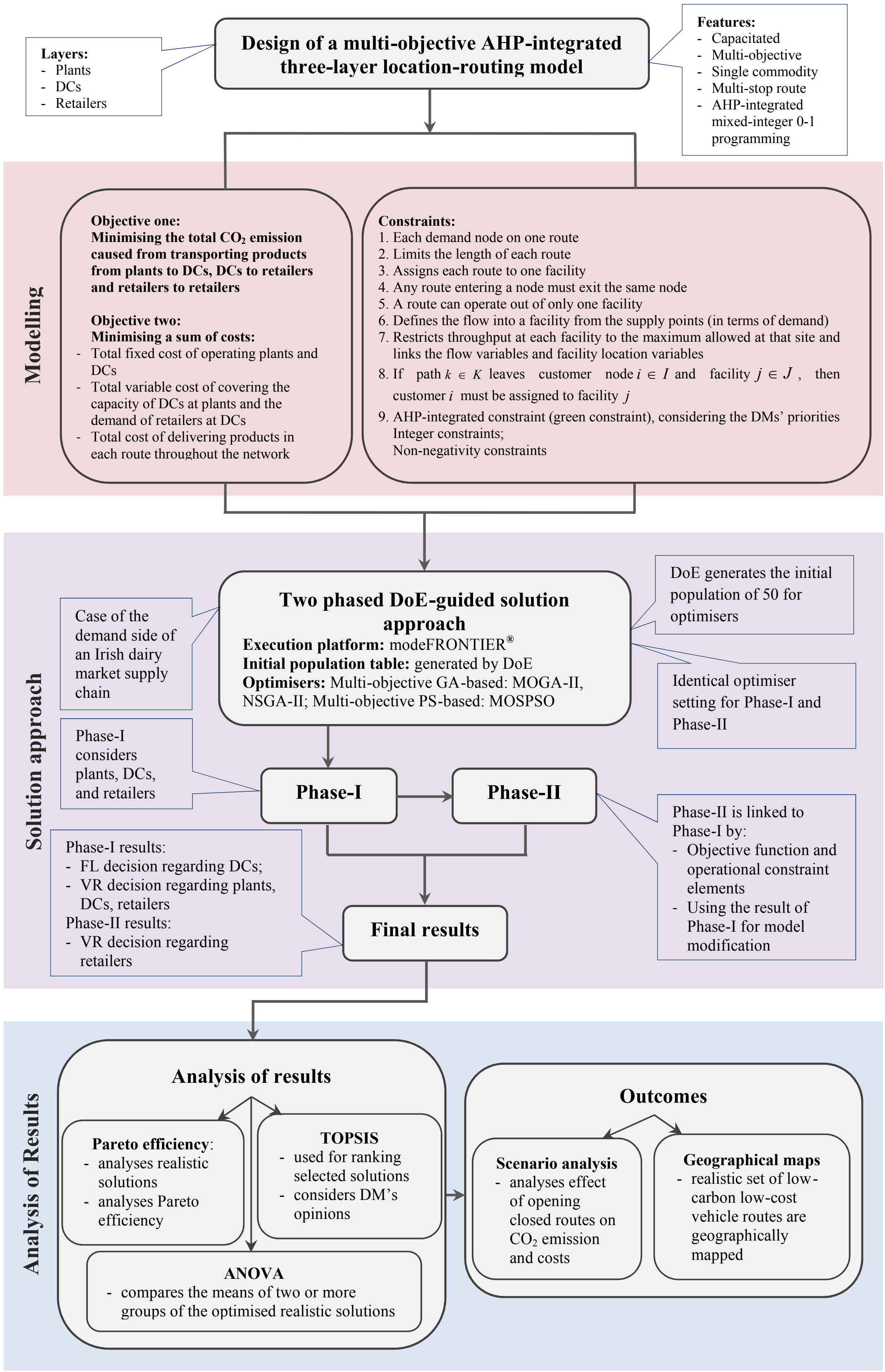


Figure 5.2 The formulation of the multi-objective three-layer location-routing model, its solution approach and analysis procedure

Part I: Modelling

5.2. Three-Layer Multi-Objective AHP-Integrated Location-Routing

The three-layer low-carbon MO-LRP is formulated integrating AHP with a 0-1 programming approach. The purpose of this model is to minimise the level of CO_2 emission caused from transportation and minimise a combination of costs on the demand side of three-layer supply chain networks. This model is generic and can be extended to any three-layer supply chain network.

The proposed model is formulated based on a set of realistic assumptions (Box 5.1). The three-layer MO-LRP considers three key players on the demand side of a SC, viz., plants, DCs and retailers. Two fleets of vehicles/trucks are considered for transporting the products throughout the SC network. A fleet of trucks transport products from plants to DCs, and a different fleet of trucks transport products from DCs to retailers and then from retailers to other retailers. Each route may be a combination of different types of roads. In every country different speed limits apply to different types of roads. Speeds in different types of routes are captured in the model by the use of an appropriate variable.

Box 5.1 Assumptions for the three-layer MO-LRP

- Demand side of the SC is considered
- Multiple facilities, multiple retailers and single product are considered
- Location of facilities (plants, DCs) are known
- Retailers have known geographical locations
- Plants are always open
- DCs can be open or closed
- Vehicle routes have known geographical start and end points
- Vehicle routes are all real and feasible
- Multi-stop routes from DCs to retailers and from retailers to retailers are considered
- Routes are capacitated
- Each vehicle route is served by one or more vehicle based on the demand at the destination
- Two fleets of vehicles/trucks are considered
- Heavy duty trucks/Heavy Goods Trucks (HGVs), class 7 are used for transporting products are considered
- If the product is perishable the vehicle is refrigerated HGV
- Fuel consumption of vehicles is dependent on the total mass of the vehicles
- HGVs are diesel operated, average price (€/lit) of Diesel in a specific period of time

is assumed in the model

- Consumption of the fuel is dependent on the speed of the vehicle/trucks
- Truck drivers' wage is dependent on the speed of the trucks
- The average wage of a truck driver (€/hr) is considered for a specific period of time
- A portion of variable cost is dependent on the capacity at the DC locations and demand at the retailer locations.

The detailed nomenclature of the three-layer MO-LRP is elucidated in Table 5.1.

Table 5.1 Nomenclature

Sets and indices

I	Set of retailer locations indexed by i
J	Set of DCs indexed by j
S	Set of processing plants indexed by s
P	Set of points $S \bigcup J \bigcup I$ indexed by $s \in S$, $j \in J$, $i \in I$
K	Set of paths defined in set P
M	Set of attributes in AHP decision matrix (CO$_2$ emission and costs) indexed by m
N	Set of alternative in AHP decision matrix (trucks) indexed by n
Parameters	
f_s	Sum of fixed cost of locating at plant $j \in J$
v_s	Sum of variable costs of serving customers at each plant $j \in J$
f_j	Sum of fixed costs of locating at plant $j \in J$
v_j	Sum of variable costs of serving customers at each plant $j \in J$
a_s	Variable cost of providing DC with the products at a processing plant per unit $s \in S$
a_j	Variable cost of providing a retailer with the products at a DC per unit $j \in J$
r_j	Capacity at DC $j \in J$
r_i	Demand at retailer location $i \in I$
c_{sj}	Cost of serving each route from plant $s \in S$ to DC $j \in J$
c_{ji}	Cost of serving each route from DC $j \in J$ to retailer $i \in I$
c_{ii}	Cost of serving each route from retailer $i \in I$ to retailer $i \in I$
$p_{V_{sj}}$	CO$_2$ emission from transportation in each route from processing plant $s \in S$ to DC $j \in J$
$p_{L_{ji}}$	CO$_2$ emission from transportation in each route from retailer $i \in I$ to retailer $i \in I$

Parameters (cont'd)

d_{sj}	Distance from plant $s \in S$ to DC $j \in J$ in km
d_{ji}	Distance from DC $j \in J$ to retailer $i \in I$ in km
d_{ii}	Distance from retailer $i \in I$ to retailer $i \in I$ in km
u_{sj}	Number of vehicles needed to transport the products; from processing plant $s \in S$ to DC
u_{ji}	Number of vehicles needed to transport the products; from DC $j \in J$ to retailer $i \in I$
u_{ii}	Number of vehicles needed to transport the products; from retailer $i \in I$ to retailer $i \in I$
τ_k	Length of combined routes limit
z	Speed in different roads in km
w_{mn}	Matrix of weights for each truck option
B_m	Right hand side matrix for green constraint
S_m	Values of p_{ji} and c_{jk} depending on the values of B_m
Decision variables	
Y_j	Set of DCs (=1 if DC $j \in J$ is open, = 0 if not)
V_{sj}	Set of feasible paths form processing plant $s \in S$ to DC $j \in J$
L_{ji}	Set of feasible paths form DC $j \in J$ to retailer $i \in I$
O_{ii}	Set of feasible paths form retailer $i \in I$ to retailer $i \in I$
Q_{sj}	Quantity shipped from processing plant $s \in S$ to DC $j \in J$
Q_{ji}	Quantity shipped from DC $j \in J$ to retailer $i \in I$
Q_{ii}	Quantity shipped from retailer $i \in I$ to retailer $i \in I$
T_n	Trucks with different specifications $n \in (1,2,3)$
X_s	Set of processing plants $s \in S$

The model addresses low-carbon element by the way of introducing two green components, viz., (i) a green objective function, and (ii) a AHP-integrated green constraint. Same set of data is fed to these two green components of the model. Considering the assumptions of the model, a three-layer multi-objective AHP-integrated 0-1 mixed integer location-routing model is developed.

The three-layer MO-LRP has two objectives:

$$\text{minimise} \sum_{s\in S}\sum_{j\in J} u_{sj}p_{V_{sj}}V_{sj} + \sum_{j\in J}\sum_{i\in I} u_{ji}p_{L_{ji}}L_{ji} + \sum_{i\in I}\sum_{i\in I} u_{O_{ii}}p_{O_{ii}}O_{ii} \qquad (5\text{-}1)$$

The first objective function (5-1) of this three-layer MO-LRP has been designed to minimise the total CO_2 emission from transportation between facilities in the SC. This objective function considers the CO_2 emitted from transporting the products in the routes from 'plants to DCs', 'DCs to retailers' and 'retailers to retailers'. Two sets of decision variables and one set of parameters are used to calculate the amount of CO_2 emission from transportation in the first objective function.

A set of decision variables V_{sj}, L_{ji} and O_{ii} define all real feasible routes from plants to DCs, DCs to retailers and routes connecting retailers to retailers respectively. V_{sj}, L_{ji} and O_{ii} are 0-1 integer decision variables where 0 refers to closed routes and 1 to open routes.

Another set of decision variables u_{sj}, u_{ji} and u_{ii} represent the number of vehicles needed to transport the products from plants to DCs, DCs to retailers, and retailers to retailers. In this three-layer MO-LRP demand is included as an objective coefficient. Therefore the number of trucks required to transport the products in the routes are one of the outcomes of the model.

A set of parameters $p_{V_{sj}}$, $p_{L_{ji}}$ and $p_{O_{ii}}$ represent the amount of CO_2 emission in each real feasible route from plants to DCs, DCs to retailers, and among retailers respectively. There is no standard formula set by the Irish government or EU for calculating the amount of CO_2 emission from road freight. In order to measure this, the following formula (5-2) developed and adapted by two UK government departments (The Department of Energy and Climate Change (DECC) 2008; Department for Environments, Food and Rural Affairs (DEFRA) 2008) is adopted:

$$CO_2 \text{ emission from a diesel vehicle in kg} = \text{Litres of diesel burnt} \times 2.64 \text{ kg} \tag{5-2}$$

According to DECC (2008) '*for vehicles, regardless of their type, engine size, axles and gross vehicle weight, 2.64kg CO_2 will be emitted for each litre of diesel burnt (or 2.30kg for petrol)*'. Therefore, in order to calculate the litres of Diesel burnt by HGVs the formula (5-3) is used:

$$\text{Litres of diesel burnt in each path} = \text{fuel efficiency (lit/km)} \times \text{Distance (km)} \tag{5-3}$$

Fuel consumption is dependent on vehicle mass and is considered in average as 0.35 lit/km for HGVs (Nylund and Erkkilä 2005; DECC 2008). Equations (5-2) and (5-3) measure the CO_2 emission for one truck. Distances among plants, DCs and retailers are measured using Google^{TM} maps. This is because the geographical start and end point of routes are known.

The second objective function (4-4) minimises the total costs:

$$\text{minimise} \quad \left[\sum_{s\in S} f_s X_s + \sum_{j\in J} f_j Y_j\right] + \left[\sum_{s\in S} v_s X_s + \sum_{j\in J} v_j Y_j\right] + \left[\sum_{s\in S}\sum_{j\in J} u_{sj} c_{V_{sj}} V_{sj} + \sum_{j\in J}\sum_{i\in I} u_{ji} c_{L_{ji}} L_{ji} + \sum_{i\in I}\sum_{i\in I} u_{O_{ii}} c_{O_{ii}} O_{ii}\right] \tag{5-4}$$

The three-layer MO-LRP considers three different types of costs in this objective function (5-4), viz. fixed costs, variable costs and vehicle-routing costs. The details of each type of costs are illustrated as followed:

- **Fixed costs**

This type of cost consists of the fixed cost for operating the plants (f_s) and the DCs (f_j). The fixed costs for operating the plants and the DCs are not dependant on the number of the products produced or processed or held at each plant or DC.

- **Variable costs**

This type of cost consists of cost of serving retailers at each plants and DCs, v_s and v_j respectively. Variable costs (v_s, v_j) are dependent on the number of products produced or processed at each plant to cover the capacity of each DC. Considering the capacity in each DC location (r_j), a variable cost of providing DC with each unit of products is defined at each plant (a_s) by equation (5-5):

$$v_s = (a_s.r_j) \tag{5-5}$$

Consequently considering the demand at retailer location (r_i), a variable cost of providing the retailers with each unit of product is calculated at each DC (a_j) by equation (5-6):

$$v_j = (a_j.r_i) \tag{5-6}$$

- **Vehicle-routing costs**

Vehicle-routing cost calculates the total cost of serving all operating routes throughout the demand side of the supply chain network. The routes connect plants to DCs, DCs to retailers, and retailers to retailers. Two main components of costs are considered, viz. total fuel cost, and total truck driver’s wage in each open route. Based on the assumptions presented in Box 4.1, equations (5-7) and (5-8) are developed to calculate the total fuel cost and the total truck driver’s wage:

$$\textit{Total Fuel Cost}\ (€) = \textit{Diesel burnt}\ (\text{lit}) \times \textit{Fuel Price}\ (€/\text{lit}) \tag{5-7}$$

$$\textit{Total Truck Driver's Wage}\ (€) = \textit{Truck Driver's wage}\,(€/\text{hr}) \times \frac{\textit{Distance}\,(\text{km})}{z\ (\text{km/hr})} \tag{5-8}$$

Driver’s wage is paid on an hourly basis and there are different speed limits set for different types of roads in each country. In order to consider the effect of speed on driver’s wage, parameter z (i.e., speed in different roads in km) is introduced to the second objective function. Considering the equations (5-7) and (5-8), cost of serving each route in € is calculated using the equation (5-9):

$$\textit{Cost of Serving Each Route}\ (€) = \textit{Total Fuel Cost}\ (€) + \textit{Total Truck Driver's Wage}\ (€) \tag{5-9}$$

Set of parameters $c_{V_{sj}}$, $c_{L_{ji}}$ and $c_{O_{ii}}$ represent the total cost of serving each route connecting plants to DCs, DCs to retailers, and retailers to retailers respectively.

Cost of serving each route is calculated for each truck. Set of variables u_{sj}, u_{ji} and u_{ii} represent the number of truck needed to transport the products from plants to DCs, DCs to retailers, and retailer to retailer.

The constraints of the three-layer MO-LRP are as followed:

Constraint 1: Each demand node on one route

$$\sum_{s\in S}\sum_{j\in J} V_{sj} = 1 \text{ : Routes from plants to DCs} \tag{5-10.a}$$

$$\sum_{j\in J}\sum_{i\in I} L_{ji} = 1 \text{ : Routes from DCs to retailers} \tag{5-10.b}$$

$$\sum_{i\in I}\sum_{i\in I} O_{ii} = 1 \text{ : Routes from retailers to retailers} \tag{5-10.c}$$

This constraint is to make sure every DC is connected to only one plant and every retailer is connected to only one DC.

Constraint 2: Limits the length of each multi-stop route

$$\sum_{j\in J}\sum_{i\in I} d_{ji}L_{ji} + d_{ii}O_{ii} \leq \tau_k \tag{5-11}$$

This constraint considers a set of multi-stop routes, wherein one route comprises of a start point from a DC to a retailer and then serving another retailer. The first fleet of trucks transport the products from the plants to the DCs. Then the second fleet of trucks transport the products from the DCs to the retailers and from one retailer to another retailer. Multi-stops are considered from the DCs to the retailers and from one retailer to another retailer.

Constraint 3: Each route to be connected to a facility

$$\sum_{s\in S}\sum_{j\in J} V_{sj} \geq 1 \text{ : Routes from plants to DCS} \tag{5-12.a}$$

$$\sum_{j\in J}\sum_{i\in I} L_{ji} \geq 1 \text{ : Routes from DCs to retailers} \tag{5-12.b}$$

$$\sum_{i\in I}\sum_{i\in I} O_{ii} \geq 1 \text{ : Routes from retailers to retailers} \tag{5-12.c}$$

The routes are assumed to have known start and end points. Therefore, there is only one route defined to connect each plant to each DC and each DC to each retailer.

Constraint 4: Any route entering a node must exit the same node

$$\sum_{j\in J} L_{ji} - \sum_{i\in I} L_{ji} = 0 \text{ : From DCs to retailers} \tag{5-13.a}$$

$$\sum_{i\in I} O_{ii} - \sum_{i\in I} O_{ii} = 0 \text{ : From a retailer to the next retailer} \tag{5-13.b}$$

As two fleets of vehicles will transport the products, this constraint is defined for routes with multi-stop.

Constraint 5: A route can operate out of only one facility

$$\sum_{s\in S}\sum_{j\in J} V_{sj} \le 1 \text{: For routes from plants to DCs} \tag{5-14.a}$$

$$\sum_{j\in J}\sum_{i\in I} L_{ji} \le 1 \text{: For routes from DCs to retailers} \tag{5-14.b}$$

$$\sum_{i\in I}\sum_{i\in I} O_{ii} \le 1 \text{: For routes connecting retailers} \tag{5-14.c}$$

The facilities are assumed to have known locations and the routes are assumed to have known start and end points.

Constraint 6: Defines the flow of the products into the facilities and nodes from the supply points

$$\sum_{s\in S} Q_{sj} - \sum_{i\in I} r_i Y_j = 0 \text{: From plants to DCs} \tag{5-15.a}$$

$$\sum_{j\in J} Q_{ji} - \sum_{i\in I} r_i Y_j = 0 \text{: From DCs to retailers} \tag{5-15.b}$$

In constraint 6 (5-15.a) the capacity is introduced to the constraint by r_i, and in (5-15.b) the demand is introduced to the constraint by r_j.

Constraint 7: Restricts throughput at each facility to the maximum allowed, and links the flow variables to facility location variables

$$\sum_{s\in S} Q_{sj} - r_j X_s \le 0 \text{: From plants to DCs} \tag{5-16.a}$$

$$\sum_{i\in I} Q_{ii} - r_i Y_j \le 0 \text{: From DCs to retailers} \tag{5-16.b}$$

Constraint 8: A retailer must be assigned to a facility if the route leaves the facility

$$\sum_{j\in J} L_{ji} + \sum_{i\in I} O_{ii} - Y_j \le 0 \text{: Defined for multi-stop routes} \tag{5-17}$$

This constraint is applied to only multi-stop routes connecting an open DC to a retailer and then through the first retailer serving other retailer(s). Retailers have no supply of products therefore open DCs and routes connecting DCs to served retailers are included in constraint 8 (5-17).

Constraint 9: AHP-Integrated constraint

$$S_m(\sum_{m\in M}\sum_{n\in N} w_{mn}T_n) \leq B_m \quad , \qquad \forall i, j \text{ and } s \text{ on } V_{sj}, L_{ji} \text{ and } O_{ii} \qquad (5\text{-}18)$$

In order to involve DMs and their priorities in the model, a green constraint is defined. A multi-criteria decision making tool, AHP, is used to formulate this constraint. The DMs prioritise the available transportation options considering a number of criteria in order to select the best one. The process of decision-making using this AHP-integrated constraint is illustrated in Figure 5.3:

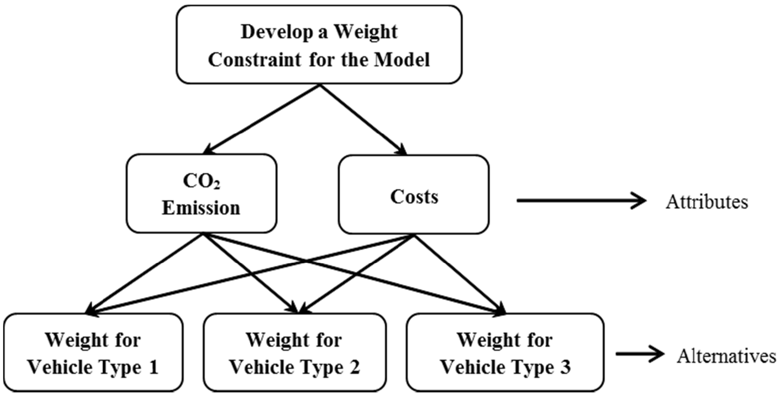


Figure 5.3 The process of developing a weight matrix in order to contract an AHP-integrated constraint

Three types of trucks are considered for transportation of products. The characteristics of the trucks are considered as followed:

T_1 : Truck type 1 (Medium CO_2 emission / Medium cost)
T_2 :Truck type 2 (Low CO_2 emission / High cost)
T_3 :Truck type 3 (High CO_2 emission / Low cost)

DMs have been asked to prioritise these three options of transportation based on two criteria, viz., CO_2 emission and cost, thereby introducing flexibility in the decision-making process. The priorities of the DMs form weight matrix (w_{mn}). The matrices B_m (i.e., right hand side of the third constraint 5-18) contribute to the parameters of the objective functions (5-1) and (5-4). Figure 5.4 depicts how the vehicles/trucks, attributes of the decision-making.

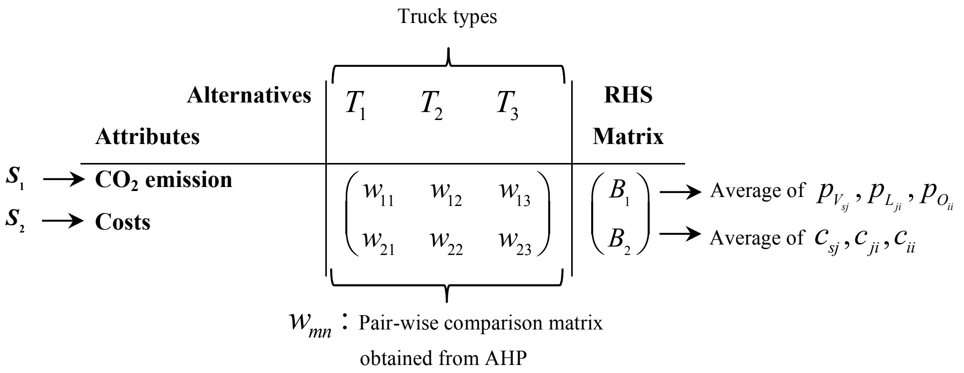


Figure 5.4 The integration of AHP to the objective functions

In Ireland or the EU no limit has been defined for CO$_2$ emissions therefore an average of the CO$_2$ emission for transportation, viz. $p_{V_{sj}}, p_{L_{ji}}, p_{O_{ii}}$, is considered as the limit for this attribute. In the case of the limit for costs an average of the total costs of serving routes, viz. c_{sj}, c_{ji}, c_{ii}, is considered as the limit for this attribute.

….

Integer constraints:

$$Y_j = \begin{cases} 1, & \text{if DC } j \in J \text{ is open} \\ 0, & \text{if not} \end{cases} \tag{5-19}$$

$$V_{sj} = \begin{cases} 1, & \text{if path } k \in P_s \text{ is operating out of processing } s \in S \\ 0, & \text{if not} \end{cases} \tag{5-20}$$

$$L_{ji} = \begin{cases} 1, & \text{if path } k \in P_j \text{ is operating out of processing } j \in J \\ 0, & \text{if not} \end{cases} \tag{5-21}$$

$$O_{ii} = \begin{cases} 1, & \text{if path } k \in P_i \text{ is operating out of retailer } i \in I \\ 0, & \text{if not} \end{cases} \tag{5-22}$$

$$T_n = \begin{cases} 1, & \text{if truck } n \in T_n \text{ is selected to transport the products} \\ 0, & \text{if not} \end{cases} \tag{5-23}$$

$$X_s = \begin{cases} 1, & \text{if processing plant s} \in S \text{ is open} \\ 0, & \text{if not} \end{cases} \tag{5-24}$$

Non-negativity constraints:

$$Q_{sj} \geq 0 \quad \text{Quantity shipped from precessing plant } s \in S \text{ to DC } j \in J \tag{5-25}$$

$$Q_{ji} \geq 0 \quad \text{Quantity shipped from precessing DC } j \in J \text{ to retailer } i \in I \tag{5-26}$$

$$Q_{ii} \geq 0 \quad \text{Quantity shipped from precessing retailer } i \in I \text{ to retailer } i \in I \tag{5-27}$$

Part II: Solution Approach

5.3. Solution Method

LRPs are conventionally single objective with the main aim of minimising the total costs of operating facilities and transportation. Mathematically LRPs are NP-hard combinatorial optimisation problems (Karp 1972; Nagy and Salhi 2007; Marinakis and Marinaki 2008; Yu et al. 2010). The three-layer MO-LRP is NP-hard as well. It is an improvement to Perl’s (1983) NP-hard LRP and is a multi-objective combinatorial optimisation model. They are very hard to solve as they combine two different conflicting-in-nature problems, viz. facility location problem, and vehicle routing problem (Daskin et al. 2010). Even for small problem sizes, the single objective three-layer LRP is substantially difficult to solve as there are more integer variables added to the formulation (Karp 1972; Daskin et al. 2010). With increasing problem size of an NP-hard problem the computational effort required for its solution grows exponentially (Erdoğan and Miller-Hooks 2012).

Multi-Objective Problems (MOP) are almost always conflicting-in-nature and mathematically NP-complete decision problems. In an MOP there is more than one objective function to optimise. Therefore, one unique solution to the problem is not yielded but a set of solutions. The set of solutions to an MOP are obtained through Pareto Optimality concept (Coello et al. 2007).

Heuristics/meta-heuristics are used to solve these types of problems as there is no unique solution to LRPs and MOPs. The solution approach divides the problem into components, viz. facility location, allocation of consumers to facilities, and vehicle routing (Hassanzadeh et al. 2009), in order to solve it. This leads to the introduction of two and three phased approaches with specific algorithms (Perl 1983; Wu et al. 2002).

In order to solve the three-layer MO-LRP, a two phased solution approach using GA-based and PS-based meta-heuristics is implemented. The two phased approach divides the main problem into two inter-linked problems. This solution approach is explained in the next section.

5.4. The Two Phased Solution Approach

The three-layer MO-LRP consists of the following components (Figure 5.5):

- Facility location component: open/close DCs, plants are considered ‘open’
- Vehicle routing component: vehicle routes connecting plants to DCs, vehicle routes connecting open DCs to retailers, and vehicle routes connecting retailers to retailers (multi-stop vehicle routing).

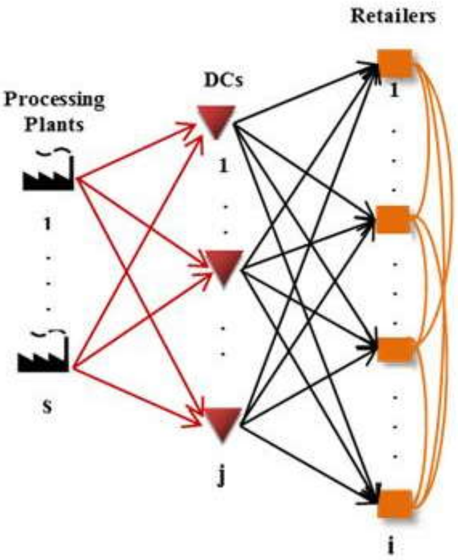


Figure 5.5 The components of the three-layer MO-LRP

The heavily constrained three-layer MO-LRP is divided into phases. The appropriate number of phases is found through numerical experimentations. A two phased approach is found to be the most efficient way for solving this three-layer MO-LRP. Therefore, the three-layer MO-LRP is divided into two inter-linked phases, viz. Phase-I and Phase-II. Phase-II is linked to Phase-I by the way of the components of the model and the solutions from Phase-I. Table 5.2 illustrates the technical details of the two phases:

Table 5.2 Technical details of the two phased three-layer MO-LRP

Phase-I	**Scope**	‘Facility location’ and ‘Vehicle routing’ within: • Plants • DCs • Retailers (connection between retailers not considered in this phase)

	Goals	Facility location decision: Open/close DCs (Plants are considered always open) Vehicle routing decision: - Routes connecting plants to DCs - Routes connecting open DCs to retailers
	Objective functions	Objective function I: Min CO_2 emission form transporting between plants and DCs Objective function II: Min total cost of operating plants and DCs and serving routes
	Constraints	Constraint 1: Each demand node on one route Constraint 3: Each route to be connected to a facility Constraint 4: Any route entering a node must exit the same node Constraint 5: A route can operate out of only one facility Constraint 6: Defines the flow into a facility from the supply points (in terms of demand) Constraint 7: Restricts throughput at each facility to the maximum allowed at that site and links the flow variables and facility location variables Constraint 8: If route $k \in K$ leaves customer node $i \in I$ and facility $j \in J$. Then retailer i must be assigned to facility j Constraint 9: AHP-integrated constraint (Green constraint), considering the DM's priorities Non-negativity constraints Integer constraints
	Outcomes from Phase-I	▪ Open/close DCs ▪ Vehicle routes connecting plants to DCs ▪ Vehicle routes connecting open DCs to retailers
Link between the two phases		Results from Phase-I: Open DCs, served retailers Model: Constraints related to DCs from Phase-I
Phase-II	**Scope**	'Vehicle routing' within: • Open DCs and the routes connecting DCs to retailers from Phase-I • Served retailers from Phase-I to un-served retailers.
	Goal	• Vehicle routing decision: Finding routes connecting served retailers to un-served retailers based on the results from Phase-I
	Objective functions	Objective function I: Min CO_2 emission form transporting between plants and DCs Objective function II: Min total cost of operating plants and DCs and serving routes
	Constraints	Constraint 1: Each demand node on one route Constraint 2: Limits the length of each road (multi-stop vehicle routes) Constraint 3: Each route to be connected to a facility Constraint 4: Any route entering a node must exit the same node Constraint 5: A route can operate out of only one facility Constraint 6: Defines the flow into a facility from the supply points (in terms of demand) Constraint 7: Restricts throughput at each facility to the maximum allowed at that site and links the flow variables and facility location variables Constraint 8: If route $k \in K$ leaves customer node $i \in I$ and facility $j \in J$. Then retailer i must be assigned to facility j Constraint 9: AHP Integrated constraint (Green constraint), considering the DM's priorities Non-negativity constraints Integer constraints

	Outcomes from Phase-II	▪ Routes connecting served retailers to un-served retailers from Phase-I As served retailers don't supply products, the routes connecting them to open DCs from Phase-I are considered in Phase-II.

As illustrated in Table 5.2 Phase-I consists of the two components of the main model, viz. facility location and vehicle routing. Phase-I covers all three layers of the model and makes decisions on open/closed DCs, vehicle routes connecting plants to DCs, and vehicle routes connecting open DCs to retailers. Figure 4.6 presents the scope of Phase-I in terms of facility location and vehicle routing components of the model. Phase-I of the solution approach is presented in the next section.

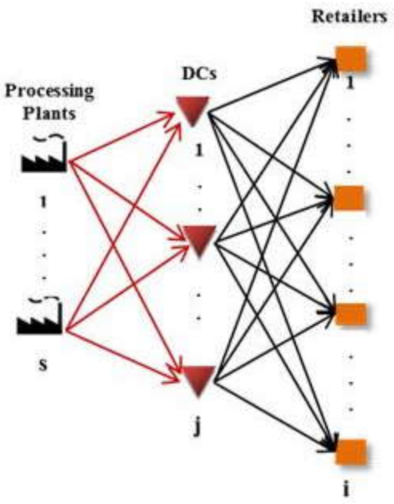


Figure 5.6 Scope of the Phase-I

5.4.1. Phase-I of the solution approach

minimise $$\sum_{s\in S}\sum_{j\in J} u_{V_{sj}} p_{V_{sj}} V_{sj} + \sum_{j\in J}\sum_{i\in I} u_{L_{ji}} p_{L_{ji}} L_{ji} \tag{5-28}$$

minimise $$\left[\sum_{s\in S} f_s X_s + \sum_{j\in J} f_j Y_j\right] + \left[\sum_{s\in S} v_s X_s + \sum_{j\in J} v_j Y_j\right] + \left[\sum_{s\in S}\sum_{j\in J} u_{sj} c_{V_{sj}} V_{sj} + \sum_{j\in J}\sum_{i\in I} u_{ji} c_{L_{ji}} L_{ji}\right] \tag{5-29}$$

subject to:

$$\sum_{s\in S}\sum_{j\in J} V_{sj} = 1 \tag{5-30.a}$$

$$\sum_{j\in J}\sum_{i\in I} L_{ji} = 1 \tag{5-30.b}$$

$$\sum_{j\in J}\sum_{i\in I} L_{ji} \geq 1 \tag{5-31}$$

$$\sum_{j\in J} L_{ji} - \sum_{i\in I} L_{ji} = 0 \tag{5-32}$$

$$\sum_{j\in J}\sum_{i\in I} L_{ji} \leq 1 \tag{5-33}$$

$$\sum_{s\in S} Q_{sj} - \sum_{i\in I} Y_j = 0 \tag{5-34}$$

$$\sum_{s\in S} Q_{sj} - r_j X_s \leq 0 \tag{5-35}$$

$$\sum_{j\in J} L_{ji} + \sum_{i\in I} O_{ii} - Y_j \leq 0 \tag{5-36}$$

$$\sum_{k\in P} w_{mn} T_n \leq B_m \tag{5-37}$$

Integer constraints:

$$Y_j = \begin{cases} 1, & \text{if DC } j \in J \text{ is open} \\ 0, & \text{if not} \end{cases} \tag{5-38}$$

$$V_{sj} = \begin{cases} 1, & \text{if path } k \in P_s \text{ is operating out of processing} s \in S \\ 0, & \text{if not} \end{cases} \tag{5-39}$$

$$L_{ji} = \begin{cases} 1, & \text{if path } k \in P_j \text{ is operating out of processing} j \in J \\ 0, & \text{if not} \end{cases} \tag{5-40}$$

$$T_n = \begin{cases} 1, & \text{if truck } n \in T_n \text{ is selected to transport the products} \\ 0, & \text{if not} \end{cases} \tag{5-41}$$

$$X_s = \begin{cases} 1, & \text{if processing plant s} \in S \text{ is open} \\ 0, & \text{if not} \end{cases} \tag{5-42}$$

Non-negativity constraints:

$$Q_{sj} \geq 0 \quad \text{Quantity shipped from precessing plant} s \in S \text{ to DC } j \in J \tag{5-43}$$

$$Q_{ji} \geq 0 \quad \text{Quantity shipped from precessing DC} j \in J \text{ to retailer } i \in I \tag{5-44}$$

Connections between retailers, objective function components and constraints related to them are excluded in the above model, as Phase-I doesn’t consider connections between retailers.

If the phases of the LRP are solved separately there is a risk of sub-optimal solutions and not reaching a universal optimal set of solutions for the main problem (Hassanzadeh et al. 2009). After executing Phase-I, Phase-II can be formed and solved based on each selected result obtained from Phase-I. Phase-II is designed to find the optimised vehicle routes connecting the served retailers to the un-served retailer from the Phase-I. Figure 5.7 shows the scope of the Phase-II.

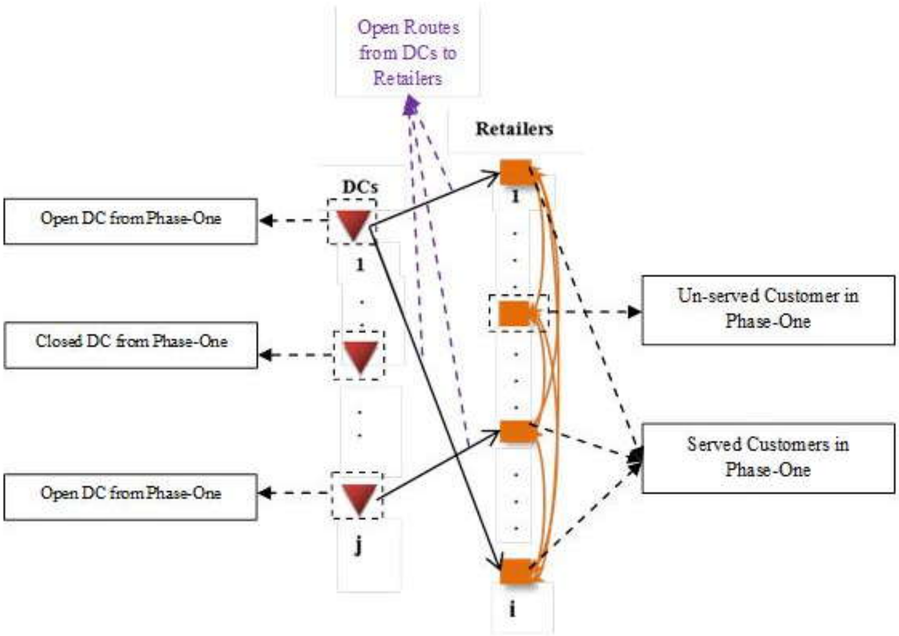


Figure 5.7 Scope of the Phase-II

The retailers are not supply points. Therefore the DCs and the routes connecting them to the served retailers from Phase-I are included in Phase-II. This is the link for connecting the two phases in order to reach to a final optimal solution for the three-layer MO-LRP. Phase-II of the solution approach is presented in the next section.

5.4.2. Phase-II of the solution approach

minimise $$\sum_{j\in J}\sum_{i\in I} u_{L_{ji}} p_{L_{ji}} L_{ji} + \sum_{i\in I}\sum_{i\in I} u_{O_{ii}} p_{O_{ii}} O_{ii} \qquad (5\text{-}45)$$

minimise $$\sum_{s\in S}\sum_{j\in J} u_{L_{ji}} c_{L_{ji}} L_{ji} + \sum_{j\in J}\sum_{i\in I} u_{O_{ii}} c_{O_{ii}} O_{ii} \qquad (5\text{-}46)$$

subject to:

$$\sum_{i\in I}\sum_{i\in I} O_{ii} = 1 \qquad (5\text{-}47)$$

$$\sum_{j\in J}\sum_{i\in I} d_{ji} L_{ji} + d_{ii} O_{ii} \le \tau_k \qquad (5\text{-}48)$$

$$\sum_{i\in I}\sum_{i\in I}O_{ii}\geq 1 \tag{5-49}$$

$$\sum_{i\in I}O_{ii}-\sum_{i\in I}O_{ii}=0 \tag{5-50}$$

$$\sum_{i\in I}\sum_{i\in I}O_{ii}\leq 1 \tag{5-51}$$

$$\sum_{j\in J}Q_{ji}-\sum_{i\in I}r_iY_j=0 \tag{5-52}$$

$$\sum_{i\in I}Q_{ii}-r_iY_j\leq 0 \tag{5-53}$$

$$\sum_{j\in J}L_{ji}+\sum_{i\in I}O_{ii}-Y_j\leq 0 \tag{5-54}$$

$$\sum_{m\in M}\sum_{n\in N}w_{mn}T_n\leq B_m \tag{5-55}$$

Integer constraints:

$$Y_j=\begin{cases}1, & \text{if DC } j\in J \text{ is open}\\ 0, & \text{if not}\end{cases} \tag{5-56}$$

$$L_{ji}=\begin{cases}1, & \text{if path } k\in P_j \text{ is operating out of processing } j\in J\\ 0, & \text{if not}\end{cases} \tag{5-57}$$

$$O_{ii}=\begin{cases}1, & \text{if path } k\in P_i \text{ is operating out of retailer } i\in I\\ 0, & \text{if not}\end{cases} \tag{5-58}$$

$$T_n=\begin{cases}1, & \text{if truck } n\in T_n \text{ is selected to transport the products}\\ 0, & \text{if not}\end{cases} \tag{5-59}$$

Non-negativity constraints:

$$Q_{ji}\geq 0 \quad \text{Quantity shipped from precessing DC } j\in J \text{ to retailer } i\in I \tag{5-60}$$

$$Q_{ii}\geq 0 \quad \text{Quantity shipped from precessing retailer } i\in I \text{ to retailer } i\in I \tag{5-61}$$

Phase-II is responsible to make connection among retailers. Two components from Phase-I are included in Phase-II:

- Open DCs
- Vehicle routes connecting open DCs to served retailers

5.5. Validation of the three-layer MO-LRP – the case of an Irish dairy SC network

A set of data, as indicated in Box 5.2, is required to run the generic three-layer MO-LRP and design a three-layer SC network.

Box 5.2 Required set of data for the three-layer MO-LRP

a. Number of plants, number of DCs and number of retailers

b. Geographical location of plants, DCs, and retailers in order to calculate the distances between each node in the SC

c. Fixed cost of:
- Operating plants
- Operating DCs

d. Variable cost of:
- Providing DCs with one unit of product at each plant
- Providing the retailer with one unit of product at each DC

e. Vehicle routing-related costs:
- Driver's wage
- Cost of fuel per litre

f. Capacity at each DC and demand at each retailer location

g. Distance between plants and DCs, and DCs and retailers

h. CO_2 emission from transportation at each route from one vehicle

i. AHP-related data:
- DM's pair-wise matrix regarding the truck types based on CO_2 emission and costs
- The limits (maximum allowed) for CO_2 emission and costs (RHS matrix).

In order to evaluate the functionality of the three-layer MO-LRP a case is considered based on an Irish dairy SC network. The structure of the three-layer SC network is validated by the means of:

a) discussions with a consultant to a number of SC companies in Ireland, one of which is an Irish based multinational dairy company,

b) interviewing experts from another two major dairy companies in Ireland. There are only a small number of main players in the dairy market in Ireland and these have been identified and a questionnaire has been prepared to gather information about the structure of the demand side of their SCs in Ireland. The questionnaire is presented in Appendix C.1, and

c) using company profiles, technical reports from dairy companies, research output on dairy SCs, and relevant documented material.

This three-layer MO-LRP consists of two main facilities on the demand side of the supply chain, viz. plants and DCs. Plants are assumed 'open' therefore the facility location decision is concerned with DCs only. In order to serve the retailers, three sets of vehicle routes are considered, vehicle routes connecting plants to DCs, DCs to retailers, and retailers to retailers. The details of the ‘case of the three-layer dairy SC network in the east of Ireland’ is illustrated in the next sections.

5.5.1. Number and geographical location of plants, DCs and retailers

Table 5.3 presents the number and the geographical location of all the nodes of the of the supply chain network. ‘Node’ in here refers to plants, DCs and retailers. Geographic locations of plants are the real locations of the two main processing plants owned by the dairy company on which the case is considered.

Table 5.3 Number and location of plants, DCs and retailers

	Nodes	Number of nodes	Geographical locations
Facilities	Plants	2	Drogheda Ballitore
	DCs	6	Dundalk, Drogheda, Dublin City, Tullamore, Bray, Waterford
Retailers	Retailers	22	Drogheda, Dundalk, Navan, Tullamore, Naas, Newbridge, Leixlip, Port Laoise, Bray, Arklow, Wicklow, Greystones, Clonmel, Waterford, Tramore, Kilkenny, Wexford, Ennoscorthy, Dublin City, Dun Laogharie/Rathdawn, Fingal, South Dublin

In total a set of six DCs are considered. The distance between any two of these DCs ranges from 30 km to 100 km. They are considered to be geographically located in the east of Ireland. Retailers are located in 15 counties in the east of Ireland. They are considered to be located in centres with populations of 10,000+ in these counties. The population data is adapted from Irish Central Statistics Organisation CSO (2012) official reports. The exact location of the DCs and retailers are presented in Table 5.3.

5.5.2. Fixed and variable costs for plants and DCs

Fixed and variable costs for plants and DCs are considered in the second objective function (5-4). These two types of costs for each plant and each DC are presented in Tables 5.4 and 5.5 respectively. The unit of product is a 2 litre bottle of milk.

Table 5.4 Fixed and variable costs at plants

Costs Plants	Fixed Costs (€)	Variable Costs (€ per unit of product)
Plant I	1,500	0.20
Plant II	2,000	0.24

Table 5.5 Fixed and variable costs at DCs

DC **Cost (€)**	**DC a** Dundalk	**DC b** Drogheda	**DC c** Dublin City	**DC d** Tullamore	**DC e** Bray	**DC f** Waterford
Fixed (f_j)	200	250	250	250	100	250
Variable per unit (v_j)	0.02	0.03	0.03	0.03	0.01	0.04

5.5.3. Capacity of DCs and demand at retailer locations

Capacities of DCs are considered in the range of 700,000 to 1,000,000 units of products. Table 5.6 depicts the capacity at each DC location.

Table 5.6 Capacity of DCs

DCs	**Capacity** (unit)
a. Dundalk	800,000
b. Drogheda	1,000,000
c. Dublin City	1,000,000
d. Tullamore	1,000,000
e. Bray	700,000
f. Waterford	1,000,000

For four of the DCs the capacities are equally considered as 1,000,000 units of product. Dundalk and Bray are the two DCs which are located the shortest distance from the closet DC to them (Drogheda and Dublin City respectively). Therefore the capacities are considered less than 1,000,000.

The demand at retailer locations is adapted from Table 4.5.

5.5.4. Distance between plants and DCs, and DCs and retailers

A variety of speeds on different roads is considered in the model as a factor affecting the green objective function. The speed limits (Table 4.6) defined in 'Road Traffic Act 2004' is currently being enforced in Ireland. An average of the speed is considered in this case study. Table 5.7 presents the distances between plants and DCs divided by the type of road:

Table 5.7 Total distances between plants and DCs; divided by the type of road

Plant ($s \in S$)	***I*** ***Drogheda***					***II*** ***Ballitore***				
DC ($j \in J$)	**Total Distance** (km)	**Distance in each Type of Road** (average) (km)				Total **Distance** (km)	**Distance in each Type of Road** (average) (km)			
		Motorway	National Route	Regional and Local Roads	Built Up Areas		Motorway	National Route	Regional and Local Roads	Built Up Areas
a. Dundalk	36.4	36.4				146.0	89.7	56.3		

b. Drogheda	2.0				2.0	117.0	61.7	55.3		
c. Dublin City	52.4	52.4				59.8		59.8		
d. Tullamore	110.0		110.0			62.5			62.5	
e. Bray	74.6	74.6				71.4		71.4		
f. Waterford	219.0	219.0				105.0	105.0			

Table C.1 (Appendix C) depicts the distances between plants and retailers and Table C.2 present the distances between retailers by the type of roads.

5.5.5. CO$_2$ emission and costs of serving each route

CO$_2$ emitted from transportation is calculated using formulae (5-2) and (5-3) The average CO2 emission caused from transporting products thorough the three-layer SC network is presented in Tables 5.8, 5.9 and B.3. Estimations account for one Diesel operated refrigerated HGV in each route.

Table 5.8 CO$_2$ emission and costs of serving each between plants and DCs

Plant ($s \in S$)	***I Drogheda***		***II Ballitore***	
DC ($j \in J$)	CO2 emission from fuel burnt(kg) p_{sj}	Cost of Serving Route(€) c_{sk}	CO2 emission from fuel burnt (kg) p_{sj}	Cost of Serving Route(€) c_{sk}
a. Dundalk	33.63	23.68	108.11	77.70
b. Drogheda	1.85	1.84	108.11	77.70
c. Dublin City	48.42	34.09	55.25	40.62
d. Tullamore	101.64	74.72	57.75	47.84
e. Bray	68.93	48.53	65.97	48.50
f. Waterford	202.36	142.46	97.02	68.30

5.5.6. Cost of serving each route

In order to calculate the total cost of serving each route for the demand side of the three-layer dairy SC, formulas 5-7, 5-8 and 5-9 have been used. Average price of fuel in April/May 2012 has been 1.53€/lit and the average wage of a HGV drive at the same period of time has been 11.50 €/hr (Part II, Chapter Three). Tables 5.9, 5.10 and C.3 (Appendix C) depict the average Cost of serving routes and transporting products from plants to DCs, DCs to retailers, and in between retailers respectively. CO$_2$ and cost estimations account for one refrigerated HGV in each route.

Table 5.9 CO$_2$ emission estimations and costs of serving route from DCs to retailers

		DC to Customer																					
		1.Drogheda	**2.Dundalk**	**3.Navan**	**4.Tullamore**	**5.Naas**	**6.Newbridge**	**7.Leixlip**	**8.Port Laoise**	**9.Bray**	**10.Arklow**	**11.Wicklow**	**12.Greystones**	**13.Clonmel**	**14.Waterford**	**15.Tramore**	**16.Kilkenny**	**17.Wexford**	**18.Enniscorthy**	**19.Dublin City**	**20.Dun Laogha-**	**21.Fingal**	**22.South Dublin**
a. Dundalk	*Average CO2 Emission from Fuel Burnt* p_{jk}	30	2	47	116	99	118	83	153	108	153	145	116	236	229	241	200	209	197	75	85	64	92
	Cost of Serving Path (€) c_{jk}	26	2	33	86	58	83	53	108	76	108	98	82	166	161	168	140	147	129	53	60	45	65
b. Drogheda	*CO2 Emission from Fuel Burnt* p_{jk}	2	31	24	102	79	83	44	132	68	118	112	76	209	202	214	155	182	137	46	58	27	57
	Cost of Serving Path (€) c_{jk}	2	26	20	72	56	61	32	93	48	74	79	54	147	143	151	100	128	125	28	41	22	47
c. Dublin City	*CO2 Emission from Fuel Burnt* p_{jk}	46	75	47	92	33	46	16	87	20	65	58	28	164	151	163	113	121	109	2	13	19	19
	Cost of Serving Path (€) c_{jk}	28	53	28	65	25	32	12	61	14	48	48	21	115	97	105	71	72	80	2	10	14	14
d. Tullamore	*CO2 Emission from Fuel Burnt* p_{jk}	101	116	77	2	59	52	80	31	108	122	108	115	114	128	140	76	134	114	92	103	106	79
	Cost of Serving Path (€) c_{jk}	72	86	54	2	49	43	56	23	79	90	79	85	84	80	74	56	99	84	65	75	75	50
e. Bray	*CO2 Emission from Fuel Burnt* p_{jk}	68	108	70	108	44	56	34	96	2	47	40	6	173	167	157	123	102	90	20	9	39	28
	Cost of Serving Path (€) c_{jk}	48	76	49	79	26	37	24	68	2	34	33	5	122	118	115	60	78	55	14	7	29	17
f. Waterford	*CO2 Emission from Fuel Burnt* p_{jk}	202	229	177	128	123	116	147	98	167	96	113	101	43	2	11	48	56	51	151	150	173	139
	Cost of Serving Path (€) c_{jk}	143	161	105	80	86	82	103	61	118	71	93	71	31	2	9	34	41	38	97	94	122	88

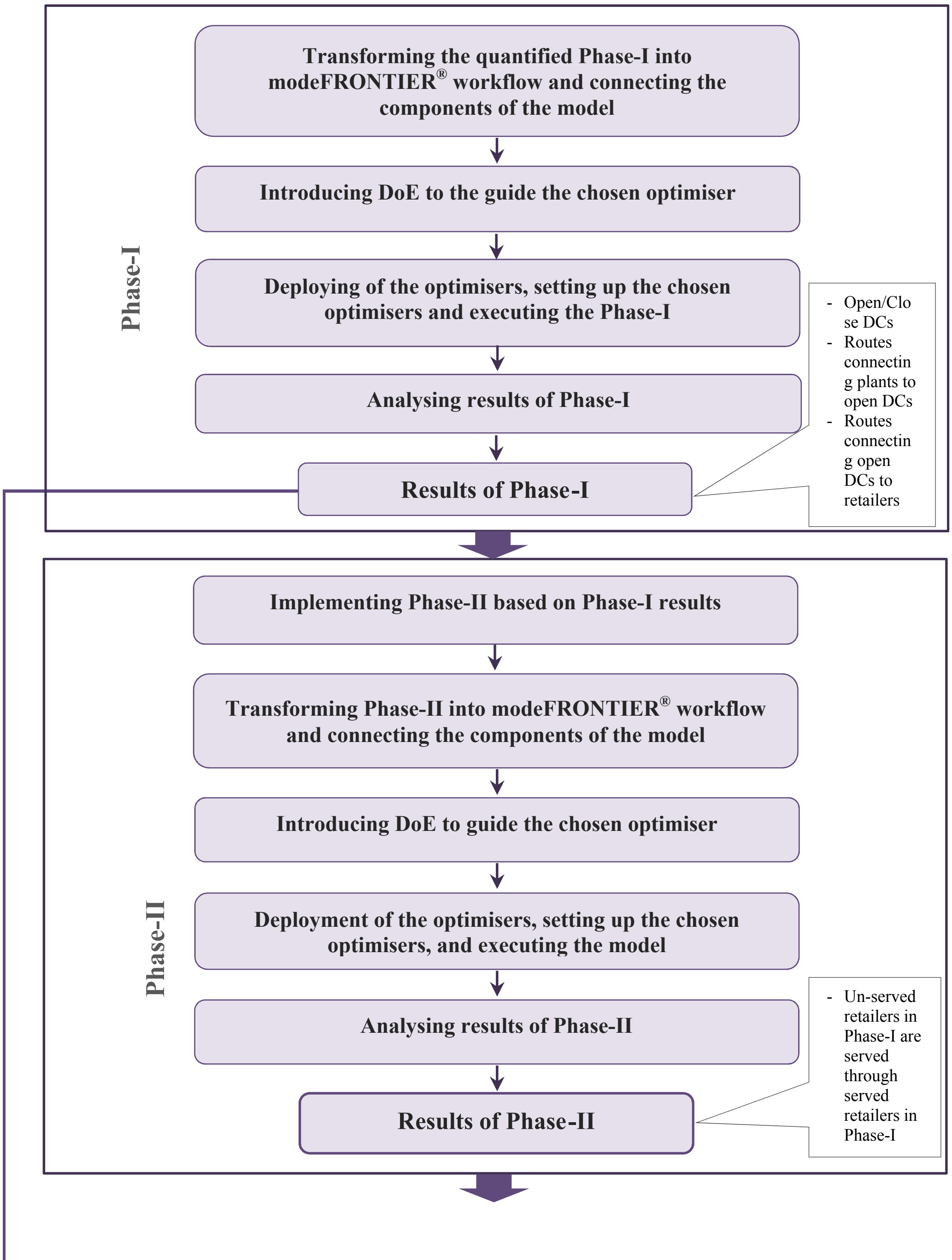
5.5.7. Green constraint data

The AHP constraint considers three types of trucks as preferred by the DM for transporting the products. Different levels of CO$_2$ emission and costs are considered for each type of truck. DMs have been asked to compare these trucks types based on two attributes: CO$_2$ emission and cost. The outcome of this comparison is a pair-wise comparison matrix which is not related or dependant on the number of layers in the SC network.

Therefore, Tables 4.6, 4.7 and 4.8 depict all the data needed for the AHP constraint in the three-layer MO-LRP.

5.6. Solution Steps

Considering the efficiency of modeFRONTIER® in implementing the two-layer MO-LRP, the same platform is considered for implementing the three-layer MO-LRP. The two-phased solution method is developed using modeFRONTIER®. A schematic illustration of the consecutive steps of the solution approach is presented in Figure 5.8:



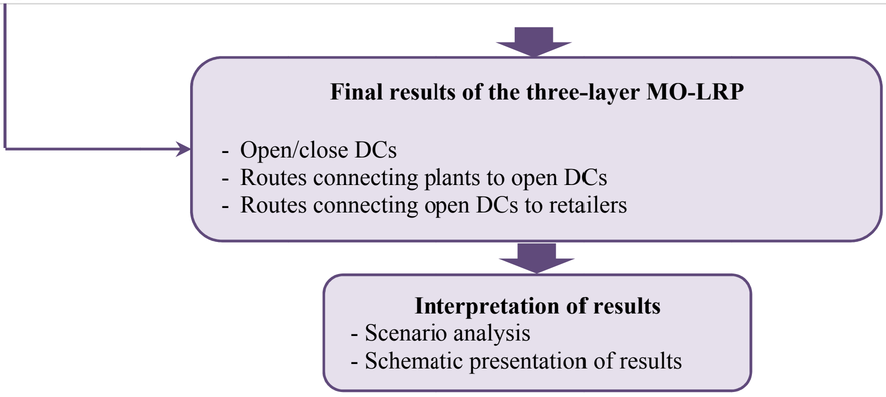


Figure 5.8 The process of implementing the three-layer MO-LRP using mode-FRONTIER®

5.6.1. Transforming the three-layer MO-LRP into modeFRONTIER®

Phase-I and Phase-II of the three-layer MO-LRP are transformed into modeFRONTIER®'s workflow. The logical designs of the two phases in modeFRONTIER® are presented disparately in Figures 5.9 and 5.10.

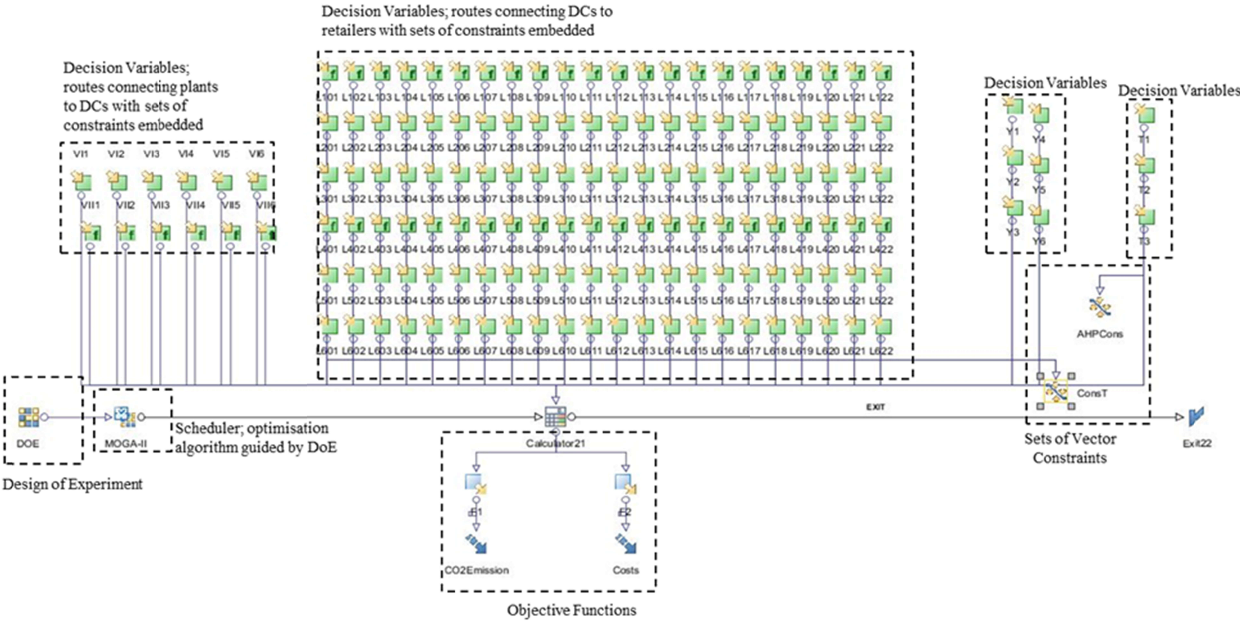


Figure 5.9 Phase-I of the three-layer MO-LRP design in modeFRONTIER®

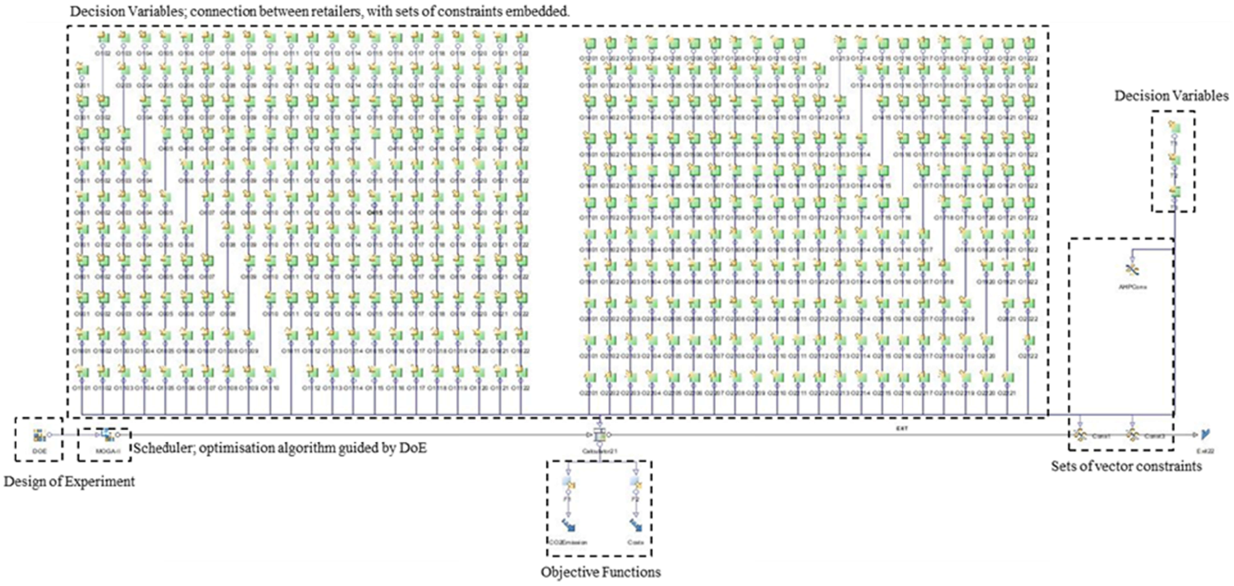


Figure 5.10 Phase-II of the three-layer MO-LRP design in modeFRONTIER®

The design shown in Figure 5.10 is a general presentation of Phase-II. Based on each result from Phase-I, Phase-II is modified and solved. Graphically the design looks the same for all optimisers in both phases. The mathematical details of Phase-I and Phase-II are all satisfied in this designed workflow using modeFRONTIER®. The setting of each optimiser in modeFRONTIER® for both phases of the solution approach is identical. Hence, in the next two sections the details of DoE setting, and then the optimiser settings are explained for both phases.

5.6.2. Introducing DoE to the chosen optimisers

DoE connects the main three-layer MO-LRP to the optimisers by generating the initial set of population for the optimisers. The initial population table consists of 50 designs. The initial 50 DoE guided designs consist of: (i) 10 design of experiment sequence, (ii) 10 random, (iii) 10 sobol, (iv) 10 uniform Latin hypercube, (v) 9 incremental space filler and (vi) 1 constraint satisfaction designs. This combination of designs in initial table works efficiently for the three-layer MO-LRP.

5.6.3. Deployment of the Optimisers

Considering the fact that the nature of the two-layer and three-layer MO-LRPs are mathematically the same, the same optimisers that were efficient in solving the two-layer MO-LRP are deployed to solve the three-layer MO-LRP. MOGA-II, NSGA-II (GA-based optimisers) and MOPSO (PS-based optimiser) proved to be more efficient in solving the two-layer MO-LRP in chapter three. These optimisers are considered to solve the three-layer MO-LRP. In the next section the set up details of the chosen optimisers are presented and explained.

5.6.4. Setting-up the Chosen Optimisers

Each one of the optimisers is set up separately. Chosen optimisers have disparate requirements and distinctive specifications. Therefore they have different set up details. Table 5.10 presents the set up details of all three optimisers:

Table 5.10 Set up details for optimisers in modeFRONTIER®, identical for both phases

MOGA-II	NSGA-II	MOPSO
Number of Generations: 250 Initial Population: 50 Probability of Crossover: 0.5 Type of Crossover: Directional Probability of Mutation: 0.1 Type of Mutation: DNA String DNA String Mutation Ratio: 0.05 Elitism: Enabled Random Generator Seed: 1	Number of Generations: 50 Initial Population: 50 Crossover Probability: 0.9 Mutation Probability for Real-Coded Vectors: 1.0 Mutation Probability for Binary Strings: 1.0 Distribution Index for Real-Coded Crossover: 20.0 Distribution Index for Real-Coded Mutation: 20.0	Number of Generations: 250 Initial Population: 50 Turbulence: 0.2 Random Generator Seed: 1

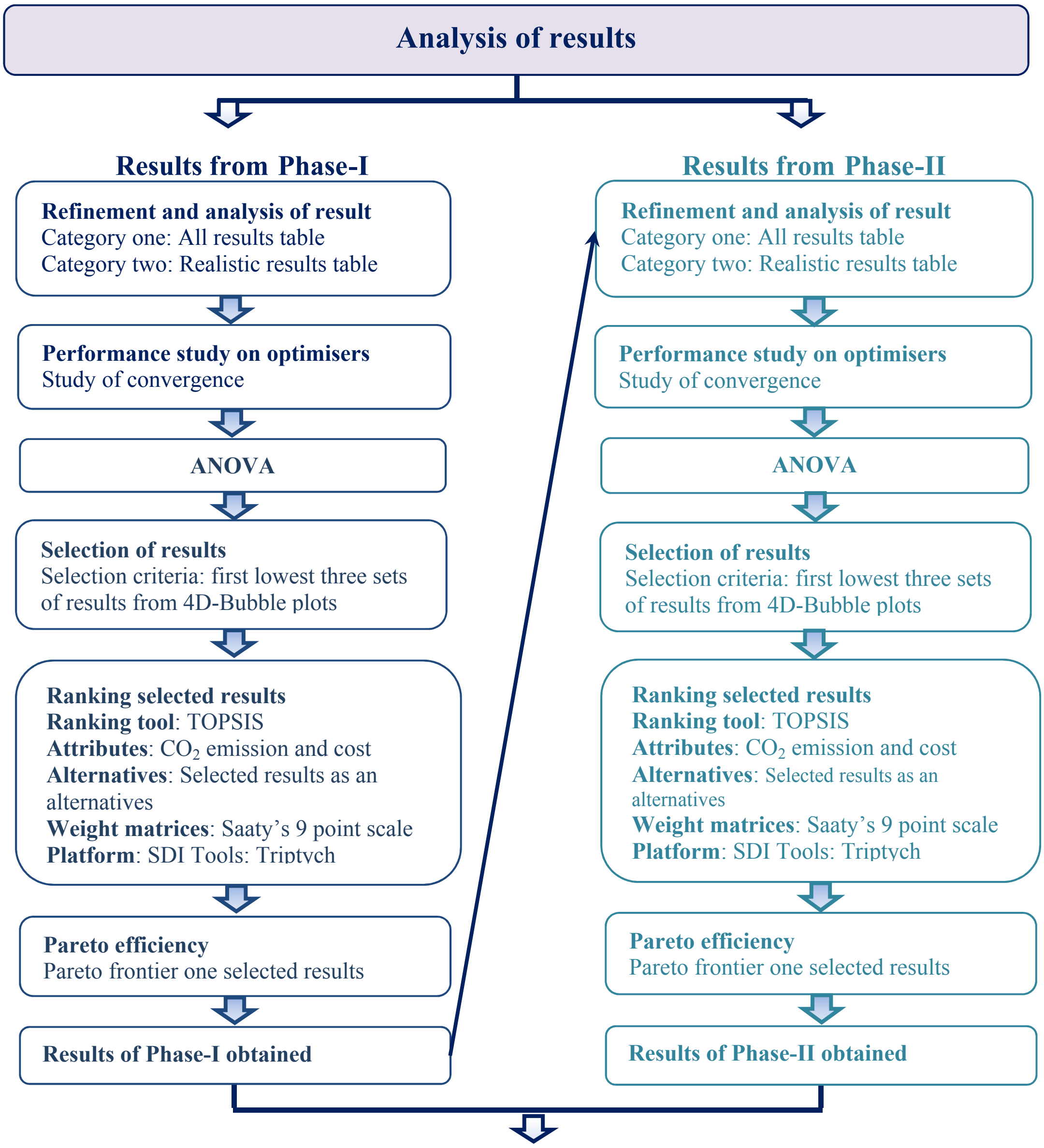
In order to compare the performance of the optimisers, two main details of set up have been kept the same initially for all optimisers; population of initial designs table and number of generations. The initial population table is generated by DoE identically.

The number of generations has been set at 250 initially for all three optimisers. The convergence of optimisers and the number of realistic results were the main criteria in choosing the number of generations. For MOGA-II and MOSPSO, 250 generations generates a larger feasible solution area. The convergence for NSGA-II shows that this optimiser converges in 50 generations and after the 50th generation the optimiser is forced to find more solutions. For this reason, the number of generations in NSGA-II is set to 50 generations. The results are categorised, analysed and presented in Part-III.

Part III: Results and Outcomes

5.7. Analysis of Results

The three-layer MO-LRP is executed in a two phased inter-linked approach. Phase-I is solved first. Based on the results from Phase-I, Phase-II is modified and then solved. The final results are obtained when both phases are complete. The process of analysing results in the two phased approach is presented in Figure 5.11.



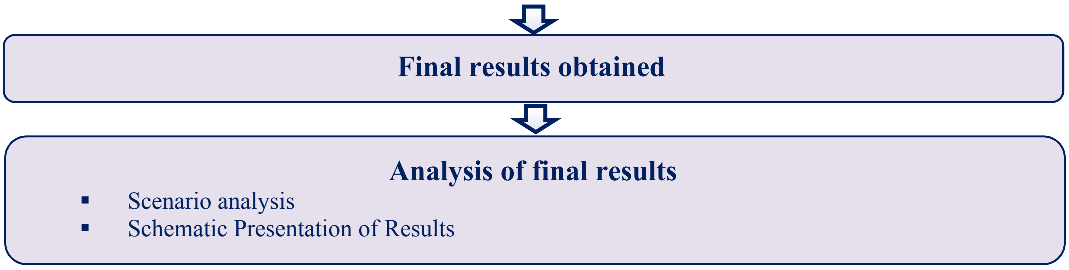


Figure 5.11 The analysis of the results from the three-layer MO-LRP

5.7.1. Phase-I

The results obtained from Phase-I of the solution approach for the three-layer MO-LRP, are presented in this section. In order to analyse the results: (i) results are refined and a set of realistic results are identified, (ii) a performance study is conducted on each optimiser, (iii) Analysis of Variance (ANOVA) test is performed to compare means of multiple groups for the optimised data, (iv) a set of results are selected for further analysis, (v) selected results are ranked using TOPSIS, and finally (vi) Pareto efficiency is examined on the selected designs.

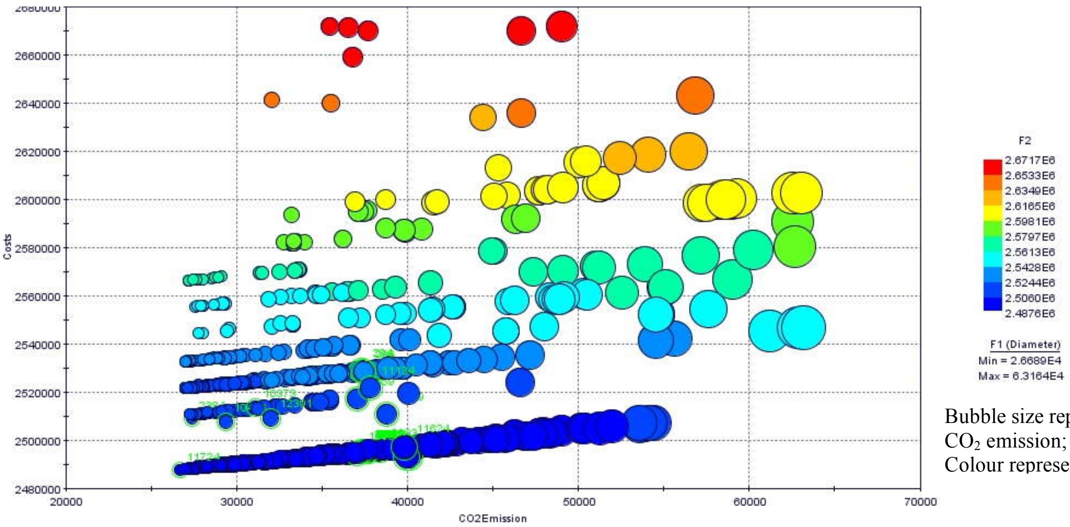
All results offered by the three optimisers are real feasible results. A statistical summary on these results is presented in Table 5.11. These statistical summaries assist in analysing: (a) the total results table which consists of all feasible real results obtained by each optimiser, (b) the refined realistic results table which consists of realistic and non-identical results, and (c) the selected results table which consists of selected results from the three lowest sets of feasible results from the 4D Bubble plots.

Table 5.11 Statistical summary on optimisers' results

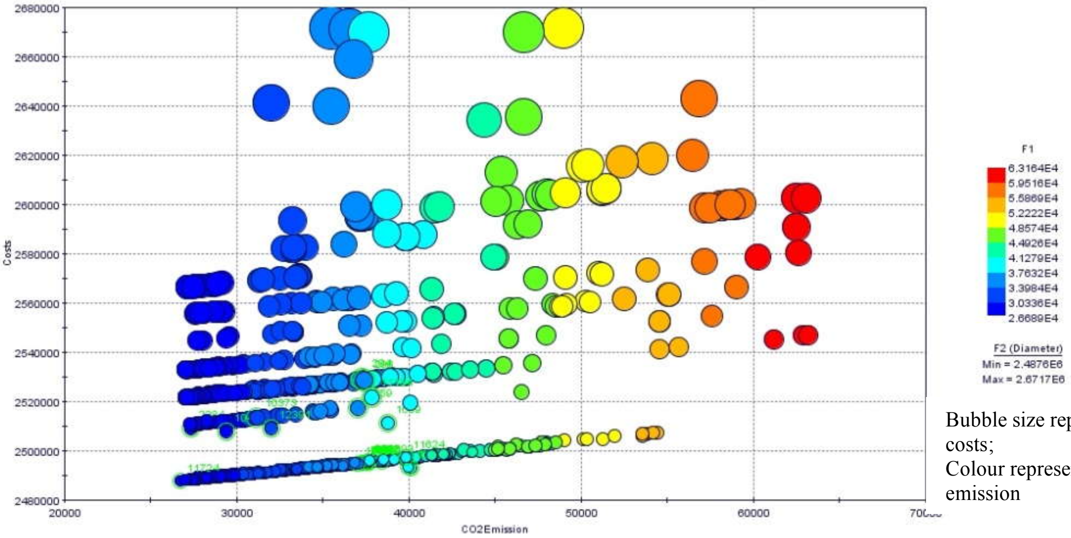
Type of results on optimisers		Number of real feasible results (alternatives)	CO_2 emission value kg (objective function *I*)		Costs value € (objective function *II*)	
			Min	*Max*	*Min*	*Max*
MOGA-II	**Total results**	12,500	26,689	63,164	2,487,644	2,671,661
	Refined realistic results	412	26,689	45,179	2,487,644	2,671,149
	Selected results	20	26,689	37,613	2,487,644	2,594,149
MOPSO	**Total results**	12,500	25,687	61,188	2,487,052	2,674,237
	Refined realistic results	528	25,687	40,550	2,487,052	2,501,195
	Selected results	20	25,687	46,663	2,487,052	2,588,256
NSGA-II	**Total results**	2,500	21,669	49,578	2,480,034	2,516,631
	Refined realistic results	184	21,699	38,253	2,480,034	2,501,134
	Selected results	20	21,699	27,445	2,480,034	2,487887

As presented in Table 5.11, the minimum value for both CO_2 emissions and costs is obtained by NSGA-II in 50 generations. This does not necessarily yield a minimum value for the total costs.

The MOGA-II, MOPSO and NSGA-II optimisers generate the feasible space of solutions by using a DoE-guided solution approach. Figures 5.12, 5.13 and 5.14 illustrate the feasible real solution space for MOGA-II, MOPSO, and NSGA-II respectively. In these 4D plots, the colour and diameter of bubbles are representatives for values of the objective functions; which are explained in the plot legend. Colours range from dark blue to red; lowest to highest value of objective function respectively. And diameter of bubbles ranges from small to large, lowest to highest value of objective function respectively.

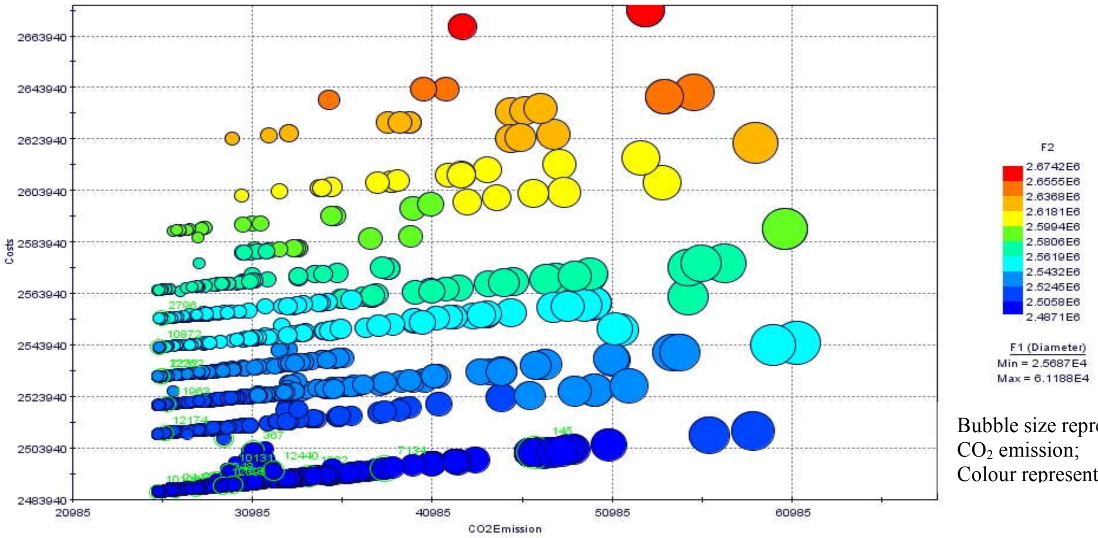


Bubble size represents CO_2 emission;
Colour represents costs

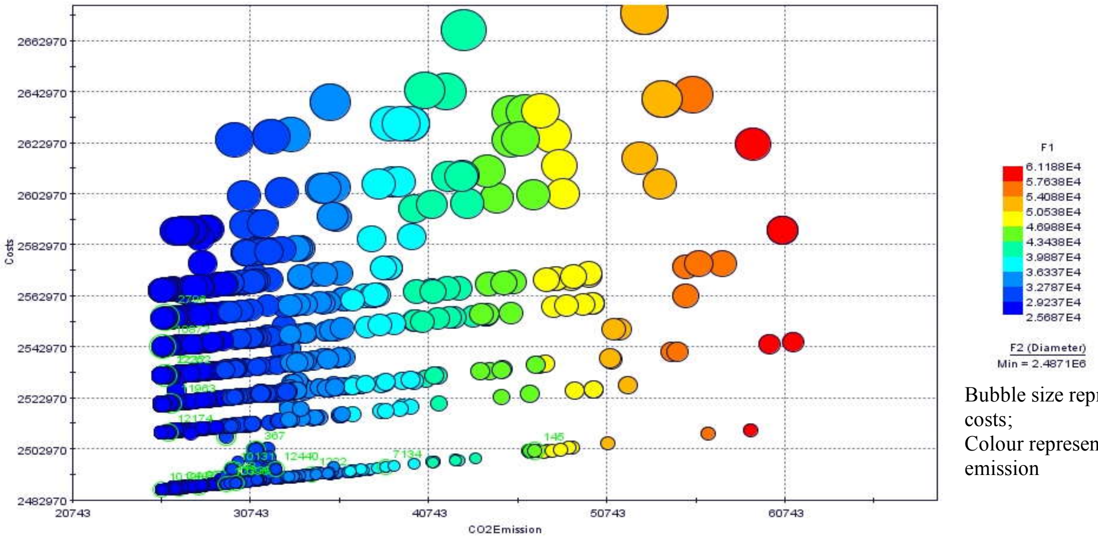


Bubble size represents costs;
Colour represents CO_2 emission

Figure 5.12 Feasible real solution space w.r.t. costs and CO_2 emission for MOGA-II optimiser



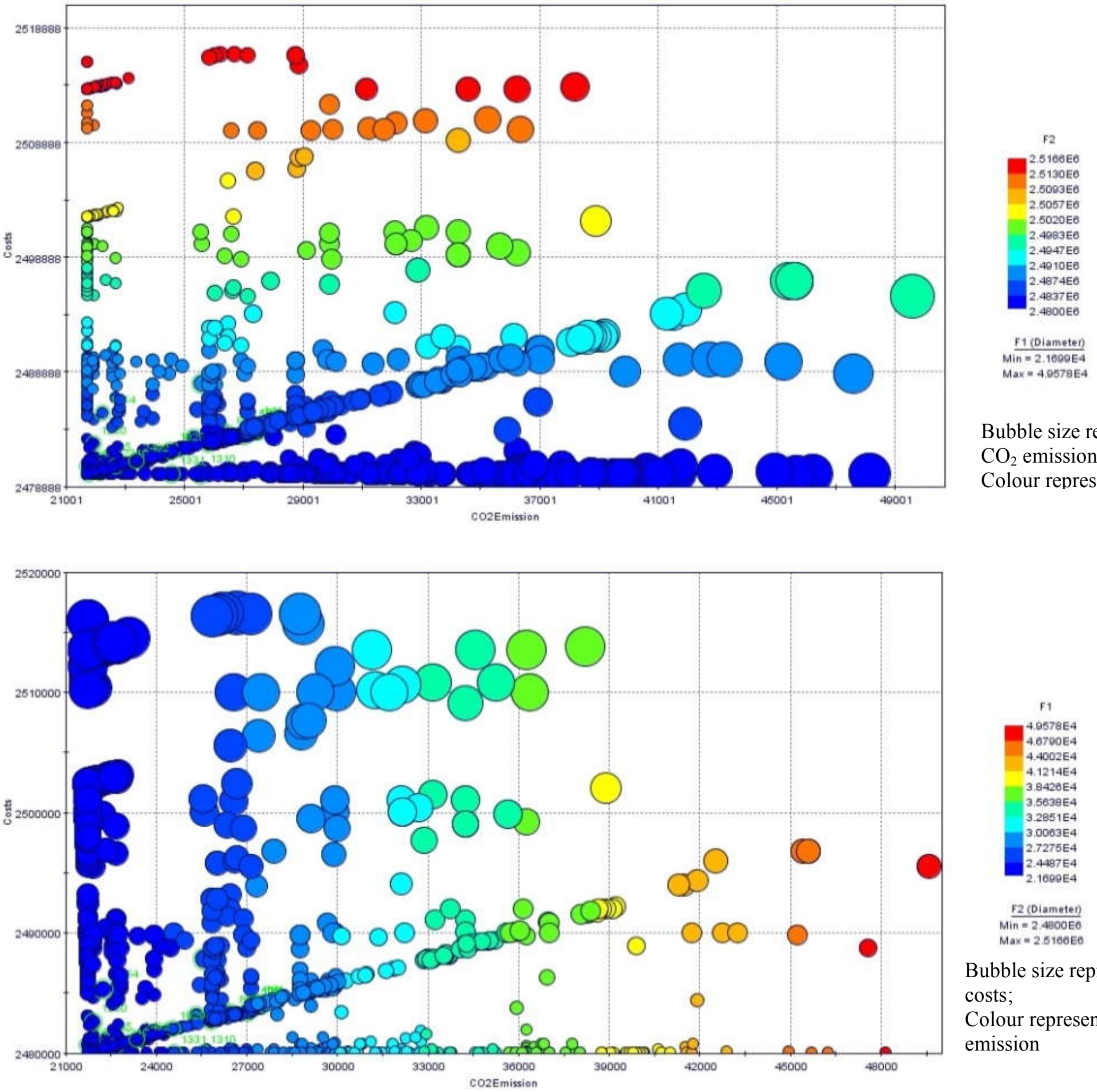
Bubble size represents CO$_2$ emission;
Colour represents costs



Bubble size represents costs;
Colour represents CO$_2$ emission

a. Bubble size represents cost, colour represents CO$_2$ emission

Figure 5.13 Feasible real solution space w.r.t. Costs and CO$_2$ emission for MOPSO optimiser



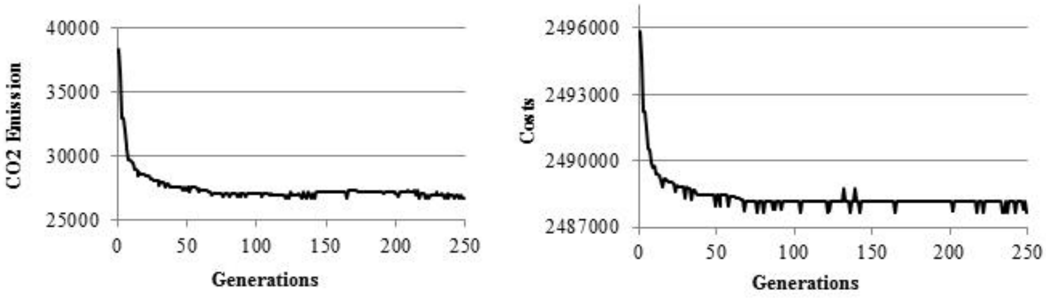
Bubble size represents CO_2 emission;
Colour represents costs

Bubble size represents costs;
Colour represents CO_2 emission

Figure 5.14 Feasible real solution space w.r.t. costs and CO_2 emission for NSGA-II optimiser

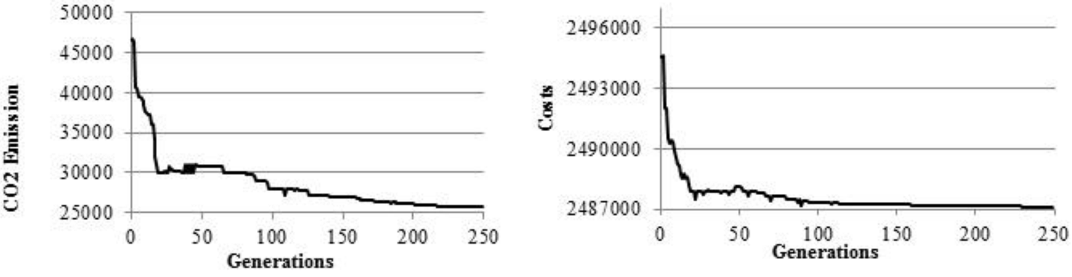
5.7.1.1. Performance study on optimisers in Phase-I

The performance of the optimisers regarding their convergence is investigated through convergence plots. Figure 5.15, 5.16 and 5.17 present the convergence plots for MOGA-II, MOPSO and NSGA-II respectively with regard to the objective functions.



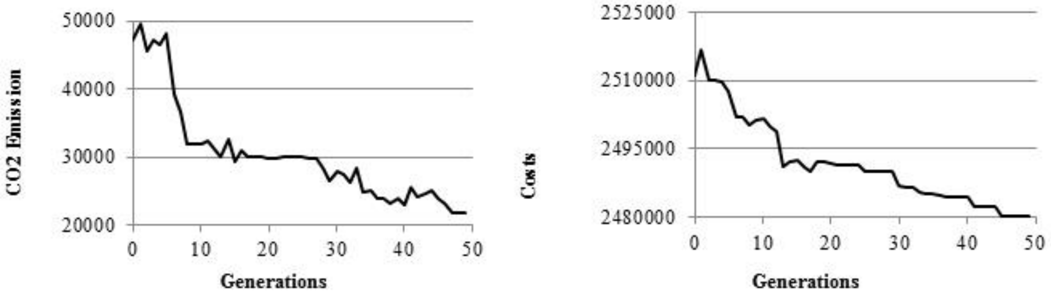
a. Convergence w.r.t CO_2 emission b. Convergence w.r.t costs

Figure 5.15 Convergence of MOGA-II w.r.t objective functions



a. Convergence w.r.t CO_2 emission b. Convergence w.r.t costs

Figure 5.16 Convergence of MOPSO w.r.t objective functions



a. Convergence w.r.t CO_2 emission b. Convergence w.r.t costs

Figure 5.17 Convergence of NSGA-II w.r.t objective functions

It can be seen from these that all optimisers are converging in a steady manner, with MOGA-II and MOPSO are converging in 250 generations and NSGA-II in 50 generations.

5.7.1.2. ANOVA for Phase-I

One-way ANOVA is performed for both the total CO_2 emissions and total costs of transportation to compare the means of multiple groups for the optimised data. Table 5.11 depicts the ANOVA statistics used to test the null-hypothesis (Walpole et al. 2006). Tables 5.12 and 5.13 present the ANOVA results for all three optimisers with respect to CO_2 emissions and costs respectively:

Table 5.12 ANOVA for CO_2 emission on the all results

Optimiser	Source of Variation	SS	Df	MS	F-ratio	p-value
MOGA-II	Between groups	6.1885E11	1.9900E2	3.1098E9	1.6694E1	0.035
	Within groups	4.2846E11	2.3000E3	1.8629E8	—	—
	Total	1.0473E12	2.4990E3			
NSGA-II	Between groups	1.0984E10	5.4000E1	2.0341E8	1.2356E1	0.088
	Within groups	4.0249E10	2.4450E3	1.6462E7	—	—
	Total	5.1233E10	2.4990E3			
MOPSO	Between groups	7.7922E10	2.5400E2	3.0678E8	1.4877E2	0.095
	Within groups	2.5250E10	1.2245E4	2.0621E6	—	—
	Total	1.0317E11	1.2499E4			

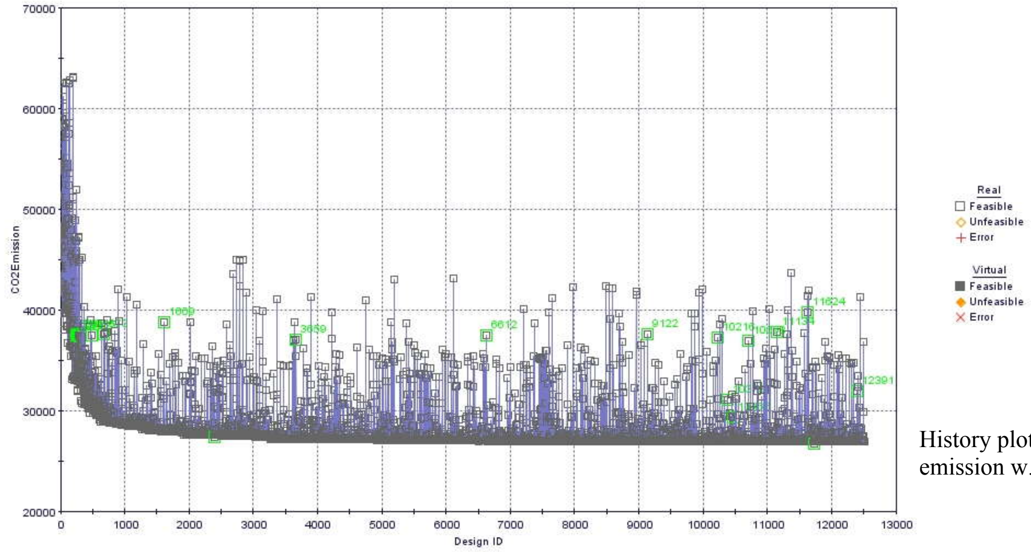
Table 5.13 ANOVA for costs on the all results

Optimiser	Source of Variation	SS	Df	MS	F-ratio	p-value
MOGA-II	Between groups	6.5794E10	1.9900E2	3.3062E8	7.2896E1	0.058
	Within groups	1.0432E10	2.3000E3	4.5355E6	—	—
	Total	7.6226E10	2.4990E3			
NSGA-II	Between groups	1.0875E10	5.4000E1	2.0139E8	4.6771E0	0.158
	Within groups	1.0528E11	2.4450E3	4.3059E7	—	—
	Total	1.1615E11	2.4990E3			
MOPSO	Between groups	1.8805E12	2.5400E2	7.4035E9	3.8102E1	0.029
	Within groups	2.3793E12	1.2245E4	1.9431E8	—	—
	Total	4.2598E12	1.2499E4			

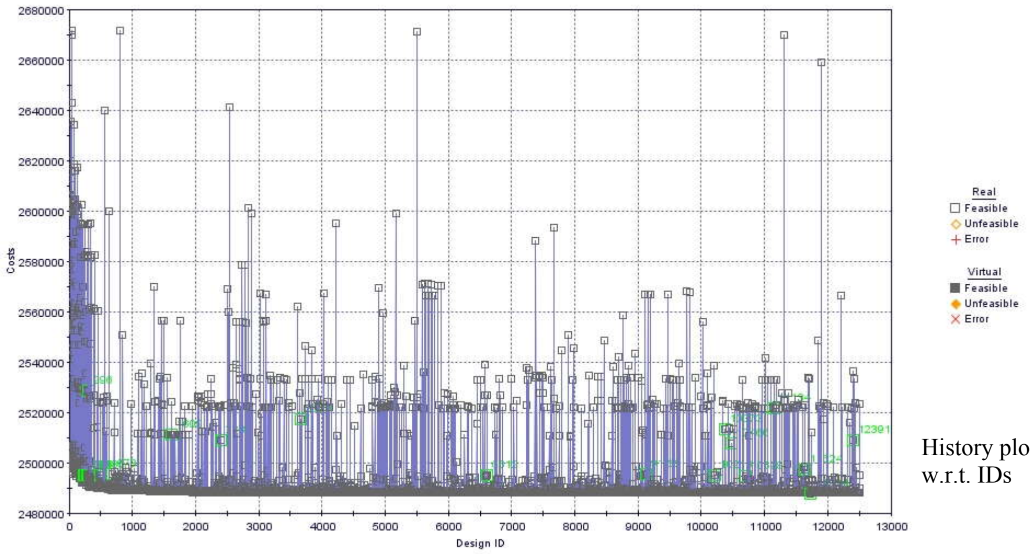
The most important assumption requested by ANOVA is that the standard deviations within each group are the same. It is found that Hartley and Bartlett's tests are both true. These two statistical tests verify that the standard deviations within each groups is the same, therefore the most important assumption requested by ANOVA is valid. It is noted that as the F-ratio increases, the p-value decreases.

5.7.1.3. Selection of Phase-I results

Within the feasible solution space, un-realistic and identical results are eliminated in order to find the refined realistic results. Statistical summary on refined realistic results with respect to all three optimisers is presented in Table 4.11. A set of 20 results from the refined realistic results are selected for further analysis. The selection process is the same process illustrated for the two-layer MO-LRP in Chapter Three. The first three shades of blue in Figures 5.12, 5.13 and 5.14 represent the lowest three sets of values for the objective functions. Therefore the selcted results, with respect to the objcetive function values, are selected from these three sets of results. A low value for one objective fucntion may not necessarily yield a low value for the other objective function and vice versa. The selected results are shown within the feasible solution spcae in Figures 5.18, 5.19 and 4.20 for MOGA-II, MOSPO, and NSGA-II respectively. The values for objective functions offered by optimisers are preseneted with reference to the Design ID of results. In the selection of the three-layer MO-LRP results, DMs' priorities are considered. Therefore in each set of the selected results at least one result represent extreme decision-making events.

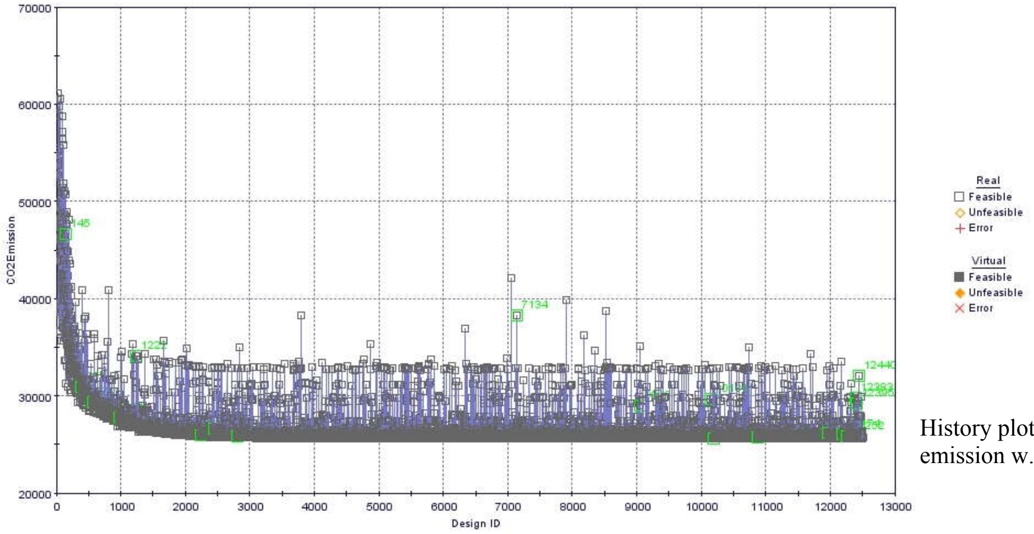


History plot on CO_2 emission w.r.t. IDs

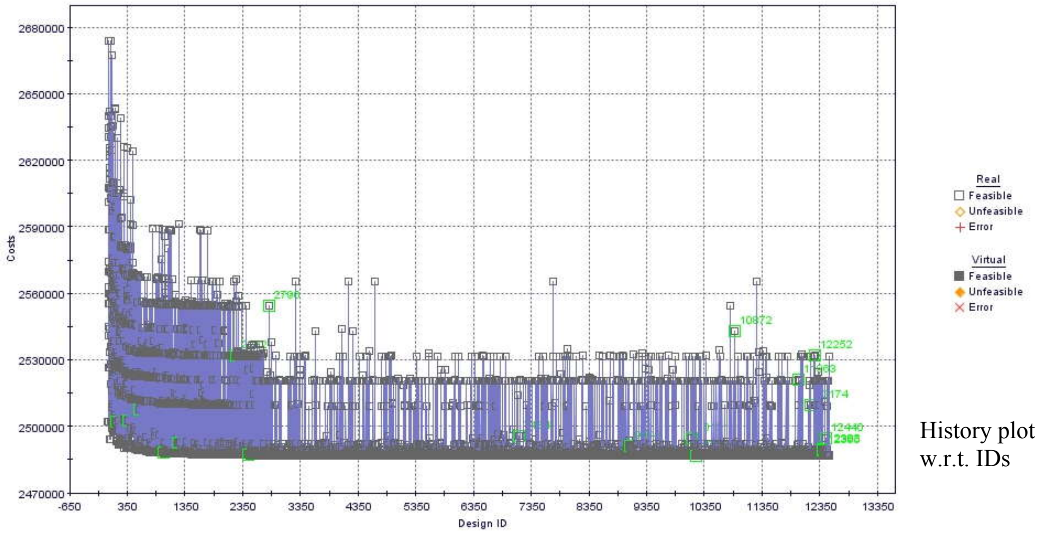


History plot on costs w.r.t. IDs

Figure 5.18 History of solution space w.r.t. CO_2 emission and costs for MOGA-II optimiser

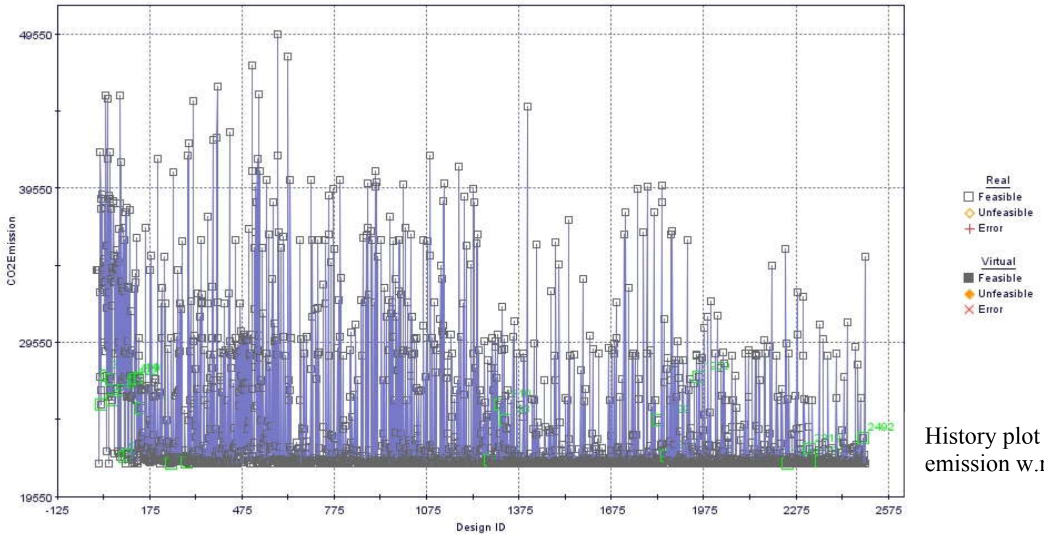


History plot on CO_2 emission w.r.t. IDs

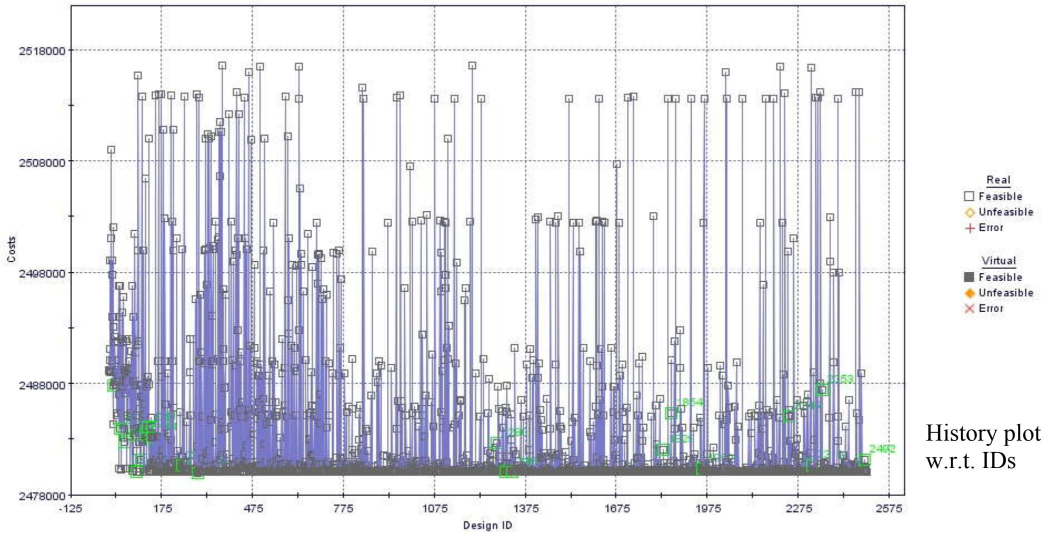


History plot on costs w.r.t. IDs

Figure 5.19 History of solution space w.r.t. CO_2 emission and costs for MOPSO optimiser



History plot on CO_2 emission w.r.t. IDs



History plot on costs w.r.t. IDs

Figure 5.20 History of solution space w.r.t. CO_2 emission and costs; NSGA-II optimiser

Selected results are ranked in order to prioritise the optimised results. The ranking process is explained in the following section.

5.7.1.4. Ranking selected results from Phase-I

After selecting sets of 20 results from MOGA-II, MOPSO and NSGA-II, these selected results are ranked using TOPSIS in order to prioritise the best results for differenet types of DMs. Nine weight matrices are defined for TOPSIS. Each one of these weight matrices represents a type of DM and by selecting all nine weight matrices from Saaty's nine-point scale (1977; 1978) all DMs are covered. The first three ranked results by TOPSIS using the weight matrix w_5 for the optimisers are presented in Table 5.14:

Table 5.14 First three ranked results w.r.t optimisers offered weight matrices w_5

	Rank	CO_2 emission	cost
MOGA-II	**1**	26,689	2,487,644
	2	27,358	2,509,288
	3	29,354	2,507,950
MOPSO	**1**	25,687	2,487,052
	2	26,689	2,487,644
	3	27,835	2,488,202
NSGA-II	**1**	21699	2480736
	2	21755	2480034
	3	22150	2480116

As shown in Table 5.14, the best result with regard to objective function values is offered by NSGA-II. In comparison, MOPSO is in the second best and MOGA-II the third optimiser.

5.7.1.5. Pareto efficiency for Phase-I

In order to evaluate the performance of the optimisers, Pareto efficiency is examined. The 20 selected results obtained from MOGA-II, MOPSO and NSGA-II optimisers are separately examined with regard to their Pareto efficiency and the results are presented in Figures 5.21, 5.22, and 5.23:

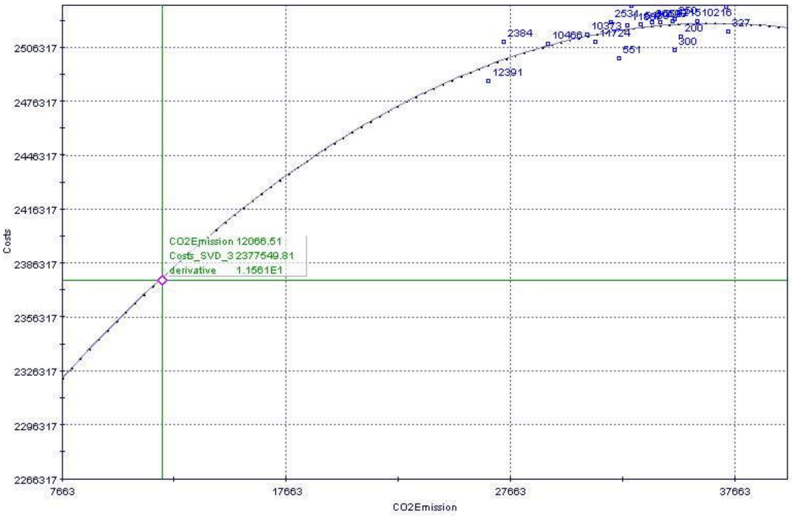


Figure 5.21 Pareto Frontier for selected results w.r.t. MOGA-II

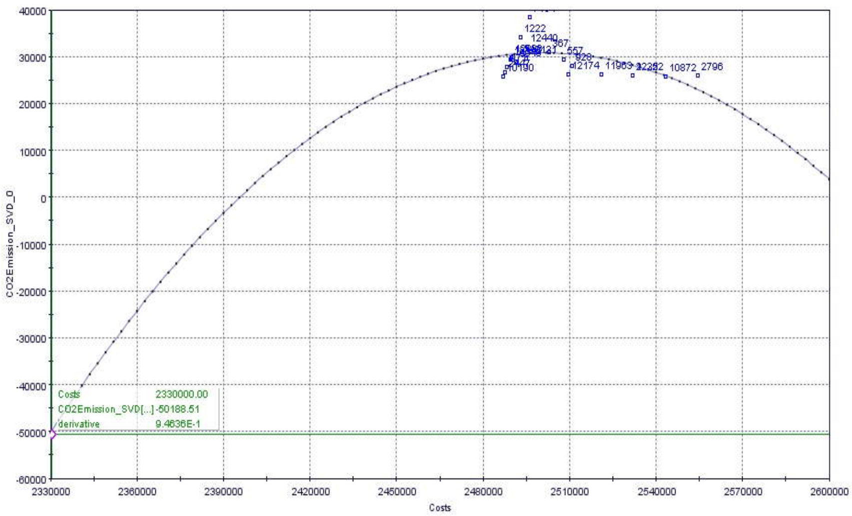


Figure 5.22 Pareto Frontier for selected results w.r.t. MOPSO

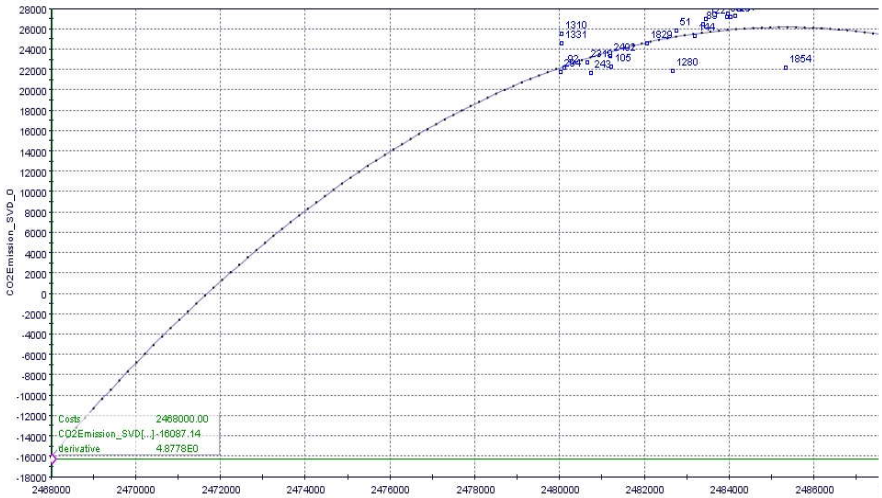


Figure 5.23 Pareto Frontier for selected results w.r.t. NSGA-II

As is evident from Figures 5.21, 5.21, and 5.23 the selected results from MOGA-II and NSGA-II optimisers follow the Pareto optimality and are strongly efficient. MOSPO shows a reasonably strong Pareto efficiency on the selected results. In the selection process of results, extreme decision-making events are considered as well. Therefore a small number of results representing these events exist in each selected results table. These results do not affect the Pareto efficiency of the selected results as they do not represent the most common decision-making events. None of the results placed outside the Pareto Frontier are ranked by TOPSIS as the first three ranked results.

5.7.2. Phase-II

The first three ranked results obtained in Phase-I using weight matrix w_5 (presented in Table 5.14) is the basis for implementing Phase-II of the three-layer MO-LRP. The same three optimisers MOGA-II, MOPSO, and NSGA-II used in Phase-I are used to implement the model in Phase-II. In order to analyse the results obtained from Phase-II: (i) results are refined and a set of realistic results are identified, (ii) a performance study is conducted on each optimiser, (iii) Analysis of Variance (ANOVA) test is performed to compare means of multiple groups for the optimised data, (iv) a set of results are selected for further analysis, (v) selected results are ranked using TOPSIS, and finally (vi) Pareto efficiency is examined on the selected designs. The process of analysing results obtained from Phase-II is illustrated as followed.

5.7.2.1. Analysis and refinement of Phase-II results in feasible real solution space

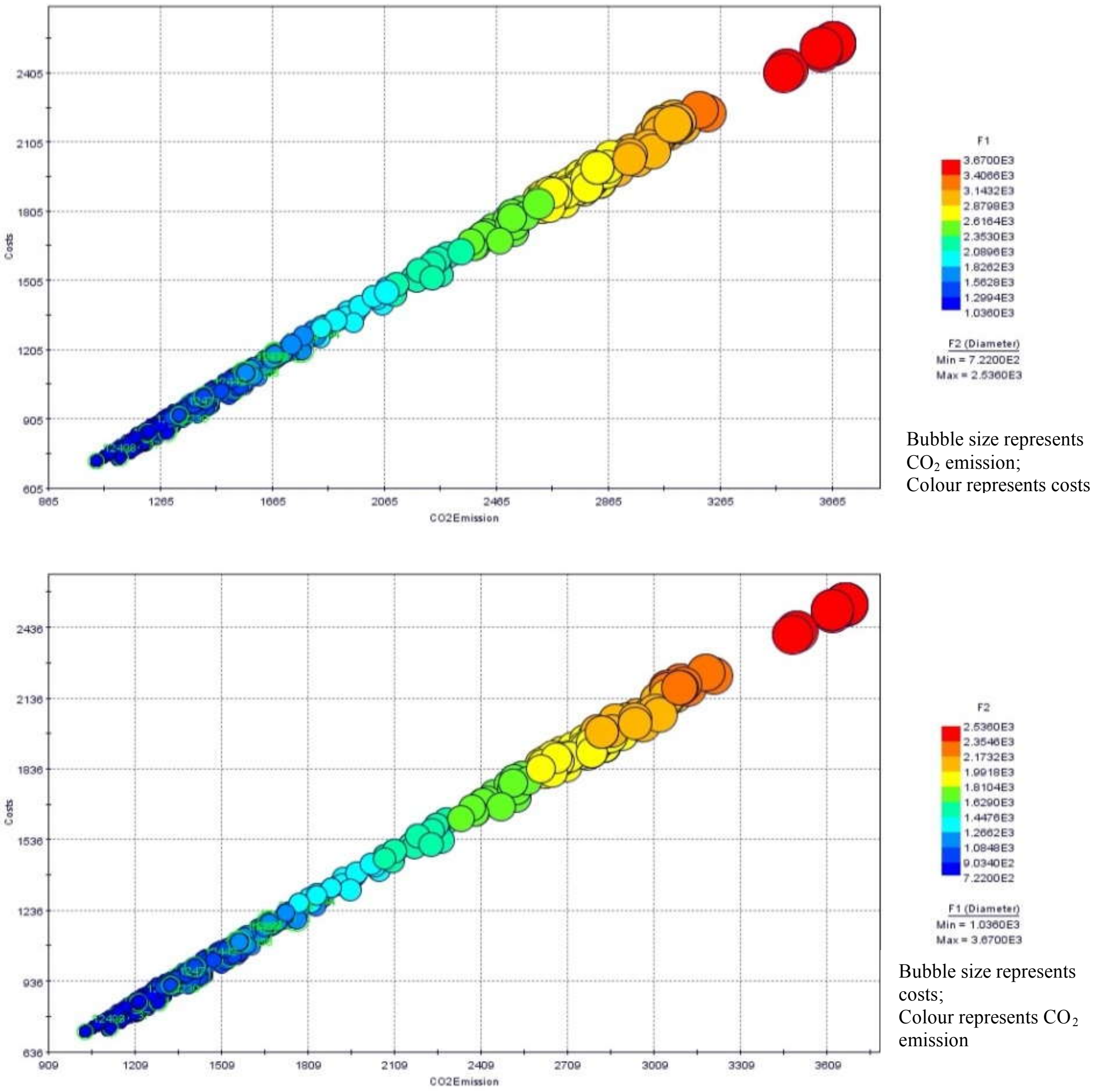
All results from the MOGA-II, NSGA-II and MOPSO optimisers in Phase-II are feasible and real. A statistical summary of these results is illustrated in Table 5.15. These results assist in analysing: a) the total result designs table consisting of all feasible real results obtained from the optimisers, b) the refined realistic results table consisting of realistic and non-identical results, and c) the selected results table consisting of selected results from the three lowest sets of feasible results from 4D-Bubble plots presented in Figures 4.24, 4.25 and 4.26.

Table 5.15 Statistical summary on results obtained in Phase-II w.r.t. optimisers

Type of results on optimisers		**Number of real feasible results** (Alternatives)	**CO2 Emission Value** kg (Objective Function *I*)		**Costs Value** € (Objective Function *II*)	
			Min	***Max***	***Min***	***Max***
MOGA-II	Total results table	12,500	988	3,622	701	2,515
	Refined realistic results table	399	988	1,778	701	1,245
	Selected results table	20	988	1,514	701	1,031
MOPSO	Total results table	12,500	1,423	4,057	690	2,504
	Refined realistic results table	422	1,423	2,213	690	1,234
	Selected results table	20	1,423	1,980	690	1,001
NSGA-II	Total results table	2,500	1,950	4,590	1,224	3,046
	Refined realistic results table	300	1,950	3,225	1,224	2,010
	Selected results table	20	1,950	2,671	1,224	1,723

As presented in Table 5.15, the minimum value for both CO_2 emissions and costs is obtained by NSGA-II in 50 generations. This does not necessarily yield a minimum value for the total costs. MOGA-II and NSGA-II are GA-bases optimisers and MOSPSO is a PS-based optimiser.

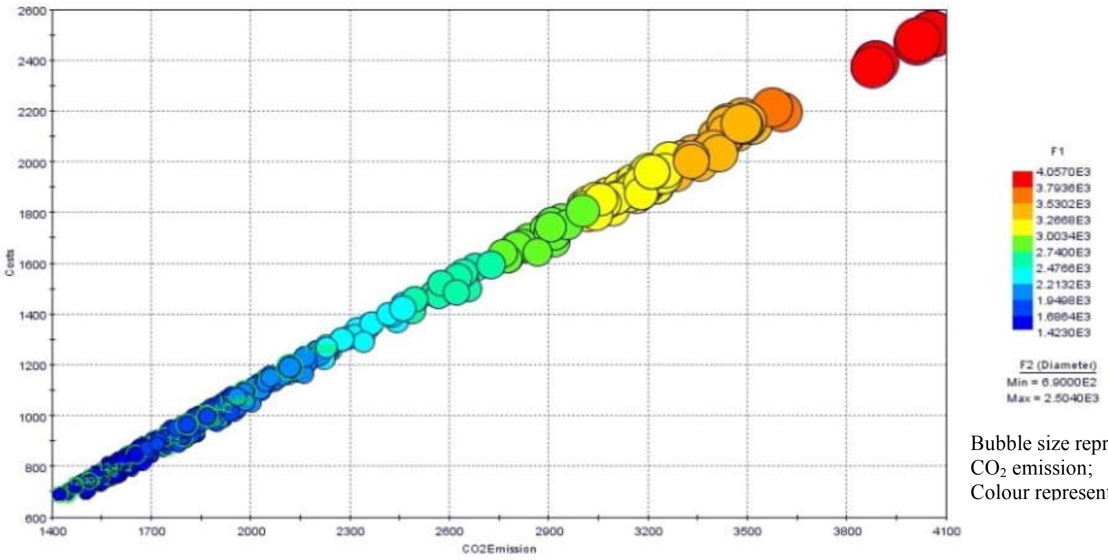
MOGA-II, NSGA-II and MOPSO generate real feasible solutions spaces in Phase-II. Figures 5.24, 5.25, and 5.26 depict the feasible real solution space for the optimisers in Phase-II. In these 4D plots, colour and diameter of bubbles are used to showcase the values of both objective functions; explained in the plot legend. Colours range from dark blue to red, lowest to highest value of the objective function respectively and the diameter of bubbles ranges from small to large, lowest to highest value of the objective function respectively.



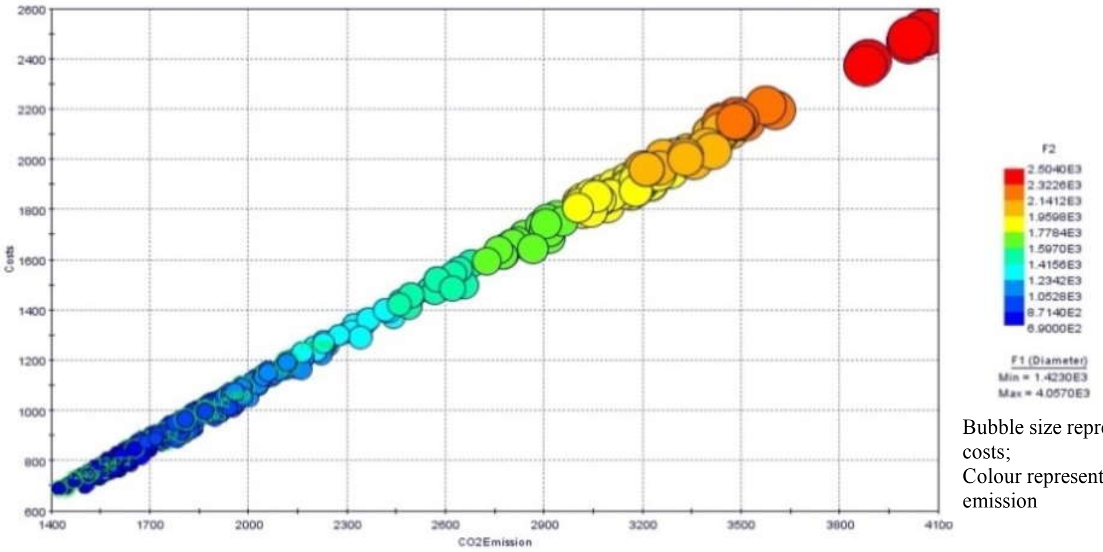
Bubble size represents CO_2 emission;
Colour represents costs

Bubble size represents costs;
Colour represents CO_2 emission

Figure 5.24 Feasible real solution space w.r.t. costs and CO_2 emission for MOGA-II optimiser

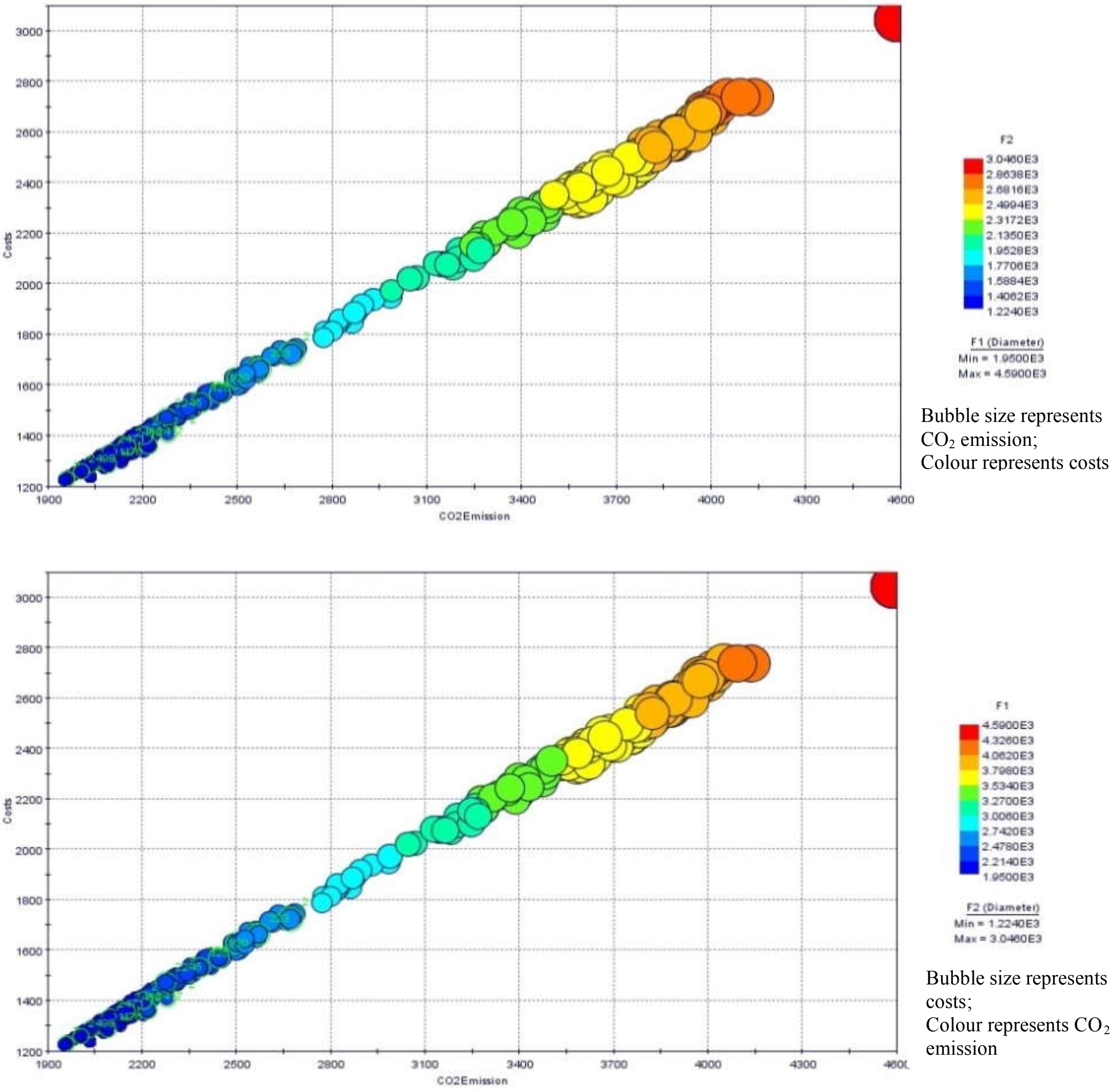


Bubble size represents CO_2 emission;
Colour represents costs



Bubble size represents costs;
Colour represents CO_2 emission

Figure 5.25 Feasible real solution space w.r.t. costs and CO_2 emission for MOPSO optimiser



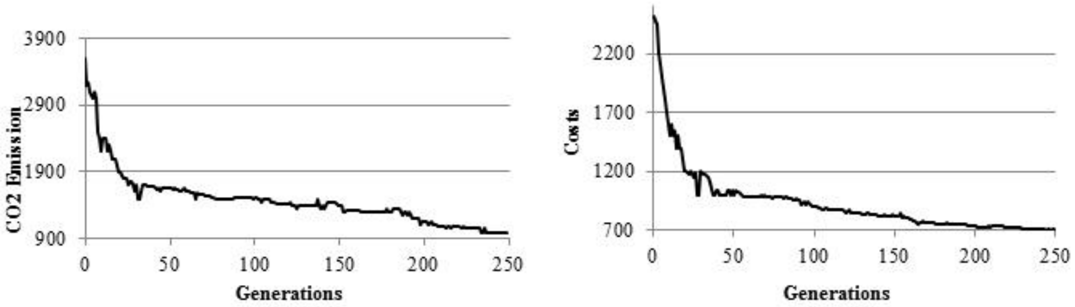
Bubble size represents CO_2 emission;
Colour represents costs

Bubble size represents costs;
Colour represents CO_2 emission

Figure 5.26 Feasible real solution space w.r.t. costs and CO_2 emission for NSGA-II optimiser

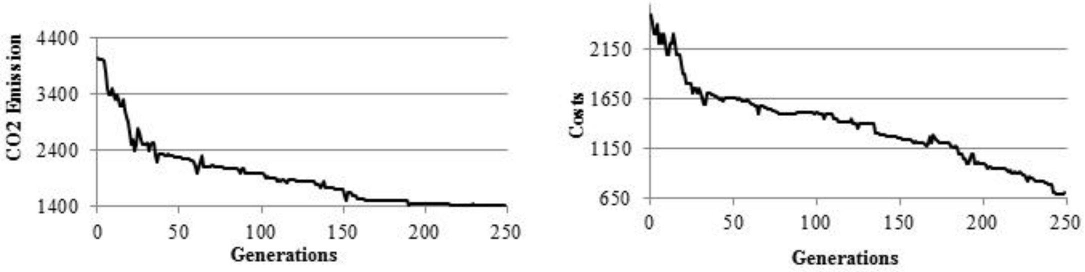
5.7.2.2. Performance study on optimisers in Phase-II

The performance of the optimisers regarding their convergence is studied comparatively through plots presented in Figure 5.27, 5.28 and 5.29 presents the convergence plots for MOGA-II, MOPSO and NSGA-II, with respect to the objective functions:



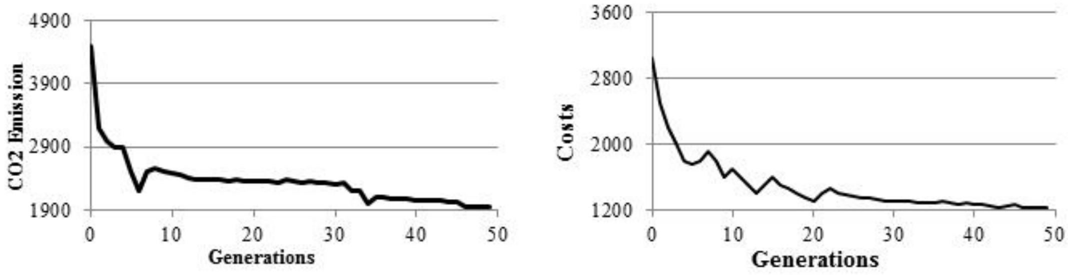
a. Convergence w.r.t CO_2 Emission b. Convergence w.r.t Costs

Figure 5.27 Convergence of MOGA-II w.r.t objective functions



a. Convergence w.r.t CO2 Emission b. Convergence w.r.t Costs

Figure 5.28 Convergence of MOPSO w.r.t objective functions



a. Convergence w.r.t CO2 Emission b. Convergence w.r.t Costs

Figure 5.29 Convergence of MOPSO w.r.t objective functions

As is evident from plot ‘a’ and plot ‘b' of Figure 5.27, 5.28 and 5.29, all optimisers are converging in a steady manner. MOGA-II and MOPSO are converging in 250 generations and NSGA-II in 50 generations.

5.7.2.3. ANOVA for Phase-II

In order to compare the means of multiple groups of the optimised data, the results of one-way ANOVA with respect to objective functions are presented in Tables 5.16 and 5.17:

Table 5.16 ANOVA for CO_2 emission on the all results

Optimiser	Source of Variation	SS	Df	MS	F-ratio	p-value
MOGA-II	Between groups	4.0428E8	1.9800E2	2.0418E6	1.1066E2	0.0000E0
	Within groups	4.2456E7	2.3010E3	1.8451E	—	—
	Total	4.4673E8	2.4990E3			
NSGA-II	Between groups	7.5800E7	5.0000E0	1.5160E7	1.1056E3	0.0227
	Within groups	3.4197E7	2.4940E3	1.3712E4	—	—
	Total	1.1000E8	2.4990E3			
MOPSO	Between groups	1.1126E8	5.4000E1	2.0603E6	6.0362E1	0.0199
	Within groups	8.5162E7	2.4950E3	3.4133E4	—	—
	Total	1.9642E8	2.5490E3			

Table 5.17 ANOVA for costs on the all results

Optimiser	Source of Variation	SS	Df	MS	F-ratio	p-value
MOGA-II	Between groups	1.9883E8	1.9800E2	1.0042E6	1.1161E2	0.0000E0
	Within groups	2.0702E7	2.3010E3	8.9969E3	—	—
	Total	2.1953E8	2.4990E3			
NSGA-II	Between groups	1.5379E8	5.0000E0	3.0758E7	1.0925E3	0.0923
	Within groups	7.0213E7	2.4940E3	2.8153E4	—	—
	Total	2.2400E8	2.4990E3			
MOPSO	Between groups	5.5239E7	5.4000E1	1.0229E6	6.0178E1	0.09871
	Within groups	4.2411E7	2.4950E3	1.6999E4	—	—
	Total	9.7650E7	2.5490E3			

The most important assumption requested by ANOVA is that the standard deviations within each group are the same. In this case it can be seen that both Hartley and Bartlett's tests are true. These two statistical tests verify that the standard deviations within each of the groups is the same, therefore the most important assumption requested by ANOVA is valid. It is also noted that as the F-ratio increases, the p-value decreases. The p-values of the ANOVA table for CO_2 emission and costs (Tables 5.16 and 5.17) in MOGA-II optimiser are zero. This suggests that there are significant differences between the groups. At least one sample mean is significantly different from the other sample means.

5.7.2.4. Selection of results in Phase-II

After eliminating the un-realistic and identical results from the feasible solutions space, the refined realistic results are considered for further analysis. The same process of analysis conducted to select results in Phase-I is adapted in here. Fiures 5.30, 5.31, and 5.32 exhibit the bubble plots on selected results for MOGA-II, MOSPO, and NSGA-II respectively.

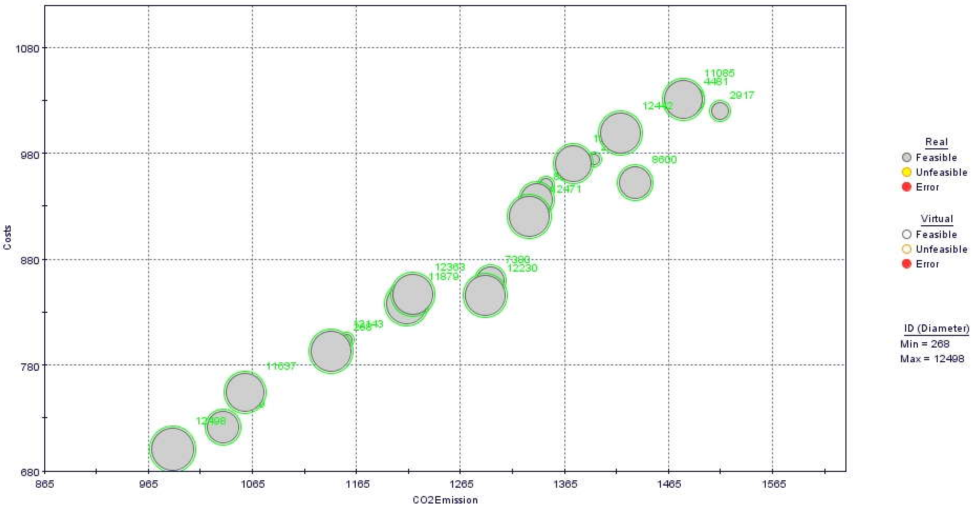


Figure 5.30 Bubble Plot for CO_2 emission and costs of selected results w.r.t. MOGA-II optimiser

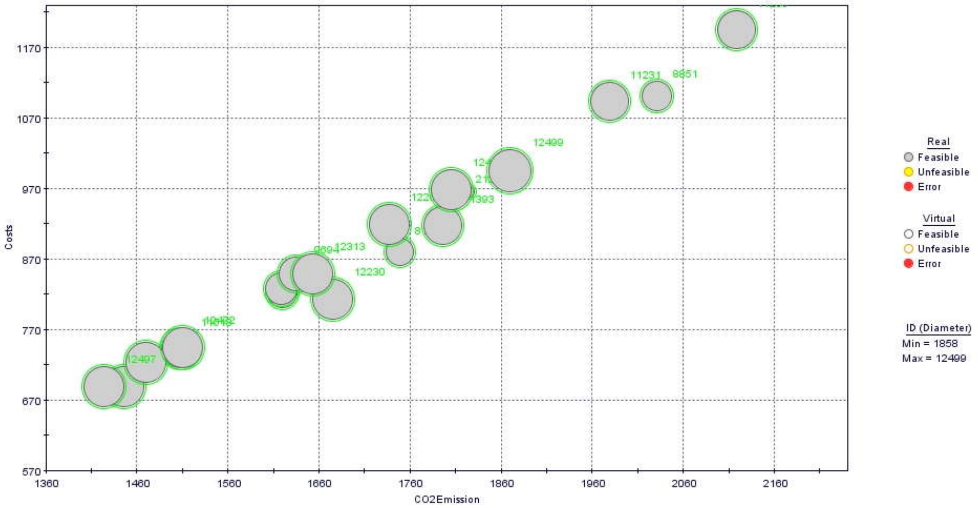


Figure 5.31 Bubble Plot for CO_2 emission and costs of selected results w.r.t. MOPSO optimiser

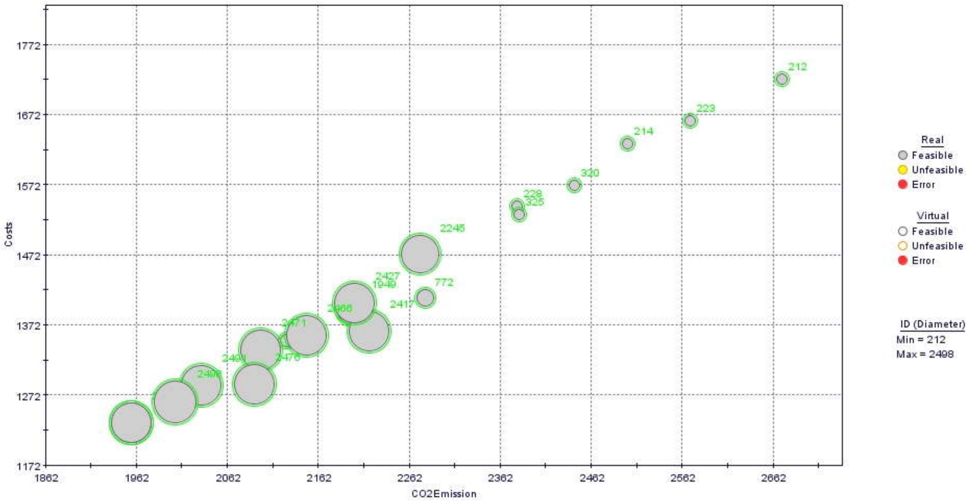


Figure 5.32 Bubble Plot; CO_2 emission and costs of selected results w.r.t. NSGA-II optimiser

5.7.2.5. Ranking selected results from Phase-II

Similar to the process of ranking rsults in Phase-I, seelcted resuts from Phase-II are ranked. The first three ranked results by TOPSIS using weight matrix w_5 for all three optimisers are presented in Table 5.18:

Table 5.18 First three ranked results w.r.t optimisers using weight matrix w_5

	Rank	<ID>	Open Routes	CO_2 Emission	Cost
MOGA-II	1	12498	O608, O1613, O1714, O1415	988	701
	2	8959	O608, O1613, 01714, O1315	1,036	722
	3	11637	O408, 01613, 01714, 01415	1,058	755
MOPSO	1	11647	O0608, O0416, O1018, O1817, O1314, O1415	1,423	1,000
	2	11872	O0608, O1018, O1817, O1514, O1315	1,445	690
	3	6162	O0408, O0616, O1018, O1817, O1314, O1415	1,452	919
NSGA-II	1	2415	O0103, O0408, O1718, O0719, O0920	1,950	1,423
	2	2199	O0301, O0102, O0605, O0608, O1011, O1413, O1416, O2022	2,445	1,224
	3	2364	O0506, O01, O1110, O0816, O1817, O0920, O1914	2,241	1,536

Similar optimisers are used to implement the modified models in Phase-II; yet the results shown in Table 5.18 are not comparable. Each model in Phase-II is based on a specific result obtained from Phase-I.

5.7.2.6. Pareto Efficiency in Phase-II

The 20 selected results obtained from MOGA-II, MOPSO, and NSGA-II optimisers are separately examined with regard to their Pareto efficiency. Pareto Frontiers are presented in Figures 5.33, 5.34, and 5.35:

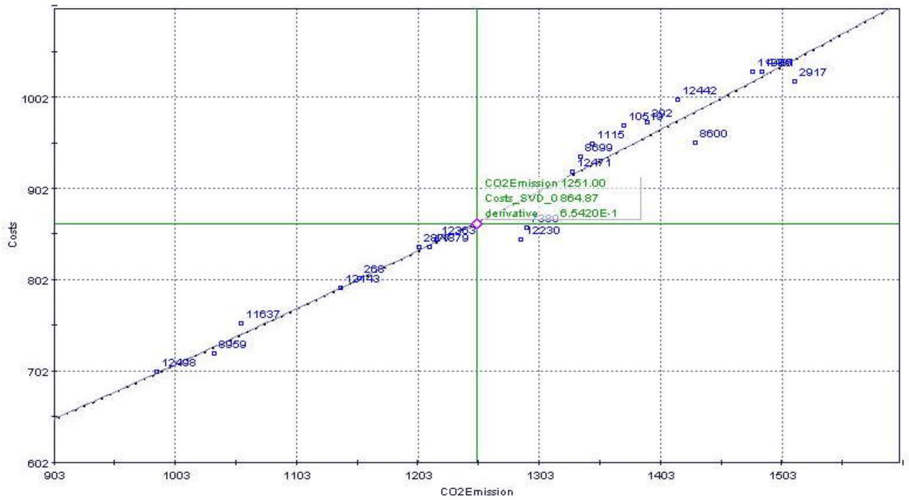


Figure 5.33 Pareto Frontier on of selected results w.r.t. MOGA-II

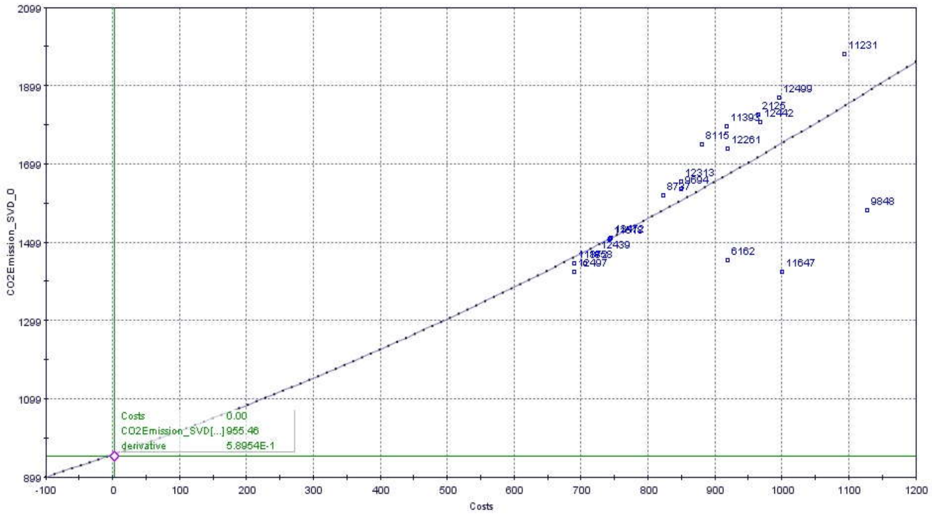


Figure 5.34 Pareto Frontier on selected result w.r.t. MOPSO

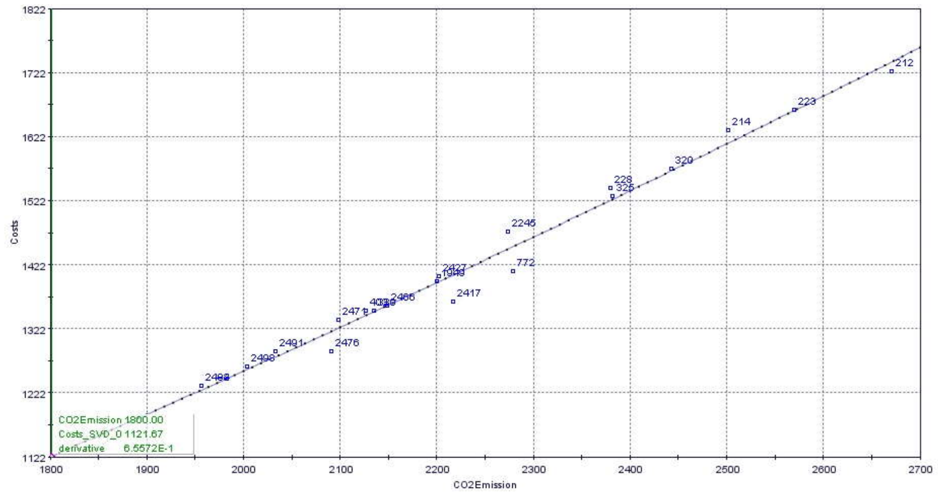


Figure 5.35 Pareto Frontier on selected results w.r.t. NSGA-II

As evident from Figures 5.33, 5.34, and 5.35 selected results from MOGA-II and NSGA-II optimisers follow the Pareto optimality and are strongly efficient. In MOPSO three results are not very strongly Pareto efficient. These results represent extreme decision-making events; therefore they don’t affect the efficiency of the results in MOPSO.

5.8. Interpretation of Results

The final outcome of the three-layer MO-LRP is a combination of the outcomes of Phase-I and Phase-II. These results concern facility and vehicle-routing decisions on the demand side of the three-layer case of the dairy SC in east of Ireland. These final results are analysed and presented in this section.

5.8.1. Final results of the three-layer MO-LRP

The three-layer MO-LRP results offer optimal facility location and vehicle-routing decision. With regard to facility location decisions, optimum open and closed DCs are offered in each result. With respect to vehicle-routing decisios: (i) optimum routes connecting plants to DCs, DCs to retailers and connection in between retailers, (i) type of vehicle and (iii) the number of HGVs required for transporting products in each route are offered. Table 5.19 depicts the ‘facility location’, ‘type of truck’ and the ‘routing pattern’ for the three-layer MO-LRP, obtained with respect to optimisers.

Table 5.19 Final result of the three-layer MO-LRP

	Phase One		Phase TWO		Final CO_2 Emission	Final Costs
	Open Routes	**Transportation Option**	**Open Routes**	**Transportation Option**		
MOGA-II	Processing Plant I routed to: DC **2, 3** Processing Plant II routed to: DC **1, 4, 5, 6** Open DCs: **3, 5** DC **3** serving Retailers: **2,3,4,5,6,7,11,13,18,21** DC **5** serving Retailers: **1,9,10, 12, 16,17,19,20,22**	T_2	Retailer 6 to retailer 8 Retailer 16 to retailer 13 Retailer 17 to retailer 14 Retailer 14 to retailer 15	T_2	**27,677**	**2,488,345**
MOPSO	Processing Plant I routed to: DC **2, 3** Processing Plant II routed to: DC **1, 4, 5, 6** Open DCs: **3 & 5** DC **3** serving Retailers: **1, 3, 4, 5, 6, 7, 19, 21, 22** DC **5** serving Retailers: **2, 9, 10, 11, 12, 13, 20**	T_3	Retailer 6 to retailer 8 Retailer 4 to retailer 16 Retailer 10 to retailer 18 Retailer 18 to retailer 17 Retailer 13 to retailer 14 Retailer 14 to retailer 15	T_3	**27,110**	**2,488,052**
NSGA-II	Processing Plant I routed to: DC **1, 2, 3** Processing Plant II routed to: DC **4, 5, 6** Open DCs: **2 & 5** DC **2** serving Retailers: **1, 2, 5, 7, 10, 13, 15, 16, 21, 22** DC **5** serving Retailers: **4, 6, 9, 11, 12, 14, 17**	T_2	Retailer 1 to retailer 3 Retailer 4 to retailer 8 Retailer 17 to retailer 18 Retailer 7 to retailer 19 Retailer 9 to retailer 20	T_3	**24,144**	**2,481,960**

As evident from Table 5.19, NSGA-II offers the best results for the three-layer MO-LRP in two inter-linked phases. NSGA-II converges and offers the best results in 50 generations while MOGA-II and MOPSO converge in 25o generations.

With regard to vehicle-routing decisions, the quantity transported in each open route and numbers of HGVs required for transporting the defined load of product are presented in Tables 5.20, 5.21 and 5.22 with respect to MOGA-II, MOPSO and NAGA-II first ranked results.

Table 5.20 Quantities and the number of vehicles in each open route for MOGA-II final result

		Open Rotes	Quantity Shipped	Number of Vehicles
Plants to DCs	Plant I	DC 2	800,000	67
		DC 3	1,000,000	67
		DC 4	1,000,000	67
	Plant II	DC 1	1,000,000	54
		DC 5	700,000	47
		DC 6	1,000,000	67
DCs to Retailers	DC 3	Retailer 2	25,000	2
		Retailer 3	19,000	2
		Retailer 4	9,000	1
		Retailer 5	14,000	1
		Retailer 6	*14,500+9,000*	2

		Retailer 7	10,000	1
		Retailer 11	7,000	1
		Retailer 18	7,000	1
		Retailer 21	182,000	13
	DC 5	Retailer 1	25,000	2
		Retailer 9	21,000	2
		Retailer 10	9,000	1
		Retailer 12	11,000	1
		Retailer 16	*16,000+12,000*	2
		Retailer 17	*13,000+35,000+7,000*	4
		Retailer 19	350,000	24
		Retailer 20	138,000	10
		Retailer 22	177,000	12
Retailers Connec-tions	Retailer 6 to Retailer 8			
	Retailer 16 to retailer 13			
	Retailer 17 to Retailer 14 to Retailer 15			
Total CO_2 Emission	**26,689+988=27,677**			
Total Costs	**2,487,644+701=2,488,345**			

Table 5.21 Quantities and the number of vehicles in each open route for MOPSO final result

		Open Rotes		Quantity Shipped	Number of Vehicles
Plants to DCs	Plant I	DC 2	1,000,000	67
		DC 3	1,000,000	67
	Plant II	DC 1	800,000	54
		DC 4	1,000,000	67
		DC 5	700,000	47
		DC 6	1,000,000	67
DCs to Retailers	DC 3	Retailer 1	25,000	2
		Retailer 3	19,000	2
		Retailer 4	9,000+16,000	3
		Retailer 5	14,000	1
		Retailer 6	14,500+9,000	2
		Retailer 7	10,000	1
		Retailer 19	350,000	24
		Retailer 21	182,000	13
		Retailer 22	177,000	12
	DC 5	Retailer 2	25,000	2
		Retailer 9	21,000	2
		Retailer 10	9,000+7,000+13,000	3
		Retailer 11	7,000	1
		Retailer 13	12,000+35,000+7,000	4
		Retailer 20	138,000	10
Retailers' Connections	Retailer 6 to retailer 8			
	Retailer 4 to retailer 16			
	Retailer 10 to retailer 18			
	Retailer 18 to retailer 17			
	Retailer 13 to retailer 14			
	Retailer 14 to retailer 15			
Total CO_2 Emission	**25,687+1,423=27,110**			
Total Costs	**2,487,052+1,000=2,488,052**			

Table 5.22 Quantities and the number of vehicles in each open route for NSGA-II final result

		Open Rotes	Quantity Shipped	Number of Vehicles
Plants to DCs	Plant I	DC 1	1,000,000	54
		DC 2	800,000	67
		DC 3	1,000,000	67
	Plant II	DC 4	1,000,000	67
		DC 5	700,000	47
		DC 6	1,000,000	67
DCs to Retailers	DC 2	Retailer 1	25,000 + 19,000	3
		Retailer 2	25,000	2
		Retailer 5	14,000	1
		Retailer 7	10,000 + 350,000	24
		Retailer 10	9,000	1
		Retailer 13	12,000	1
		Retailer 15	7,000	1
		Retailer 16	*16,000*	
		Retailer 21	182,000	13
		Retailer 22	177,000	12
	DC 5	Retailer 4	9,000 + 9,000	2
		Retailer 6	*14,500*	1
		Retailer 9	21,000 + 138,000	11
		Retailer 11	7,000	1
		Retailer 12	11,000	1
		Retailer 14	*35,000*	3
		Retailer 17	13,000 +7,000	2
	Retailer 1 to retailer 3			
	Retailer 4 to Retailer 8			
	Retailer 17 to retailer 18			
	Retailer 7 to retailer 19			
	Retailer 9 to retailer 20			
Total CO_2 Emission	**21,699 + 2,445 = 24,144**			
Total Costs	**2,480,736 + 1,224 = 2,481,960**			

5.8.2. Scenario Analysis on final results of the three-layer MO-LRP

Disparate scenario analysis on the first ranked results obtained from the three optimisers is presented in Tables 5.23, 5.24 and 5.25:

Table 5.23 Scenario analysis for the Final result of MOGA-II

		All Routes	**CO_2 Emission if route opens**	**Costs if route opens**
Processing Plants to DCs	**Plant I**	DC 1	1,836	1,296
		DC 2	-	-
		DC 3	-	-
		DC 4	-	-
		DC 5	2,585	1,927
		DC 6	4,422	3,216
	Plant II	DC 1	-	-
		DC 2	6,834	5,025
		DC 3	13,534	9,514
		DC 4	7,236	5,226
		DC 5	-	-

		DC 6	-	-
DCs to Retailers	**DC 3**	Retailer 1	92	56
		Retailer 2	-	-
		Retailer 3	-	-
		Retailer 4	-	-
		Retailer 5	-	-
		Retailer 6	-	-
		Retailer 7	-	-
		Retailer 8	87	61
		Retailer 9	40	28
		Retailer 10	65	48
		Retailer 11	-	-
		Retailer 12	28	21
		Retailer 13	164	115
		Retailer 14	435	291
		Retailer 15	163	105
		Retailer 16	226	142
		Retailer 17	121	72
		Retailer 18	-	-
		Retailer 19	48	48
		Retailer 20	130	100
		Retailer 21	-	-
		Retailer 22	228	168
	DC 5	Retailer 1	-	-
		Retailer 2	216	152
		Retailer 3	140	98
		Retailer 4	108	79
		Retailer 5	44	26
		Retailer 6	56	37
		Retailer 7	34	24
		Retailer 8	96	68
		Retailer 9	-	-
		Retailer 10	-	-
		Retailer 11	40	33
		Retailer 12	-	-
		Retailer 13	173	122
		Retailer 14	501	354
		Retailer 15	157	115
		Retailer 16	-	-
		Retailer 17	-	-
		Retailer 18	90	55
		Retailer 19	-	-
		Retailer 20	-	-
		Retailer 21	336	204
		Retailer 22	-	-

Table 5.24 Scenario analysis for the Final result of MOPSO

	All Routes		CO_2 Emission if route opens	Costs if route opens
Processing Plants to DCs	**Plant I**	DC 1	1,836	1,296
		DC 2	-	-
		DC 3	-	-
		DC 4	7,236	5,226
		DC 5	2,585	1,927
		DC 6	4,422	3,216
	Plant II	DC 1	-	-
		DC 2	6,834	5,025
		DC 3	13,534	9,514
		DC 4	-	-
		DC 5	-	-
		DC 6	-	-
DCs to Retailers	**DC 3**	Retailer 1	-	-
		Retailer 2	150	106
		Retailer 3	-	-
		Retailer 4	-	-
		Retailer 5	-	-
		Retailer 6	-	-
		Retailer 7	-	-
		Retailer 8	87	61
		Retailer 9	40	28
		Retailer 10	65	48
		Retailer 11	48	58
		Retailer 12	28	21
		Retailer 13	164	115
		Retailer 14	435	291
		Retailer 15	163	105
		Retailer 16	226	142
		Retailer 17	121	72
		Retailer 18	109	80
		Retailer 19	-	-
		Retailer 20	130	100
		Retailer 21	-	-
		Retailer 22	-	-
	DC 5	Retailer 1	136	96
		Retailer 2	-	-
		Retailer 3	140	98
		Retailer 4	108	79
		Retailer 5	44	26
		Retailer 6	56	37
		Retailer 7	34	24
		Retailer 8	96	68
		Retailer 9	-	-
		Retailer 10	-	-
		Retailer 11	-	-
		Retailer 12	-	-
		Retailer 13	-	-
		Retailer 14	501	354
		Retailer 15	157	115
		Retailer 16	246	120
		Retailer 17	102	78
		Retailer 18	90	55
		Retailer 19	480	336

		Retailer 20	-	-
		Retailer 21	494	377
		Retailer 22	336	204

Table 5.25 Scenario analysis for the Final result of MOGA-II

		All Routes	CO$_2$ Emission if route opens	Costs if route opens
Processing Plants to DCs	**Plant I**	DC 1	-	-
		DC 2	-	-
		DC 3	-	-
		DC 4	7,236	5,226
		DC 5	2,585	1,927
		DC 6	4,422	3,216
	Plant II	DC 1	108	108
		DC 2	6,834	5,025
		DC 3	13,534	9,514
		DC 4	-	-
		DC 5	-	-
		DC 6	-	-
DCs to Retailers	**DC 2**	Retailer 1	-	-
		Retailer 2	-	-
		Retailer 3	48	40
		Retailer 4	72	44
		Retailer 5	-	-
		Retailer 6	83	61
		Retailer 7	-	-
		Retailer 8	132	93
		Retailer 9	136	96
		Retailer 10	-	-
		Retailer 11	112	79
		Retailer 12	76	54
		Retailer 13	-	-
		Retailer 14	606	429
		Retailer 15	-	-
		Retailer 16	-	-
		Retailer 17	182	128
		Retailer 18	137	125
		Retailer 19	1,104	672
		Retailer 20	580	410
		Retailer 21	-	-
		Retailer 22	-	-
	DC 5	Retailer 1	136	96
		Retailer 2	216	152
		Retailer 3	140	98
		Retailer 4	-	-
		Retailer 5	44	26
		Retailer 6	-	-
		Retailer 7	34	24
		Retailer 8	96	68
		Retailer 9	4	4
		Retailer 10	47	34
		Retailer 11	-	-
		Retailer 12	-	-
		Retailer 13	173	122
		Retailer 14	501	354

		Retailer 15	157	115
		Retailer 16	246	120
		Retailer 17	-	-
		Retailer 18	90	55
		Retailer 19	480	336
		Retailer 20	90	70
		Retailer 21	494	377
		Retailer 22	336	204

Table 5.23, 5.24 and 5.25 are examples of the guidance available to DMs for locating the feasible and realistic optimal distribution routes, considering the trade-offs with respect to the objective functions, if a closed route is forcibly opened.

The final results are presented schematically in the next section.

5.8.3. Schematic presentation of final results of the three-layer MO-LRP; an example of an output

In order to present the results in a more tangible way, a geographical presentation of one of the selected results are shown on the map of Ireland. Figure 3.36 presents a geographical presentation of MOGA-II final result from Table 5.19:

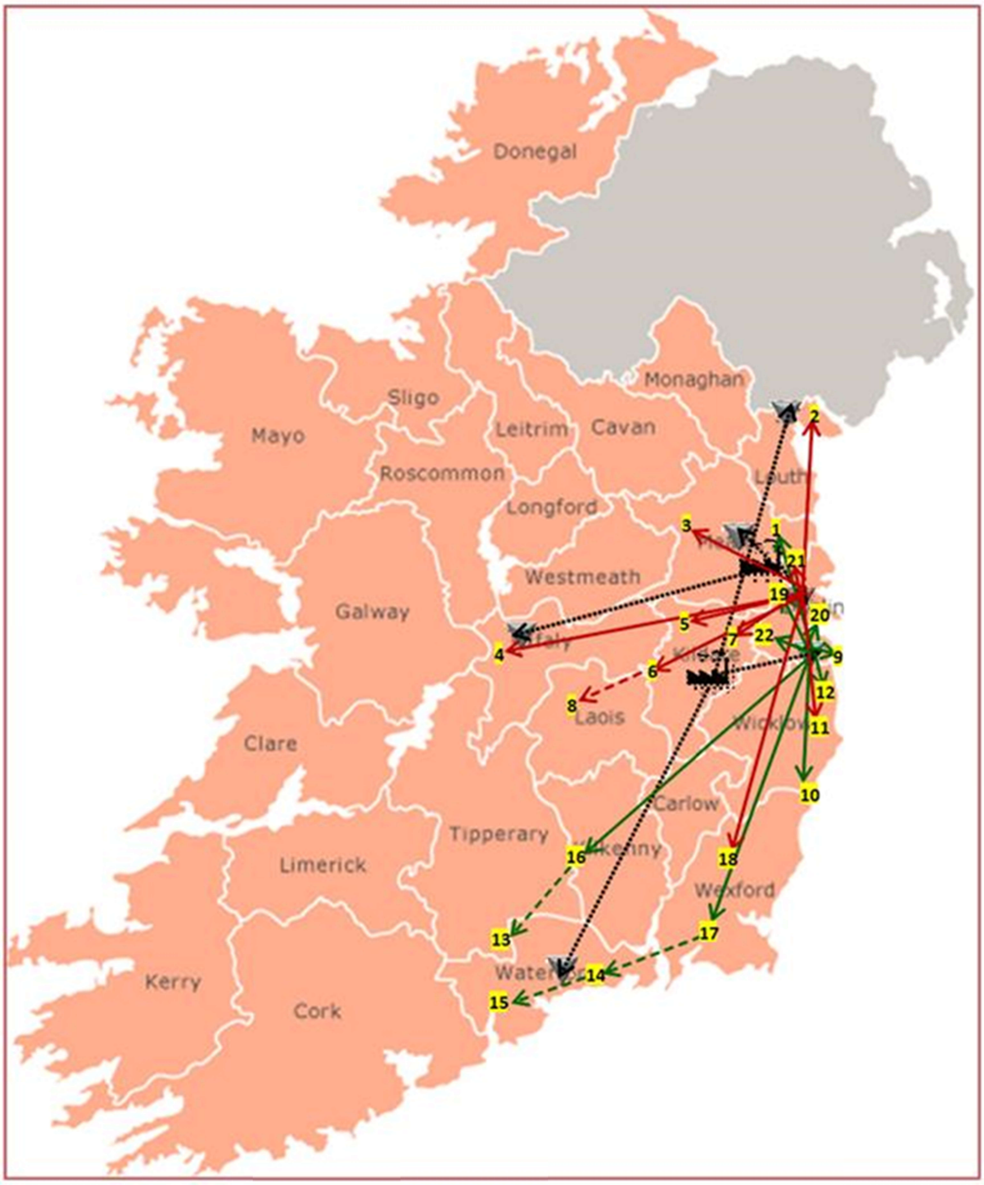


Figure 5.36 Geographical presentation of the final result obtained from MOGA-II

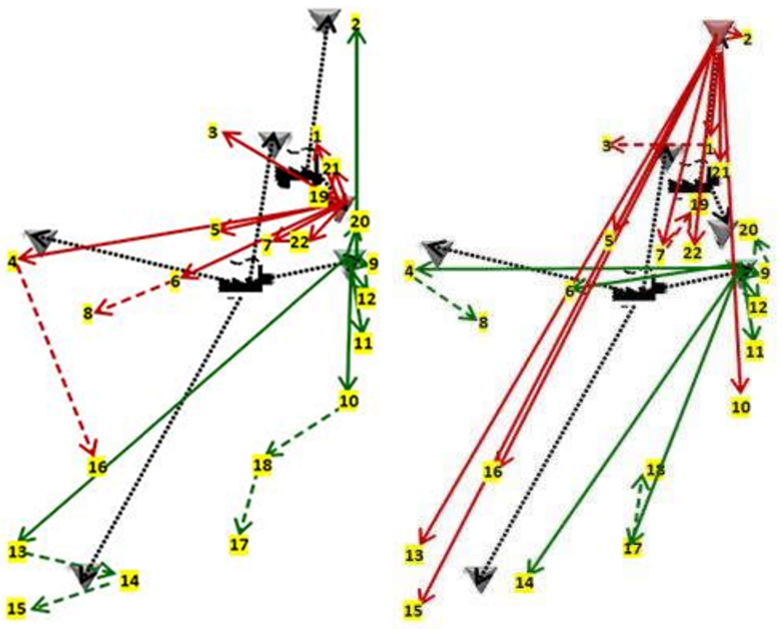
🏭 Plants Open DCs ▼ ▼ Closed DCs ▼

1, …, 22 Retailers

···> Routes conning plants to collection stations

→ Routes connecting DCs to retailers - -> Connection routes among retailers

Schematic presentation of the final results obtained from MOPSO and NSGA-II are showcased in Figure 5.37:



a. MOPSO **b. NSGA-II**

Figure 5.37 Schematic presentation of the final result obtained from MOPSO and NSGA-II

5.9. Summary and Conclusion

The formulation of the three-layer AHP-integrated MO-LRP, its robust two phased solution approach, and the process of analysing the final results obtained from the solution approach have been discussed in three parts. The three-layer MO-LRP considers three key players on the demand side of the SCs, viz. plants, DCs and retailers. Conventional LRPs consider single objective and only focus on minimisation of the total costs. The three-layer MO-LRP minimises the: (i) total cost and (ii) total CO_2 emission caused from transportation. The process of minimising the CO_2 emission caused from transportation introduces one green element into the model. The second green element is introduced to the three-layer MO-LRP by the way of an AHP-integrated constraint. This AHP-integrated constraint considers the consensus opinions of the DMs in regard to the selection of HGV for transporting products. Two attributes for selecting the vehicles are 'cost' and 'CO_2 emission'. Three candidate-alternative trucks are considered.

Conventionally, 'demand' appears as a constraint co-efficient in three-layer LRPs. In addition, the three-layer MO-LRP considers the demand as a co-efficient in the objective function. The reason for this is to bring into account the level of CO_2 emission form all the vehicles required to transport the products from plants to DCs, from DCs to retailers and retailers to retailers.

modeFRONTIER®, a multi-disciplinary optimisation commercial solver, is used as the execution platform for the three-layer MO-LRP. modeFRONTIER® has proven to be an efficient solver for implementing the NP-hard two-layer MO-LRP as discussed in Chapter Three. Therefore, the same solver is used as the implementation platform for solving the heavily constrained three-layer MO-LRP. Three GA-based and PS-based optimisers have performed efficiently in reaching to optimum result for the two-layer MO-LRP. The same set of optimisers is adopted for solving the three-layer MO-LRP.

The three-layer MO-LRP has been validated using a case of an Irish dairy supply chain network based in the east of Ireland. The case SC network has 2 processing plants, 6 DCs and 22 retailers. A questionnaire has been used to validate the structure of the assumed SC network and the data has been generated is based on a set of realistic assumptions.

The three-layer MO-LRP is heavily constrained and impossible to solve in single phase. A two phased approach is suggested and implemented. Three-layer LRPs deal with two types of decision in the design of the SC network, viz. facility location decisions and vehicle routing decision. These two decisions are dealt with in two phases in order to reach to a final solution to the three-layer MO-LRP. Phase-I considers facility location decision regarding opening and closing DCs and vehicle routing decision regarding routing patterns for connecting plants to DCs and connecting open DCs to retailers. Phase-II is executed based on the results obtained from the Phase-I. Phase-II deals with vehicle routing decision by the way of finding the optimum routing patterns for connecting retailers.

The DCs and the routes connecting them to the served retailers from the Phase-I are included in Phase-II. The objective function and constraint elements related to open DCs and routes connecting them to retailers from Phase-I are considered in Phase-II. This is the link for connecting the two phases in order to reach to a final optimal solution for the three-layer MO-LRP.

The solution approach to the three-layer MO-LRP is DoE-guided. DoE generates the initial population for the optimisers in modeFRONTIER®. The optimisers have been set as identical as possible in order to compare their performances in solving the three-layer MO-LRP. Experimentally a set of designs generated by DoE is proved to be efficient in offering the optimum set of results for the three-layer MO-LRP. The convergence of optimisers is examined with regard to the objective functions for each optimiser. One way ANOVA is performed for all results obtained from each optimiser for the objective functions. The Hartley and Bartlett's statistics tests verify that the standard deviations within each groups is the same. Therefore the most important assumption requested by ANOVA is valid.

Based on the statistical selection criteria a set of results are selected and consequently ranked by TOPSIS. Pareto efficiency of the selected results is studied. Selected results from all the three optimisers are proved to be strongly Pareto efficient.

Synergistically the final results are obtained when both the phases are executed. The final results of the three-layer MO-LRP consist of (i) information on the open/close DCs, (ii) the vehicle routing patterns connecting the plants to DCs, (iii) the vehicle routing patterns connecting the open DCs to the retailers, (iv) the vehicle routing patterns connecting the retailers to retailers, and (v) the number of trucks required in each route to transport the products. By obtaining the above optimal setting, the physical distribution network on the demand side of the SC network can be structured with the main aim of minimising the total cost, minimising the total CO_2 emission caused from transportation while satisfying the operational constraints.

Scenario analysis is performed on the final results. This scenario analysis provides guidance to DMs when a closed route is forcibly opened. Various scenarios depict the amount of CO_2 emitted and the total costs from a closed route if forced to be open. This provides a support to SC network resilience.

The performance of the optimisers in Phase-I and Phase-II shows that NSGA-II is more efficient in solving the multi-objective NP-hard three-layer low-carbon MO-LRP under the modeFRONTIER® platform.

CHAPTER SIX

Discussion

6.1. Introduction

This research introduced green elements to both a two and a three layer location-routing model. In order to address this issue the research formulates two computationally NP-hard AHP-integrated multi-objective location-routing models that minimise both the CO_2 emission and associated costs. A commercial solver, modeFRONTIER$^{®}$, has been deployed for implementation of the DoE-guided meta-heuristic-based solution approaches for both location-routing models. In order to illustrate the efficacy of the integrated model a case of an Irish dairy market supply chain has been solved using the DoE-guided meta-heuristics-based approaches. The results obtained from the solutions approaches are analysed (prioritised and ranked) using Pareto frontier and a multi-attribute decision-making tool, TOPSIS. One of the best location-routing solutions selected by TOPSIS is geographically mapped for both the two and three-layer SC-networks. The principal focus of this research is on the two and three-layer low-carbon 0-1 mixed-integer AHP-integrated multi-objective location-routing models, its DoE-guided meta-heuristic based solution approaches and further decision-making analysis of the realistic solution sets.

The following sections delineate issues related to location-routing models, the solution approaches and analysis procedures. Section 6.2 revisits the research aims and objectives and then in the following sections the findings are discussed. Section 6.3 deals with modelling. The 6.3.1 sub-sections of this section discuss the introduction of the green elements to the two and three-layer MO-LRPs while sub-section 6.3.2 talks about the location-routing component in the two-layer MO-LRP. Section 6.4 deals with solution approach. The three sub-sections of this section discuss the optimiser performance in two-layer MO-LRP, two-phased three-layer MO-LRP and optimiser performance in the three-layer MO-LRP. Section 6.5 discusses the analysis procedure with two sub-sections dealing with TOPSIS and scenario analysis.

6.2. Re-Visiting Research Aims and Objectives

The main aims were to include the eco-friendly concerns in location-routing decisions in the context of supply chain network design. This main has been pursued by improving Berger's (1997) two-layer LRP and Perl's (1983) three-layer LRP. The improvement is introducing low-carbon elements to these LRPs. The specific objectives explained in Chapter One are briefly as follows:

- Developing low-carbon location-routing models (Modelling)
- Finding an effective solution approach to implement the developed models (Solution Approach)
- Offering targeted and tailored low-carbon low-cost scenarios to DM's considering their priorities (Analysis Procedure)

In the following sections the above objectives are discussed in more details.

6.3. Modelling

6.3.1. Introducing green elements to the two-layer and the three-layer MO-LRPs

One of the aims of this research was to improve Berger's (1997) two-layer location-routing model. The improvement is focused on inclusion of the green elements into the Berger's (1997) two-layer model. The green elements have been introduced to the model through additions to the 'objective function' and a 'constraint'. The green constraint is developed by integrating AHP within the multi-objective 0-1 mixed-integer programming framework. AHP is integrated to the parameters of the two objective functions of the MO-LRPs (Figure 6.1). The two decision-making attributes, viz., CO_2 emissions from transportation (p_{ji} and $p_{V_{sj}}, p_{L_{ji}}, p_{O_{ii}}$) and costs of serving the routes (c_{jk} and c_{sj}, c_{ji}, c_{ii}), are the parameters that link AHP to the mixed-integer programming framework through the constraint of the optimisation model. The two MO-LRPs are re-presented as follows:

Two-layer MO-LRP:

$$\text{minimise} \quad \sum_{j\in J}\sum_{i\in I}\sum_{k\in P_j} p_{ji}V_{jk} \tag*{(4-1)}$$

$$\text{minimise} \quad \sum_{j\in J} f_j X_j + \sum_{j\in J}\sum_{k\in P_j} v_j V_{jk} + \sum_{j\in J}\sum_{k\in P_j} c_{jk}V_{jk} \tag*{(4-4)}$$

$$\sum_{j\in J}\sum_{k\in P_j} V_{jk} = 1 \tag*{(4-9)}$$

$$\sum_{j\in J} V_{jk} - X_j \le 0 \qquad , \qquad \forall k \in P_j \tag*{(4-10)}$$

$$S_m(\sum_{m\in M}\sum_{n\in N} w_{mn}T_n) \le B_m \qquad , \qquad \forall i \text{ and } j \text{ on } V_{jk} \tag*{(4-11)}$$

$$V_{jk} \in \{0 \quad 1\} \tag*{(4-12)}$$

$$T_n \in \{0 \quad 1\} \tag*{(4-13)}$$

$$X_j \in \{0 \quad 1\} \tag*{(4-14)}$$

Three-Layer MO-LRP:

$$\min \sum_{s\in S}\sum_{j\in J} u_{sj}p_{V_{sj}}V_{sj} + \sum_{j\in J}\sum_{i\in I} u_{ji}p_{L_{ji}}L_{ji} + \sum_{i\in I}\sum_{i\in I} u_{O_{ii}}p_{O_{ii}}O_{ii} \tag*{(5-1)}$$

$$\min \left[\sum_{s\in S} f_s X_s + \sum_{j\in J} f_j Y_j\right] + \left[\sum_{s\in S} v_s X_s + \sum_{j\in J} v_j Y_j\right] +$$

$$\left[\sum_{s\in S}\sum_{j\in J} u_{sj}c_{V_{sj}}V_{sj} + \sum_{j\in J}\sum_{i\in I} u_{ji}c_{L_{ji}}L_{ji} + \sum_{i\in I}\sum_{i\in I} u_{O_{ii}}c_{O_{ii}}O_{ii}\right] \tag*{(5-4)}$$

subject to:

$$\sum_{s\in S}\sum_{j\in J} V_{sj} = 1 \tag*{$(5-10.a)$}$$

$$\sum_{j\in J}\sum_{i\in I} L_{ji} = 1 \tag*{$(5-10.b)$}$$

$$\sum_{i\in I}\sum_{i\in I} O_{ii} = 1 \tag*{$(5-10.c)$}$$

$$\sum_{j\in J}\sum_{i\in I} d_{ji}L_{ji} + d_{ii}O_{ii} \le \tau_k \tag*{$(5-11)$}$$

$$\sum_{s\in S}\sum_{j\in J} V_{sj} \ge 1 \tag*{$(5-12.a)$}$$

$$\sum_{j\in J}\sum_{i\in I} L_{ji} \ge 1 \tag*{$(5-12.b)$}$$

$$\sum_{i\in I}\sum_{i\in I} O_{ii} \ge 1 \tag*{$(5-12.c)$}$$

$$\sum_{j\in J} L_{ji} - \sum_{i\in I} L_{ji} = 0 \qquad (5-13.a)$$

$$\sum_{i\in I} O_{ii} - \sum_{i\in I} O_{ii} = 0 \qquad (5-13.b)$$

$$\sum_{s\in S} \sum_{j\in J} V_{sj} \le 1 \qquad (5-14.a)$$

$$\sum_{j\in J} \sum_{i\in I} L_{ji} \le 1 \qquad (5-14.b)$$

$$\sum_{i\in I} \sum_{i\in I} O_{ii} \le 1 \qquad (5-14.c)$$

$$\sum_{s\in S} Q_{sj} - \sum_{i\in I} r_i Y_j = 0 \qquad (5-15.a)$$

$$\sum_{j\in J} Q_{ji} - \sum_{i\in I} r_i Y_j = 0 \qquad (5-15.b)$$

$$\sum_{s\in S} Q_{sj} - r_j X_s \le 0 \qquad (5-16.a)$$

$$\sum_{i\in I} Q_{ii} - r_i Y_j \le 0 \qquad (5-16.b)$$

$$\sum_{j\in J} L_{ji} + \sum_{i\in I} O_{ii} - Y_j \le 0 \qquad (5-17)$$

$$S_m(\sum_{m\in M} \sum_{n\in N} w_{mn} T_n) \le B_m \quad , \quad \forall i,\ j \text{ and } s \text{ on } V_{sj},\ L_{ji} \text{ and } O_{ii} \qquad (5-18)$$

$$Y_j \in \{0 \quad 1\} \qquad (5-19)$$

$$V_{sj} \in \{0 \quad 1\} \qquad (5-20)$$

$$L_{ji} \in \{0 \quad 1\} \qquad (5-21)$$

$$O_{ii} \in \{0 \quad 1\} \qquad (5-22)$$

$$T_n \in \{0 \quad 1\} \qquad (5-23)$$

$$X_s \in \{0 \quad 1\} \qquad (5-24)$$

$$Q_{sj} \ge 0 \qquad (5-25)$$

$$Q_{ji} \ge 0 \qquad (5-26)$$

$$Q_{ii} \ge 0 \qquad (5-27)$$

The estimated CO_2 emission and costs related data presented in Table 3.7 is shared by this constraint and the objective functions. Therefore, the MO-LRPs are AHP-integrated optimisation model. Figure 5.1 illustrates how AHP is integrated to the 0-1 programming framework and links to the objective functions.

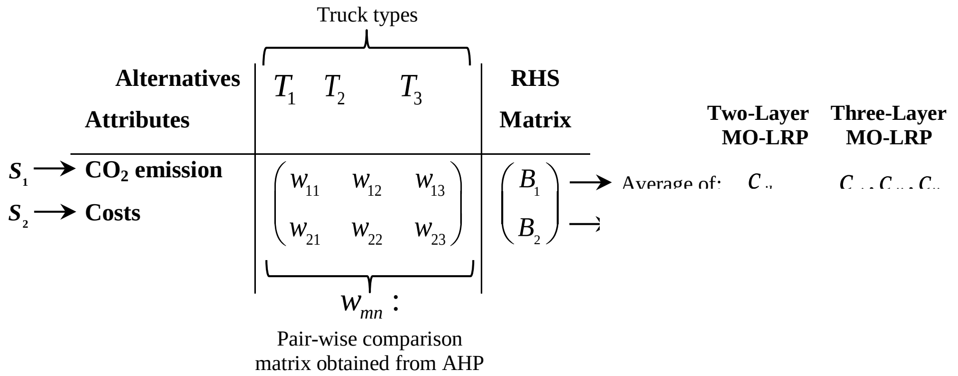


Figure 6.1 The integration of AHP to the objective functions parameters for the MO-LRPs

The green AHP-integrated constraint is mathematically identical in both the MO-LRPs. This constraint is applicable to any multi-layer LRP in order to introduce green elements. It can also be further modified to consider any number of criteria.

6.3.2. Location-routing components in the two-layer MO-LRP

Min et al. (1998) discloses that the 'hierarchical level' of LRP may have either one or two levels. The two-layer model presented in this research uses single level of hierarchy with one facility. According to Min et al. (1998) the 'facility layer' can be of 'primary' or 'secondary / intermediate'. The two-layer location-routing model uses the 'primary' facility layer. The two-layer low-carbon location-routing model obeys the characteristics of the variants of LRP models provided in Min et al. (1998), Nagy and Salhi (2007) and Laporte (1988). Therefore, the variant of the two-layer LRP proposed in this research contains both the "location" and "routing" elements.

The two-layer LRP presented in this research is a 'static LRP' in nature (Albareda-Sambola et al. 2005). The characteristics of static LRP differ from each other in the following ways (Albareda-Sambola et al. 2005):

- the type of facilities to be located: primary if they are the origins and destinations of vehicle journeys, secondary when they can only be intermediate depots
- the number of facilities to be located and whether they have capacities or not
- the number of available vehicles and whether they have capacities or not.

The two-layer ‘static LRP’ model uses ‘primary’ facilities, i.e., they are the origins and destinations of vehicle journeys. Considering Min et al. (1998), Nagy and Salhi (2007) and Laporte (1988) and all the aspects of our capacitated multi-objective two-layer AHP-integrated model it is confirmed that the two-layer model contains the elements of a ‘standard location problem’.

The ‘routing’ component of the two-layer MO-LRP can be seen from the results. Tables 3-17 and 3-21 of Chapter Three show the routing patterns. These Tables show that the two-layer MO-LRP aids in routing trucks in combination with the ‘standard location problem’. Further, the second objective function of the model considers the ‘costs for vehicle-routing’. The ‘standard location problem’ and ‘routing of the vehicles’ are both addressed in this model. It is therefore concluded that this model is truly a location-routing problem.

6.3.3. Findings

In terms of modelling, this research contributes to the LR literature by inclusion of eco-friendly concerns in modelling two-layer and three-layer LRPs. The focus has been on two LR models:

- Berger’s (1997) two-layer LR model: this model has been improved by inclusion of low-carbon elements in the model
- Perl’s (1983) three-layer LR model: this model has been improved by inclusion of low-carbon elements

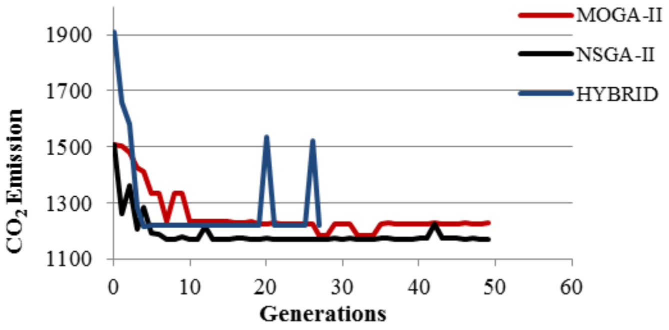
Low-carbon elements have been included by developing: i) an objective function to minimise the carbon emission from transportation throughout the SC, and ii) an AHP-integrated constraint to include the DM’s priorities. To the best of our knowledge, the AHP-integrated green constraint is the first of its kind in LR modelling. The developed models are generic Multi-Objective Location-Routing models.

6.4. Solution Approach

6.4.1. Optimiser performance in two-layer MO-LRP

In addition to the results presented earlier, two more optimisers have been used to implement the two-layer MO-LRP model in addition to MOGA-II, NSGA-II and MOPSO optimisers. These two optimisers are a GA-based (HYBRID) and a Simulated Annealing (SA)-based optimiser (MOSA).

HYBIRD (in modeFRONTIER$^{®}$) is an algorithm which combines the global exploration capabilities of genetic algorithms with the accurate local exploitation guaranteed by SQP implementations. It is ‘a combination of a steady-state genetic algorithm with a Sequential Quadratic Programming optimiser’ (Turco 2011). The MOSA algorithm, which is inspired by thermodynamics, is based on a Single and Multi-Objective Simulated Annealing optimiser in modeFRONTIER$^{®}$. The results obtained from these two optimisers show that they are not efficient in obtaining optimal results for the two-layer MO-LRP. Figure 5.2 presents a comparative convergence study on GA-bases optimisers used for solving the two-layer MO-LRP.



Figures 6.2 Comparative convergence on GA-based optimisers

As can be seen from Figure 6.2, HYBRID is converging in a very unusual way and is still not showing the convergence of results after the 27th generation. The combination of GA and SQP in HYBRID doesn’t perform effectively in reaching an optimal result for the two-layer MO-LRP.

MOSA is a Simulated Annealing based optimiser. The final state of the MOSA algorithm, unlike the genetic algorithms, appears out of the ‘cloud’ during the cold phase of the evolution – the track from generation to generation during the hot phase isn’t really indicative of progressive convergence. Basically the very idea of a convergence plot in

MOSA is not appropriate, since it should not be converging during the hot phase - it should be exploring. It's only in the cold phase that it starts to really make use of convergence, with the Pareto set emerging from the mist. Therefore, a convergence study on the results obtained from MOSA is not possible. Table 5.1 presents the results obtained from MOSA in 50 generations for the two-layer MO-LRP.

Table 6.1 Statistical summary of results obtained from MOSA

Type of results	**Number of Real Feasible Results**	**CO_2 emission (Objective Function I)**		**Costs (Objective Function II)**	
		Min	**Max**	**Min**	**Max**
Results table	2,550	1,347	2,228	187,969	300,560
Realistic results table	50	1,486	2,187	187,969	299,879
Selected results table	30	1,486	2,002	187,969	298,396

In comparison with the other optimisers used to solve the two-layer MO-LRP, the results obtained from MOSA are not optimum. Tables 4.11 and 4.15 presented a summary of the results for the MOGA-II, NSGA-II and MOPSO optimisers in Phase-I and Phase-II. Therefore, HYBRID and MOSA optimisers were deemed not suitable for solving the three-layer MO-LRP.

A Comparative study on the performance of optimisers, reveals that NSGA-II works efficiently as compared with MOGA-II and MOPSO in obtaining the optimal results for the two-layer MO-LRP. This is because: (i) NSGA-II is converging in a more steady manner over 50 generations, (ii) the selected results obtained from NSGA-II are strongly Pareto efficient, (iii) the results obtained from NSGA-II are more optimum than the results obtained form MOGA-II and MOPSO with respect to the value of objective functions (Tables 4.11 and 4.15).

6.4.2. Two phased three-layer MO-LRP

In the literature multi-phases heuristics, algorithms and solution approaches are used to solve three-layer LRPs. These solution approaches typically divide the problem into its components, viz. facility location, allocation of consumers to facilities, and vehicle routing (Hassanzadeh et al. 2009). Perl (1983) and Wu et al. (2002) offer multi-phased heuristics. These algorithms solve the three-layer LRP in consecutively connected multi-phases. Perl (1983) solves the three-layer LRP using a three phased heuristic. The first phase finds the optimum routes. In the second phase, open facilities are determined with routes from phase one being connected to open facilities. The third phase improves the solution '*by moving customers between facilities and re-solving the routing problem* *with the set of open facilities fixed*' (Daskin et al. 2010). Wu et al. (2002) solves the three-layer LRP in two phases. The two phased algorithm proposed by Wu et al. (2002) is similar to the Perl (1983) algorithm. It combines the first two phases of Perl's (1983) three phased approach. Perl's (1983) algorithm and Wu et al.'s (2002) two phased algorithm connect the multi-phases of the solution approach by including the results of each phase in the next phase. The three-layer MO-LRP presented in Chapter Four considers the reported practices in order to implement the model in two inter-linked phases.

The two phased solution approach introduced to solve the three-layer MO-LRP in chapter four is implemented in two inter-linked phases. Phase-I of the solution approach: (i) connects the open plants to DCs (allocation and vehicle-routing decision), (ii) finds the optimal open DCs (facility location decision), and (iii) allocates retailers to open DCs (allocation and vehicle-routing decision). Phase-II of the solution approach considers the connections among retailers. The solution approach in this phase allocates the un-served retailers to served retailers from Phase-I. Retailers do not supply products. Therefore, DCs serving the open retailers have to be included in Phase-II. The final result is obtained when both the phases are solved.

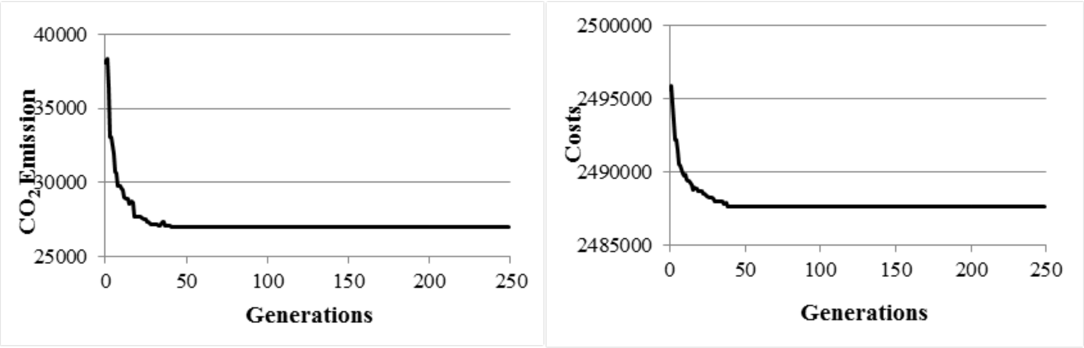
6.4.3. Optimiser performance in three-layer MO-LRP

The three-layer MO-LRP is a variant of the two-layer MO-LRP. The two MO-LRPs are both computationally NP-hard with a multi-objective nature. MOGA-II, NSGA-II and MOPSO optimisers that performed efficiently in solving the two-layer MO-LRP are used to execute the three-layer MO-LRP. The solution approach of the three-layer MO-LRP is of two phases. If an optimiser is selected to implement Phase-I, the same optimiser is used to solve the Phase-II. MOGA-II and MOSPSO reach the optimum solution space in 250 generations while NSGA-II reaches the optimum solution in 50 generation. Table 6.2 presents the results obtained form NSGA-II in 250 generations. Figure 6.3 presents the convergence plots for NSGA-II in 250 generations with regard to objective functions.

Table 6.2 Statistical summary on the performance of NSGA-II

Type of results		Number of real results	CO$_2$ emission (Objective function I)		Costs (Objective function II)	
			Min	**Max**	**Min**	**Max**
Phase-I	Results table	12,500	26,689	55,621	2,487,644	2,552,395
	Realistic results table	398	26,689	35,369	2,487,644	2,507,100
	Selected results table	40	26,689	34,239	2,487,644	2,501,009
Phase-II	Results table	12,500	1,036	3,670	722	2,536
	Realistic results table	388	1,036	1,826	722	1,266
	Selected results table	40	1,036	1,625	722	1,252

As compared with results obtained from MOGA-II and MOPSO (Tables 5.11 and 5.15), NSGA-II obtains a set of less optimum results. It is evident from Figure 6.3 that NSGA-II repeats the last result it obtained before the 50th generation. The curve is asymptotic to the ‘generations’ axis. Therefore, it can be concluded that this optimiser is not converging properly over 250 generations.



a. Convergence w.r.t CO$_2$ emission b. Convergence w.r.t costs

Figure 6.3 Convergence of NSGA-II w.r.t. objective functions

In comparison with results obtained from NSGA-II in 50 generations (Tables 4.11 and 4.14), the optimum results with regard to both objective functions is reached by NSGA-II in 50 generations.

A comparative study on MOGA-II, NSGA-II and MOPSO reveals that NSGA-II is performing efficiently among the three optimisers in solving the three-layer MO-LRP. Some conclusive observations are: (i) the number of realistic results obtained from MOGA-II is 3% and from MOSPO is 4% while from NSGA-II it is 7% of the total results, (ii) NSGA-II achieves the best optimal results within 50 generations, and (iii) NSGA-II is converging in a more steady manner (Figures 5.16, 5.16 and 5.17).

6.4.4. Findings

One of the objectives of this research was to find a proper platform to execute the developed models. modeFRONTIER® has been recognised as the most suitable execution platform. The solution approach is DoE-guided. The DoE-guided solution approach is efficiently finding optimised solution spaces. Literature reveals that this form DoE-guided solution approach haven't been used before to solve LRPs. Optimisers with different natures have been used and their performance have been compared and discussed in Chapter 4, 5 and 6).

As explained in Chapter Two, three-layer LRPs are usually solved using multi-phase algorithms. This research has solved the three-layer MO-LRP using a two-phased approach. This solution approach approved to be efficient in finding an optimised solution space for the three-layer MO-LRP.

6.5. Analysis Procedure

6.5.1. TOPSIS

The analysis process (Figure 4.11) starts with analysing the total set of results obtained from each optimiser and ends with finding a set of selected ranked results using TOPSIS in each phase. TOPSIS with its specifications is more suitable for ranking results obtained from MO-LRPs compared to other MCDM techniques such as ELECTRE.

Methodologically, TOPSIS and ELECTRE (ELimination Et Choix Traduisant la REalité or ELimination and Choice Expressing Reality) (Roy et al. 1968) are widely accepted tools for ranking purposes. ELECTRE is a family of MCDM methods and consists of two main phases. The first phase constructs one or several outranking relations while the second phase elaborates on the recommendations which are obtained from phase one. Originally ELECTRE was used to outrank some alternatives to the problem which are not acceptable. When the un-acceptable alternatives are eliminated, another MCDM method can be used for ranking and selecting the results (Roy et al. 1968; Jose et al. 2005). ELECTRE later was applied to choosing, ranking and selecting alternatives as well. On the contrary, the concept behind TOPSIS is that the selected alternatives must have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution. It compares a set of alternatives based on a set of criteria. The comparison process is conducted by identifying weights for each criterion, normalising the scores for each criterion and then calculating the geometric distance between each alternative and the ideal alternative which is the best score in each criterion (Hwang and Yoon 1981; Zavadaska et al. 2006).

The solution spaces of the two and three-layer MO-LRPs are defined by DOE-guided optimisers. The GA and PS-based optimisers start from an initial point within a solution space which is defined by DoE to ensure robustness. The optimisers converge from the initial point towards the best possible point(s) based on the objective(s) of the optimisation model. Sets of optimal solutions reached by the optimisers for the MO-LRPs are all real and feasible and range from maximum values for both objective functions towards minimum values. The maximum and minimum results can be considered as negative ideal and positive ideal solutions while the objective functions work as criteria for selecting a solution from one generation to another. Furthermore, the obtained results are refined and selected considering the priorities of DMs. These set of selected results are then ranked. Considering these specifications of the solution approach and the process of analysing results, TOPSIS is more suitable to rank the real selected results.

6.5.2. Scenario analysis

Tables 3.17 and 3.21 present the effect of opening a closed route on total CO_2 emission and total cost. One of the general shortcomings of LRPs is their static nature; in the case of such static models, re-solving is necessary if any changes are made to the models original settings. Inclusion of the scenario analysis on routing patterns enables the DMs to rapidly respond to critical situations (e.g. natural disasters, constructions on roads, etc.) with a good set of clear accurate alternatives for the short term. The availability of the alternative scenarios in critical situations is a cost-efficient green competitive advantage for SCs and DMs.

6.5.3. Findings

The developed MO-LPRs have been tested on a dairy supply chain in east of Ireland. The obtained results have been ranked using TOPSIS. Different types of DMs with regard to two main criteria (Cost and CO_2 Emission) have been considered. This approach suggests tailored solutions form the feasible optimise solution space to DMs.

As a part of the analysis procedure, scenario analysis is performed. This analysis offers flexibility and a variety of scenarios to DMs and managers.

6.6. Summary

This chapter summarised and discussed the findings of the research by re-visiting the aims and objectives of the research. The main areas of discussion have been modelling, solution approach and analysis procedure. The next chapter of this dissertation will conclude the findings of the research and will highlight the contributions.

CHAPTER SEVEN

Conclusions

7.1. Introduction

Sustainable development in supply chains has become one of the most important socio-economic issues in recent years. SC network design decisions are considered to be one of the major concerns in supply chains with substantial implications for low-carbon issues. Besides the environmental concerns of SCs, there is a significant contribution from product distribution costs which is attributable to total SC costs. Location-routing decisions have a dual decision-making impact on SC networks by assisting in decision-making for both facility location and vehicle-routing patterns.

This research on low-carbon location-routing contributes to the literature in the area of SC network design. Two and three layers of a SC network are considered and two generic multi-objective low-carbon location-routing models are designed and developed. The generic models integrate AHP into the multi-objective 0-1 mixed-integer programming framework. These models minimise the total CO_2 emission and the total cost of location-routing throughout two and three-layer SC networks. The green MO-LRPs are a combined strategic and tactical decision-making procedure within the SC networks.

The green models assist in optimising the total carbon emission stemming from the transportation and optimise the total cost involved the process. Two independent GA-based and one PS-based optimisers are employed to solve the green capacitated optimisation models. DoE plays a pivotal role in achieving the optimal and realistic solution spaces. The performances of the two GA-based and one PS-based optimisers involved in implementing the computationally NP-hard green integrated models are compared based on the objective function values and convergence. The selected Pareto efficient realistic results are evaluated using TOPSIS thereby suggesting the best candidate-results. It is found that NSGA-II is the best optimiser as compared with the other optimisers. The optimal facility location, vehicle routing patterns, truck types and number of trucks in each route are offered. The low-cost and low-carbon routing patterns are identified and mapped geographically. Various scenarios are offered for routing patterns to analyse the effect of opening the closed routes which may be required to open when disruption events strike a SC network. The proposed green models can be applied for any capacitated two-layer and three-layer SC network.

7.2. Contributions

The two-layer MO-LRP is an improvement to the model of Berger (1997) and the three-layer MO-LRP in an improvement to Perl's (1983) model. The three-layer MO-LRP is a variant of the two-layer MO-LRP as well. The improvement is focused on inclusion of eco-friendly consideration into the models. These two generic models have been implemented on the case of a two and three-layer dairy SC network in Ireland using the modeFRONTIER® commercial solver and a variety of GA-based and PS-based optimisers. The realistic Pareto efficient results are ranked using TOPSIS. Examples of results are geographically mapped.

The main contributions of this research are as follows:

- Designing a generic low-carbon two-layer MO-LRP applicable to various SC networks
- Designing a generic low-carbon three-layer MO-LRP applicable to various SC networks
- Integration of AHP with the 0-1 mixed-integer framework of the two MO-LRPs
- DoE-guided solution approach for the two and three-layer MO-LRPs
- Introduction of a two phased solution method for the three-layer MO-LRP
- Ranking selected results by using TOPSIS
- Providing scenario analysis
- Identification of low-carbon routing patterns and mapping them geographically

The green elements of the models are twofold: a green objective function is defined in order to minimise the total CO_2 emission from transporting the products throughout the SC network. An AHP-integrated green constraint introduces the DMs' priorities to the models on their consensus opinions in regard to selection of the trucks. AHP-integrated constraint brings in the priorities of DMs with regard to the choice of the trucks. The trucks are categorised based on two main attribute (criteria), viz. total cost and total CO_2 emission.

DoE is responsible for generating the initial population table for the optimisers in modeFRONTIER®. Disparate optimisers are used for obtaining a real feasible solution space and sets of solutions. A two phased inter-connected DoE-guided solution method is implemented to execute the NP-hard three-layer MO-LRP. TOPSIS, a MCDM ranking technique, is implemented to rank the selected results.

Scenario analysis is providing the MDs with alternatives in order to maintain the delivery of products to customers when there is a routing-related interruption in the SC network.

Nowadays companies are increasingly interested in optimising their SC networks considering eco-friendly considerations. In Ireland, Glanbia plc (one of Ireland's largest food supply chain companies and a global nutritional and dairy business groups) has invested in optimising its SC network and gained good results. In 2009 Glanbia invested in Paragon Software Systems, a multi depo routing and scheduling system. In 2010 the company announced that it has saved 16% in delivery costs within six months. According to the companies announcements in 2012, implementing the new system cut 106,000 km from delivery routes, improved vehicle utilisation by 15% and reduced the annual number of routes by 10%. As a result an overall reduction in CO_2 emissions of over 100 tonnes per year has veen achieved. In late 2010 LLamasoft announced that its SAP Guru Connector module within Supply Chain Guru® has achieved certified integration with SAP® applications. According to the SC director of Glanbia, the company has 'completed a highly successful supply chain network design and cost to serve initiative using LLamasoft earlier this year'. In late 2012 head of operations in Glanbia said that supply chain sustainability is a priority for blue chip firms. This firm has a Carbon Trust Accreditation and operates under ISO 50001 Global Energy Management Standard. Many more examples of global supply chain companies interested in sustainable supply chain network design are available in public record.

7.3. Validation and the Limitation of the Models

In this research, in order to test the validity of the developed models on the test case, main players of the dairy market in Ireland have been recognised. The information has been gathered about the structure of demand side of SCs in Ireland by using a questionnaire. The structure of the two-layer and three-layer SC cases have been then validated by: (a) interviewing a consultant to few dairy companies in Ireland, (b) interviewing experts from two major dairy companies in Ireland, (c) using company profiles, technical reports from dairy companies, outcomes of researches on dairy SCs, and SC text books.

The main limitation of this research is that the generic two-layer and three-layer low-carbon MO-LRPs have been tested only on dairy supply chains in Ireland. This limitation is due to time limits and unavailability of real data from other companies and their specific supply chain structures. If these constraints allow, the developed models can be tested on various types of supply chains with different structures. Testing the models on more than one supply chain will result in the possibility of comparing and further analysis of the obtained results.

7.4. General Recommendations

The literature review reveals that green issues are generally well represented in recent times. However in the field of facility location and location-routing decisions have not been widely studied. Considering the importance of environmental issues and the contribution of facility and vehicle-routing decisions to the environment, green issues should be more focused on in this field.

It is also noted from the literature that DM’s opinions are generally not involved in SC network design models and a ‘one size fits all’ approach is generally applied. Facility location and location-routing models would benefit in being more flexible by including DMs’ preferences. MCDM techniques such as proposed here allows this flexibility.

Another area of advancement in this this study in solving LRPs, is the use of a DoE-guided solution approach for NP-hard multi-objective LRPs. This approach worked successfully with the models developed in this study and can also be considered for similar models.

In order to offer DMs alternatives when facing sudden changes in their vehicle-routing patterns, scenario analysis is suggested.

7.5. Suggestions for Future Research

The developed MO-LRP models have the possibility of being tested by integrating other MCDM techniques into the 0-1 mixed-integer programming framework in order to bring flexibility to the integrated models. The traversed distance throughout the SC network can be minimised by including a new objective function in the models. The implementation of the sustainable MO-LRPs does not consider the dynamicity of the problem. The capacitated models do not take into account the variability in the demand. Therefore, a future research direction may be towards appropriate integration of dynamic programming with the existing green integrated optimisation models. The routing patterns would be fortified if closely-located multiple retailers are served by a single vehicle. This emerges as a more realistic and complex scenario having a large number of objective functions, constraints and parameters. Minimisation of the CO_2 emission from the facilities can be another issue for future research.

The DoE-guided solution approach has scope for further improvement. Adequate, preventative post-hoc control can be conducted to investigate the type-I error rate. This analysis will assist in finding patterns of the GA-based optimisers and relationships among the parameters. Further, the investigation on the performance of the designed green models can be extended using a multi-objective agent-based approach. In order to benchmark the MO-LRPs different types of SC networks should be considered. The effect of testing different sizes of SC networks on the proposed MO-LRPs would be another scope for future research.

There is a possibility of using other MCDM methods for selecting and ranking results. The inclusion of the facility location decisions in the scenario analysis for both the MO-LRPs is another scope for future research. Geographical simulation of the optimal and realistic vehicle routes on the map using software packages like Route LogiX is another scope for further research. Use of eco-friendly vehicles and fuels would contribute to the minimisation of the CO_2 emission in the SC networks.

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Appendix A

Table A.1 Logistics decisions (Source: Riopel et al. 2009)

Decisions	**Previous decision(s)**	**Additional information**
Strategic planning level		
1. Definition of customer service		▪ Organizational mission and strategy ▪ Customer expectation ▪ Competitive environment ▪ Financial resource availability ▪ Existing logistics system
2. Customer service objectives	1.Definition of customer service	
3. Degree of vertical Integration & Outsourcing	2.Customer service objectives	▪ Resource availability (capital, personnel, facilities, and equipment)
Physical Facility (PF) network		
4. PF Network Strategy	2.Customer service objectives 3.Degree of vertical Integration & Outsourcing	▪ Existing suppliers ▪ Existing customers ▪ Potential suppliers ▪ Potential customers & markets
5. PF Network Design, including: - Type of facility - Number of each type of facility - Size of facility - Facility location - Activities & services from each facility - Utilization of new or existing facilities - Links between facilities	4.PF Network Strategy	▪ Capability & availability of labour & support services ▪ Availability of appropriate facilities & sites ▪ Availability of transportation ▪ Government incentives ▪ Community attitudes ▪ Standards & regulations ▪ Utilities ▪ taxes
Communication and Information (C&I) network		
6. C & I network strategy	2.Customer service objectives 3.Degree of vertical Integration & Outsourcing 4.PF Network Strategy	▪ existing C&I systems of the organization ▪ existing suppliers ▪ existing customers ▪ potential suppliers ▪ potential customers
Inventory management		
7. C&I network design, including: - Network architecture & capacities - Hardware selection - Software selection -vendor selection -Extent of information technology used	5. PF Network Design 6. C & I network strategy	▪ Capability & availability of labour & support services ▪ Availability of appropriate facilities & sites ▪ Government incentives ▪ Community attitudes ▪ Standards & regulations
Demand forecasting		
8.Forecasts of demand magnitude, timing and locations		▪ Historical sales data ▪ Environmental & economic data ▪ Marketing strategies
9.Inventory management strategy	2. Customer service objectives 7.C&I network design	▪ Nature of products ▪ Nature of demand
10. Relative importance of inventory	20. Suppliers	▪ Item value ▪ Historical sales data
11. Control methods	10. relative importance of in-	▪ Nature of products

	ventory	▪ Nature of demand
12. Desired inventory level	2. Customer service objectives 8.Forecasts of demand magnitude, timing and locations 20. Suppliers	▪ Product equipment / personnel characteristics ▪ Replenishment delay
13. Safety stock	12. Desired inventory level	▪ Item value ▪ Replenishment delay
Production		
14. Product routing		▪ Product characteristics ▪ Production equipment / Personnel characteristics
15. Facility layout	2. Customer service objectives 5. PF network design 14. Product routing	▪ Product equipment / personnel characteristics
16. Master production schedule	5. PF network design 12. Desired inventory level	▪ Current inventory levels
17. Production scheduling	14. Product routing 15. Facilities layout 16. Master production schedule	▪ Product equipment / personnel characteristics
Production and supply management		
18. Procurement type	2. Customer service objectives 5. PF network design	▪ Cost to make & cost to buy ▪ Resource availability (capital, personnel, facilities, & equipment) ▪ Availability of products ▪ Nature & magnitude of risks
19. Specifications of goods procured	18. Procurement type	▪ Product design specifications ▪ Product equipment / personnel characteristics
20. Suppliers	5. PF network design 9. Inventory management strategy 19. Specifications of goods procured	▪ Suppliers performance & capabilities ▪ Procurement policies ▪ Transportation options
21. Order intervals & quantities	16. Master production schedule 20. Suppliers	▪ Discount opportunities
22. Quality control	20. Suppliers	▪ Characteristics of products to procure
Transportation		
23. Transportation modes	2. Customer service objectives 5. PF network design 16. Master production schedule	▪ Transportation options ▪ Standards & regulations ▪ Product characteristics
24. Types of carriers	17. Production scheduling 23. Transportation modes	▪ Historical sales data ▪ Carrier options ▪ Standards & regulations ▪ Product characteristics
25. Carriers	24. Types of carriers	▪ Carriers' performance & capabilities
26. Degree of consolidation	5. PF network design 21. Order intervals & quantities 24. Types of carriers	▪ Customer location ▪ Product characteristics
27. Transportation fleet mix	8.Forecasts of demand magnitude, timing and locations 24. Types of carriers 26. Degree of consolidation	▪ Product characteristics ▪ Transport fleet options
28. Assignment of customers to vehicles	27. Transportation fleet mix 35. Packaging design	▪ Customer location ▪ Customer demands ▪ Product characteristics ▪ Access to receiving/shipping

		docks
29. Vehicle routing & scheduling	5. PF network design 28. Assignment of customers to vehicles	▪ Customer location ▪ Customer demands ▪ Time windows
30. Vehicle load plans	29. Vehicle routing & scheduling	
Product Packaging		
31. Level of protection needed	12. Desired inventor level 23. Transportation modes 37. Types of material handling equipment	▪ Product value ▪ Environmental conditions ▪ Standards & regulations ▪ Product characteristics ▪ Duration of storage
32. Information to be provided with product		▪ Product characteristics ▪ Customer needs ▪ Standards & regulations
33. Information media	32. Information to be provided with product	▪ Options of communicating information
34. Types of packaging	31. Level of protection needed 32. Information to be provided with product	▪ Product characteristics ▪ Packaging material options ▪ Reusing/recycling options
35. Packaging design	34. Types of packaging	▪ Product characteristics ▪ Customer needs
Material handling		
36. Unit loads	9. Inventory management strategy 17. Production scheduling 21. Order intervals & quantities 35. Packaging design	▪ Characteristics of objects to handle ▪ Customer needs ▪ Production equipment/personnel characteristics
37. Types of material handling	15. Facility layout 36. Unit loads 41. Warehouse layout 47. Order picking procedure	▪ Material handling options
38. Material handling fleet mix	37. Types of material handling equipment	▪ Production equipment/personnel characteristics ▪ Material handling equipment performance & capabilities
39. Material handling fleet control	9. Inventory management strategy 17. Production scheduling 38. Material handling fleet mix 47. Order picking Procedure	
Warehousing		
40. Warehousing mission & function	2. Customer service objectives	▪ Product characteristics ▪ Nature of demand
41. Warehouse layout	9. Inventory management strategy 12. Desired inventory level 35. Packaging design 37. Types of material handling equipment 40. Warehousing mission & functions	▪ Safety of employees
42. Stock location	2. Customer service objectives 10. Relative importance of inventory 41. Warehouse layout	▪ Product characteristics
43. Receiving/shipping dock	23. Transportation modes	▪ Characteristics of received &

design	35. Packaging design 36. Unit modes 38. Material handling fleet mix 40. Warehousing mission & functions	shipped goods ▪ Amount of product to handle at dock ▪ Safety of employees
44. Safety systems	40. Warehousing mission & functions 41. Warehouse layout 43. Receiving/shipping dock design	▪ Product characteristics
Order Processing		
45. Order entry procedure	6. C&I network strategy 7. C&I network design	▪ Customer demands ▪ Range of products ▪ Capability & availability of labour & support services
46. Order transmission means	45. Order entry procedure	
47. Order picking procedures	6. C&I network strategy 35. Packaging design 36. Unit modes 38. Material handling fleet mix 42. Stock location	▪ Customer demands
48. Order follow-up procedures	5. PF network design 7. C&I network design	▪ Customer demands

A.2. Facility Location Models

Inputs and sets:

I : set of customer locations, indexed by i

J : set of candidate facility locations, indexed by j

h_i : demand at customer location $i \in I$

f_j : fixed cost of locating facility at candidate site $j \in J$

c_{ij} : unit cost of transporting between candidate facility site $j \in J$ and customer location $i \in I$

Decision variables:

$$X_j = \begin{cases} 1, & \text{if we locate at candidate site} j \in J \\ 0, & \text{if not} \end{cases}$$

Y_{ij} = fraction of the demand at customer location $i \in I$ that is served by a facility at site $j \in J$

- **Uncapacitated facility location model with single sourcing** (Daskin et al., 2005):

Considering the above notations, the formulation of the mode is as follows:

$$\text{minimise} \sum_{j \in J} f_j X_j + \sum_{j \in J} \sum_{i \in I} h_i c_{ij} Y_{ij}$$

$$\begin{aligned} \text{subject to: } \sum_{j \in J} Y_{ij} &= 1 && \forall i \in I \\ Y_{ij} - X_j &\le 0 && \forall i \in I; \forall j \in J \\ X_j &\in \{0,\ 1\} && \forall j \in J \\ Y_{ij} &\in \{0,\ 1\} && \forall i \in I; \forall j \in J \end{aligned}$$

- **Capacitated facility location model** (Daskin et al., 2005)

If b_j : the maximum demand that can be assigned to a facility at candidate site $j \in J$ is added to the above notations, the formulation of the model is as follows:

$$\text{minimise} \sum_{j \in J} f_j X_j + \sum_{j \in J} \sum_{i \in I} h_i c_{ij} Y_{ij}$$

subject to: $\sum_{j \in J} Y_{ij} = 1 \qquad \forall i \in I$

$$\sum_{i \in I} h_i Y_{ij} - b_j X_j \leq 0 \qquad \forall i \in I; \forall j \in J$$

$$X_j \in \{0,\ 1\} \qquad \forall j \in J$$

$$Y_{ij} \in \{0,\ 1\} \qquad \forall i \in I; \forall j \in J$$

- **Locating plants and distribution centres with multiple commodity** (Geoffrion and Garves, 1974):

Inputs and sets:

K: set of plant locations, indexed by k

L: set of commodities, indexed by l

D_{li}: demand for commodity $l \in L$ at customer $i \in I$

S_{lk}: supply of commodity $l \in L$ at plant $k \in K$

V_j: variable unit cost of throughput at candidate site $j \in J$

c_{lkji}: unit cost of producing and shipping commodity $l \in L$ between $k \in K$, candidate facility site $j \in J$ and customer location $i \in I$

Decision variable:

$$Y_{ij} = \begin{cases} 1, & \text{if demand at customer site } i \text{ are served by facility at candidate site } j \in J \\ 0, & \text{if not} \end{cases}$$

Z_{lkji} = quantity of commodity $l \in L$ shipped between plant $k \in K$, candidate facility site $j \in J$ and customer location $i \in I$

Formulation for model:

$$\text{minimise} \sum_{j \in J} f_j X_j + \sum_{j \in J} v_j \Big(\sum_{i \in I} \sum_{l \in L} D_{li} Y_{ij}\Big) + \sum_{l \in L} \sum_{k \in K} \sum_{j \in J} \sum_{i \in I} c_{lkji} Z_{lkji}$$

$$\text{subject to: } \sum_{j \in J} \sum_{i \in I} Z_{lkji} \leq S_{lk} \qquad k \in K; 1 \in L$$

$$\sum_{k \in K} Z_{lkji} = D_{li} \mathrm{Y}_{ij} \qquad 1 \in L; j \in J; i \in I$$

$$\sum_{j \in J} Y_{ij} = 1 \qquad i \in I$$

$$V_j X_j \leq \sum_{i \in I} D_{li} Y_{ij} \leq V_j X_j \qquad j \in J$$

$$X_j \in \{0,\ 1\} \qquad j \in J$$

$$Y_{ij} \in \{0,\ 1\} \qquad i \in I; j \in J$$

$$Z_{lkji} \geq 0 \qquad i \in I; j \in J; k \in K; l \in L$$

A.3. Mathematical formulation of two-layer and three-layer LRPs

The notations for the mathematical formulation of a two-layer LRP (Berger 1997) are as follows:

Inputs and sets:

I : set of customer locations, indexed by i

J : set of candidate facility locations, indexed by j

f_j : fixed cost of locating facility at candidate site $j \in J$

c_{ij} : unit cost of transporting between candidate facility site $j \in J$ and customer location $i \in I$

P_j : set of feasible paths from candidate distribution centre $j \in J$

c_{jk} : cost of serving the path $k \in P_j$

a_{ik}^{j} : 1 if delivery path $k \in P_j$ visits customer $i \in I$; 0 if not

Decision variables:

$$V_{jk} = \begin{cases} 1, & \text{if path } k \in P_j \text{ is operated out of distributiin centre } j \in J \\ 0, & \text{if not} \end{cases}$$

Considering the above notations Berger (1997) formulates the two-layer LRP based on the classical fixed charge facility location model as follows:

$$\text{minimise} \quad \sum_{j \in J} f_j X_j + \sum_{j \in J} \sum_{k \in P_j} c_{jk} V_{jk}$$

$$\begin{aligned} \text{subject to: } & \sum_{j \in J} \sum_{k \in P_j} a_{ik}^{j} V_{jk} = 1 && \forall i \in I \\ & V_{jk} - X_j \le 0 && \forall j \in J; \forall k \in P_j \\ & X_j \in \{0, 1\} && \forall j \in J \\ & V_{jk} \in \{0, 1\} && \forall j \in J; \forall k \in P_j \end{aligned}$$

Objective function of this model minimises the sum of the facility location costs and the vehicle-routing costs. The first constraint of this model requires each demand node to be connected to one route. The second constraint states that a route can only be assigned to one open facility. The third and fourth constraints and are standard internality constraints.

Berger ‘s (1997) LRP is very much similar to the classical fixed charge facility location model but it is more difficult to solve. Daskin et al. (2010) states two reasons for this difficulty. The first reason is regarding the linear programming relaxation which has a weak lower bound. Daskin et al. (2005) suggested a solution to this issue by replacing the second constraint with the following constraint:

$$\sum_{k\in P_j} a_{ik}^{j} V_{jk} - X_j \le 0 \qquad \forall i \in I; \forall j \in J$$

This new constraint strengthens the linear programming relaxation of Berger’s (1997) LRP. The second reason for the difficulty in solving the Berger’s (1997) two-layer LRP is that an ‘exponential number of feasible paths associated with any candidate facility’.

The three-layer LRP typically considers three players on the demand side of the SC. These three layers are plant(s), DC(s) and retailer(s). Perl (1983) and Perl and Daskin (1985) extend the Geoffrion and Garves (1974) model to consider multiple stop tours serving the retailer. This model is limited to single commodity. Perl (1983) defines the following additional notations:

Inputs and sets.

P: set of points $= I \cup J$

d_{ij}: distance between node $i \in P$ and node $j \in P$

$\underline{V}_j, \overline{V}_j$: minimum and maximum annual throughput allowed at DC $j \in J$

v_j: variable cost per unit processed by a facility at candidate facility site $j \in J$

t_j: maximum throughput for a facility at candidate facility site $j \in J$

h_i: demand at customer location $i \in I$

S: set of supply points (analogous in the Geoffrion and Garves (1974) model)

c_{sj}: unit cost of shipping from supply point $s \in S$ to candidate facility site $j \in J$

Z_{ijk}: the quantity shipped from DC $j \in J$ to customer location $i \in I$

K: set of candidate vehicles, indexed by k

σ_k : capacity of vehicle $k \in K$

τ_k : maximum allowable length of a route served by vehicle $k \in K$

α_k : cost per unit distance for deliver on route $k \in K$

Decision variables.

$$Z_{ijk} = \begin{cases} 1, & \text{if vehicle } k \in K \text{ goes directly from point } i \in I \text{ to point } j \in P, \\ 0, & \text{if not} \end{cases}$$

$W_{sj} =$ quantity shipped from supply source $s \in S$ to facility site $j \in J$

Considering the above notations and the notations previously defined for the two-layer LRP, Perl (1983) formulates the following three-layer LRP:

$$\text{minimise} \quad \sum_{j\in J} f_j X_j + \sum_{s\in S}\sum_{j\in J} c_{sj} W_{sj} + \sum_{j\in J} v_j \sum_{i\in I} h_i Y_{ij} \sum_{j\in P}\sum_{i\in P} d_{ij} Z_{ijk}$$

$$\begin{array}{lll}
\text{subject to:} & \sum_{k\in K}\sum_{j\in P} Z_{ijk} = 1 & \forall i \in I \\
& \sum_{i\in I} h_i \sum_{j\in P} Z_{ijk} \le \sigma_k & \forall k \in K \\
& \sum_{j\in P}\sum_{i\in P} d_{ij} Z_{ijk} \le \tau_k & \forall k \in K \\
& \sum_{j\in P}\sum_{i\in P} d_{ij} Z_{ijk} \le \tau_k & \forall k \in K \\
& \sum_{i\in V}\sum_{j\in \bar{V}}\sum_{k\in K} Z_{ijk} \ge 1 & \forall V \subset P; \forall J \subset K \\
& \sum_{j\in P} Z_{ijk} - \sum_{j\in P} Z_{ijk} = 0 & \forall i \in P; \forall k \in K \\
& \sum_{j\in J}\sum_{i\in I} Z_{ijk} \le 1 & \forall k \in K \\
& \sum_{s\in S} W_{sj} - \sum_{i\in I} h_i Y_{ij} = 0 & \forall j \in J \\
& \sum_{s\in S} W_{sj} - t_j X_j \le 0 & \forall j \in J \\
& \sum_{m\in P} Z_{imk} - \sum_{h\in P} Z_{ihk} - Y_{ij} \le 1 & \forall j \in J; \forall i \in I; \forall k \in K \\
& X_j \in \{0,\ 1\} & \forall j \in J \\
& Y_{ij} \in \{0,\ 1\} & \forall i \in I; \forall j \in J \\
& Z_{ijk} \in \{0,\ 1\} & \forall i \in P; \forall j \in P; \forall k \in K
\end{array}$$

The objective function minimised the total fixed facility location costs, the transportation costs from supply points (plants) to the facilities, the variable facility throughput costs and the routing costs to customers. First constraint requires each customer to be on one route. Second constraint sets a capacity restriction for each vehicle and the third constraint limits the length of each route. The fourth constraint requires each route to be connected to a facility. The fifth constraint imposes any route entering node $i \in P$ must exit that same node. The sixth constraint states that each route can operate out of only one facility. The seventh constraint represents the flow into a facility from the supply point(s) in terms of demand. The eighth constraint limits the throughput at each facility to the maximum allowed at that facility and links the flow variables and the facility location variables. If a facility is not opened, the ninth constraint prevents customers from being assigned to that facility. The tenth constraint indicates that if route $k \in K$ leaves customer node $i \in I$ and also leaves facility $j \in J$, then customer $i \in I$ must be assigned to facility $j \in J$. Vehicle routing variable (Z_{ijk}) wand assignment variable (Y_{ij}) are linked by the tenth constraint. The eleventh, twelfth and thirteenth constraints are integer and non-negativity constraints of the model.

A.4. modeFRONTIER®: A multi-disciplinary design environment

modeFRONTIER® is a multi-disciplinary and multi-objective optimisation and design environment developed by ESTECO SpA (ESTECO 2013). It is a multi-disciplinary and multi-objective software capable of handling complex optimisation problems. The complex algorithms within modeFRONTIER® can spot the optimal results, even conflicting with each other or belonging to different fields. modeFRONTIER® consists of Design of Experiments (DoE), optimisation algorithms, and robust design tools, capable of blending to create an efficient strategy to solve complicated multi-disciplinary problems. It is offering a wide range of evolutionary optimisers to manage continuous, discrete, and mixed variable problems.

The concept behind modeFRONTIER® is schematically presented in Figure 2.8.

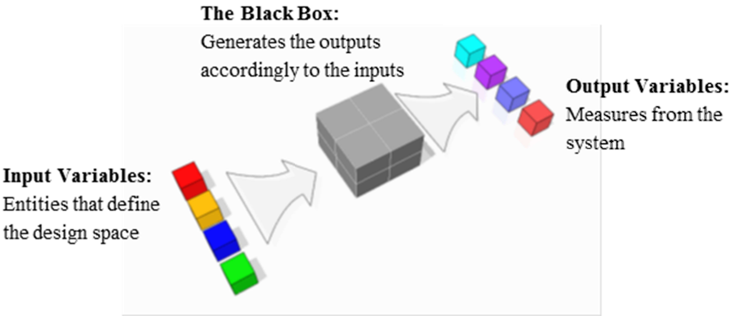
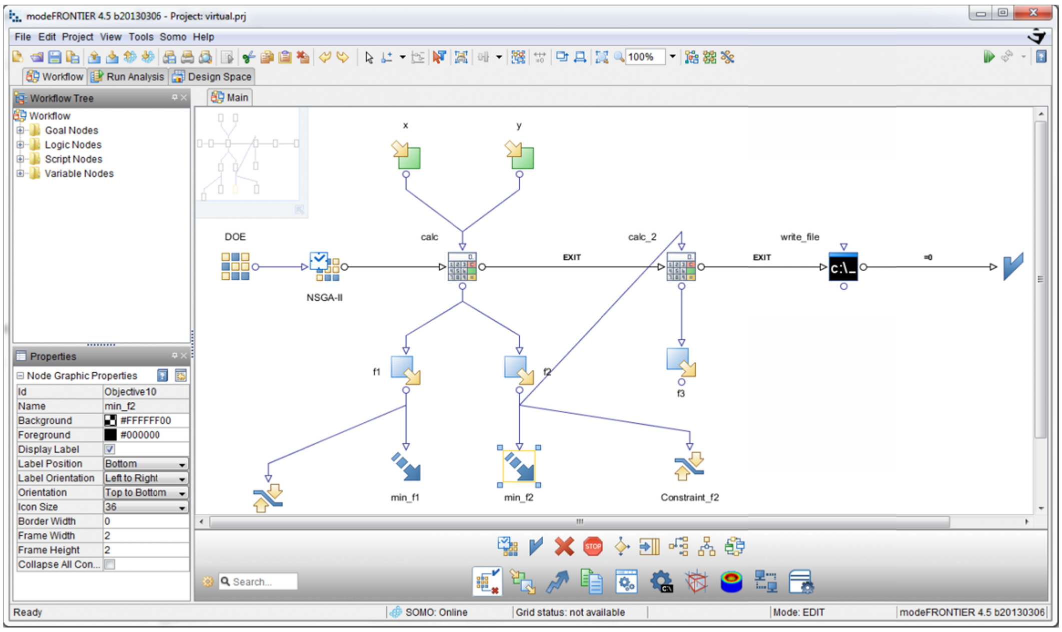


Figure 2.8 The concept behind modeFRONTIER® (ESTECO 2013)

The optimisation technology within modeFRONTIER® starts a workflow to input the data, connect the components of the models and provide the usage of its solution capabilities. This workflow transfers data from one simulation to the next, updating all parameter values according to the optimization algorithms, thus extracting relevant outputs. Figure 2.9 is an example of a workflow in modeFRONTIER® (ESTECO 2013). The elements of the workflow consist of input, process, output components and the proper connections links to connect all the elements of the models in modeFRONTIER®.

modeFRONTIER® combines opposing objectives and considers user-defined constraints, it helps to manage the complexity. It offers a considerable selection of innovative algorithms and able to tackle discrete or continuous variables to solve single and multi-objective problems. This design environment empowers the user to outline the appropriate robust optimisation strategy according to the design space boundaries.



Properties

Node Graphic Properties

Id	Objective10
Name	min_f2
Background	#FFFFFF00
Foreground	#000000
Display Label	☑
Label Position	Bottom
Label Orientation	Left to Right
Orientation	Top to Bottom
Icon Size	36
Border Width	0
Frame Width	2
Frame Height	2
Collapse All Con...	☐

Figure 2.9 An example of a workflow in modeFRONTIER® (ESTECO 2013)

A very strong capability of modeFRONTIER® is its DoE guided solution approach. DoE connects the optimiser to the optimisation model. It generates the initial population for the optimiser(s) using a variety of distributions and designs. The details of the distributions and designs forming the initial population using DoE are as follows (source: modeFRONTIER® 4.4.3, 2013).

Strong non-linearity, high or low constrained problems, sizable problem dimensions can be addressed by modeFRONTIER®. Optimisation algorithms cover deterministic, stochastic and heuristic methods for both single and multi-objective problems. Figure 2.10 illustrates optimisation algorithms families offered by modeFRONTIER®.

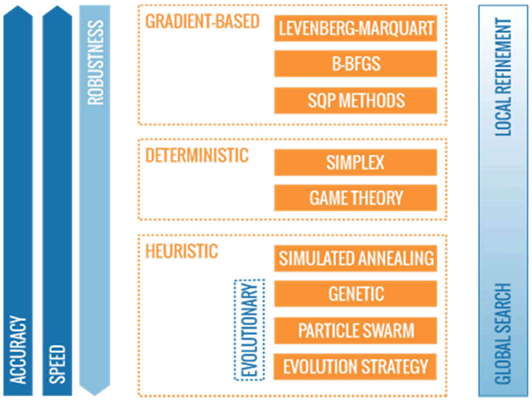


Figure 2.10 Optimisation algorithms families (ESTECO 2013)

The heuristics/meta-heuristics evolutionary algorithms offered by modeFRONTIER® with different natures are as followed:

MOGA-II: Scheduler based on a multi-objective genetic algorithm (MOGA) designed for fast Pareto convergence. This GA-based algorithm: (i) supports geographical selection and directional cross-over, (ii) implements Elitism for multi-objective search, (iii) enforces user defined constraints by objective function penalization, (iv) allows Generational or Steady State evolution, (v) allows concurrent evaluation of independent individuals. The n (num. of individuals) entries in the DOE table are used as the problem's initial population

NSGA-II: Non-dominated Sorting Genetic Algorithm II of prof. K. Deb et al. (2000, KanGAL Report No. 200001). This GA-based algorithm: (i) allows both continuous ("real-coded") and discrete ("binary-coded") variables, (ii) allows user defined discretization (base), (iii) the constraint handling method does not make use of penalty parameters, (iv) implements different elitism strategies for multi-objective search, (v) diversity and spread of solutions is guaranteed without use of sharing parameters, (vi) allows concurrent evaluation of the n independent individuals. The n (number of individuals per generation) entries in the DOE table are used as the problem's initial population.

MOSA: Algorithm based on a single and multi-objective simulated annealing (MOSA). This algorithm: (i) obeys boundary constraints on continuous variables, (ii) allows user defined discretization (base), (iii) enforces user defined constraints by objective function penalization, (iv) allows concurrent evaluation of the n independent points, (v) after a 'hot phase' (T>0) a 'cold phase' (T=0) follows, (vi) the evolution is governed by the Temperature Scheduler and by the Spatial Perturbation Length Scheduler. The entries in the DOE table are used as initial points.

MOGT: Multi-objective scheduler based on Game theory (J.F.Nash) coupled with a Simplex algorithm. This Game theory-based algorithm: (i) obeys boundary constraints on continuous variables, (ii) allows user defined discretization (base), (iii) enforces user defined constraints by objective function penalization, (iv) decomposes automatically the variables space among the players (in charge of each objective), (v) allows concurrent evaluation of configurations proposed by each player, (vi) best suited for highly constrained, highly non-linear and competitive objectives, finds a compromise solution (Nash equilibrium) by a low number of evaluation points. The number of objectives has not to be greater than the number of variables. Only the first entry of the DOE table is used.

MOPSO: Scheduler based on multi-objective Particle Swarm. Particle Swarm Optimization is motivated from the simulation of social behaviour of bird flocking. Each single solution is a "bird" in the search space with a velocity which directs the flying of all the particles through the problem space. This PS-based algorithm: (i) allows both continuous and discrete variables, (ii) the constraint handling method does not make use of penalty parameters, (iii) a clustering method is used to prune non-dominated set.

HYBRID: HYBRID is an algorithm which combines the global exploration capabilities of Genetic Algorithms with the accurate local exploitation guaranteed by SQP implementations. In this algorithm: (i) the scheduler works following a steady-state scheme, (ii) SQP runs are launched as particular operators for the GA, (iii) the user can choose to approximate derivatives with finite differences method or through RSM predictions, (iv) the algorithm produces repeatable sequences (if the number of concurrent design evaluations is 1). HYBRID can be used for single and multi-objective problems, constrained or unconstrained. The SQP solver is AFilterSQP which works on a scalarized version of the original problem obtained through an improved epsilon-constrained technique.

SAnGeA: Multi-Objective scheduler based on Screening method and genetic algorithm. This algorithm: (i) allows both continuous and discrete variables, (ii) manages problems with many variables, (iii) writes in the log which variables are important for the model according to screening method. SAnGeA is designed for unconstrained problems. The screening method inside SAnGeA needs at least 10 points in DOE table. If the DOE table is empty or has less than 10 rows, the missing initial designs are randomly generated.

After initial evaluation of available software solution platforms, it was concluded that modeFRONTIER® was the most suitable platform for solving complex NP-hard multi-objective LRPs as are being developed in this study based on its extended capabilities and multi optimiser availability. modeFRONTIER® is a commercial solver, which can be described as a design environment in contrast to a final stage software package. As such a development platform it allows significant scope and flexibility to the designer.

In modeFRONTIER®, MOGA-II, NSGA-II, MOSPOS, MOSA and HYBRID are selected to solve the two and three-layer MO-LRPs. MOGT works using a combination of Game Theory and a Simplex algorithm and uses only the first entry of DoE table, therefore this optimiser is not selected to solve the models in this study. SAnGeA is developed for unconstrained models. As the MO-LRPs are both constrainted in this study, it is deemed not suitable for these models.

Appendix B

B.1. Questionnaire

Green Location-Routing Decisions in Dairy Processing Supply Chain

Location Decisions

1. **Processing Plants:**

a. How many dairy processing plant(s) does your company own?
b. Where are the processing plants located geographically?
c. How do you make decision on the geographical location of your dairy processing plants? What criteria are considered? (i.e. costs, distance from market, etc.)

2. **Distribution Centres (DCs):**

a. If DCs are owned by your company:
- How many DC(s) does your company own?
- Where are these DC(s) located geographically?
- What criteria are considered in making a decision on the location of the DCs?
- Do you use any decision support tool/technique to make decisions about the location of DC(s)? If yes please explain.
- What is the capacity of these DC(s)?
- How do you make a decision about the capacity of DC(s)?
- Do you rent any DC(s) in Ireland?
  If yes; how do you decide what DC to rent?

b. In case a third party is renting the DC(s) to you:
- Do you rent the entire or a part of the DC(s)?
- How do you decide on the capacity you require from each DC?
- How many DC(s) have you rented?
- How do you decide about the geographical location of DCs?

3. **Customers (Wholesalers/Retailers):**

a. How do you make a decision about what part of the dairy market in Ireland (geographically) you want to cover? (or do you cover the whole Ireland dairy market?)
b. How many counties in Ireland do you consider as your customers? Do you know how much is the total demand for each dairy product in these counties? How much of the dairy demand (unit of each dairy product) in these counties do you cover?
c. How do you decide on the part of demand for dairy products in these counties to cover?

Routing and Transportation Decisions

a. What criteria are taken into account to select the best route to connect the processing plants to DC(s), and DC(s) to retailers?
b. Do you use any decision support tool/technique to make routing decisions?
c. Have you ever considered serving retailers directly from your dairy processing plants?
d. Have you ever considered serving one retailer through another retailer and not from the DC(s)?
e. Does your company own the transportation system?
If the answer to the above question is 'Yes';
- What types of vehicles (in terms of: capacity of the vehicles; refrigerated vehicles or not; etc.) are used to transport your dairy products from dairy processing

plants to DCs and from DCs to retailers?
- How do you make a decision on the type of vehicles you require for transporting your products?
- What criteria do you consider when choosing the type of vehicle for transporting your products?
- Do you consider a speed limit for vehicles in different types of roads while transporting the dairy products through your dairy supply chain? If yes, please explain.

f. Does your company outsource the transportation?
If the answer to the above question is ‘Yes’;
- How do you decide on what transportation company to choose? What criteria are considered?

Environmentally Friendly Policies

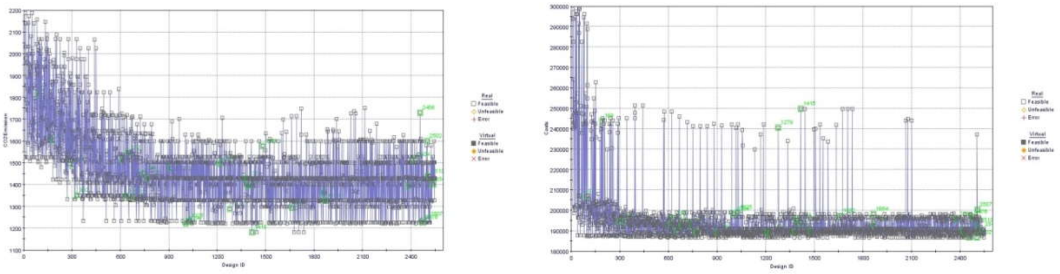
a. Does your company have green (environmentally friendly) supply chain considerations?
If the answer to the above question is ‘Yes’;
   - What are the green (environmentally friendly) supply chain considerations?
   - How these green policies are implemented?
   - What parts of your business these green policies focus on?
b. If your company own the transportation system; have you conducted a study to measure the transportation impact on the environment?
c. If transportation is sourced out; does your company ask the transportation company to measure the carbon footprint?
d. Do you know how much is your annual supply chain carbon footprint contribution is?

B.2. TableA.2.Detailed Distances between Plants and Retailers

TableA.2. Total Distance and the Type of the Road in each Defined Route Between Plants and Customers

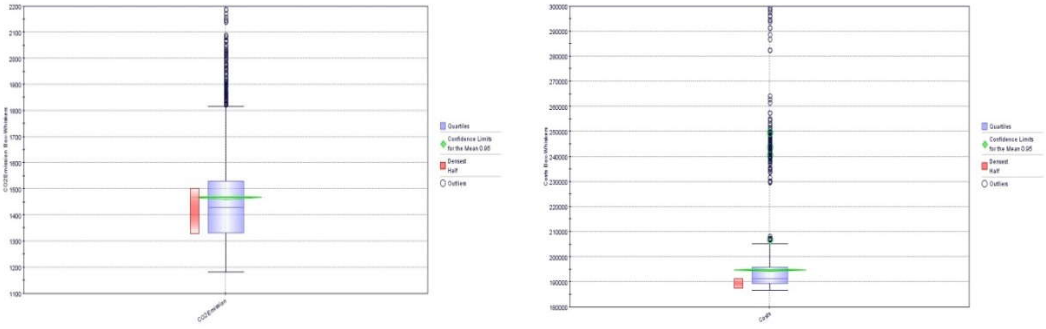
Plant ($j \in J$)	*I* ***Drogheda***					*II* ***Ballitore***				
Customer ($i \in I$)	**Total Distance** (km)	**Distance in each Type of Road** (km)				**Distance** (km)	**Distance in each Type of Road** (km)			
		Motorway	National Route	Regional and Local Roads	Built Up Areas		Motorway	National Route	Regional and Local Roads	Built Up Areas
1.Drogheda	**2.0**			2.0		**117.0**	61.7	55.3		
2.Dundalk	**36.4**	36.4				**146.0**	89.7	56.3		
3.Navan	**25.8**			25.8		**105.0**	105.0			
4.Tullamore	**110.0**		110.0			**62.5**			62.5	
5.Naas	**75.4**			75.4		**29.1**			29.1	
6.Newbridge	**103.0**	103.0				**24.5**			24.5	
7.Leixlip	**47.5**			47.5		**61.1**	61.1			
8.Port Laoise	**143.0**	143.0				**37.1**		11.8	25.3	
9.Bray	**74.6**	74.6				**71.4**		71.4		
10.Arklow	**128.0**	128.0				**57.6**			57.6	
11.Wicklow	**121.0**	121.0				**48.0**			48.0	
12.Greystones	**83.6**	83.6				**70.4**			70.4	
13.Clonmel	**239.0**	239.0				**111.0**	61.3	49.7		
14.Waterford	**219.0**	219.0				**105.00**	105.0			
15.Tramore	**232.0**	232.0				**117.0**	117.0			
16.Kilkenny	**178.0**	178.0				**63.4**	63.4			
17.Wexford	**197.0**	197.0				**94.8**		94.8		
18.Enniscorthy	**184.0**		184.0			**72.4**	24.2		48.2	
19.Dublin City	**52.4**	52.4				**59.8**		59.8		
20.Dun Laoghaire/Rathdawn	**62.9**	62.9				**66.7**		66.7		
21.Fingal	**29.2**			29.2		**85.5**		85.5		
22.South Dublin	**61.5**			61.5		**45.1**		45.1		

B.3. History Plots, Box Whiskers, and Density Plots on total result designs for MOGAII and NSGAII, respectively



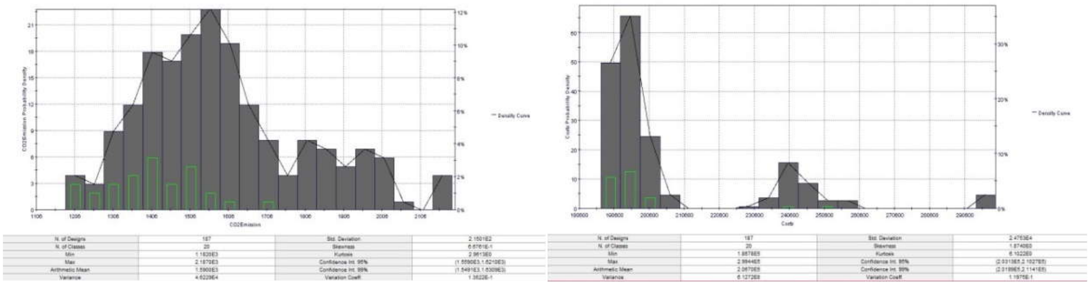
a. CO_2 emission **b. Costs**

Figure A.3.1-a. History plots; MOGAII



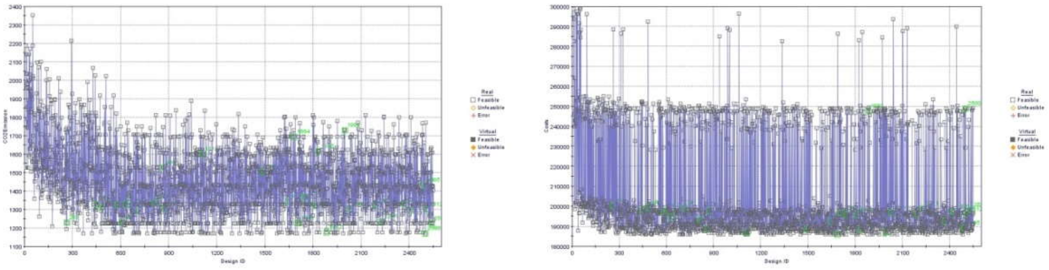
a. CO_2 emission **b. Costs**

Figure A.3.1-b. Box Whiskers; MOGAGAII



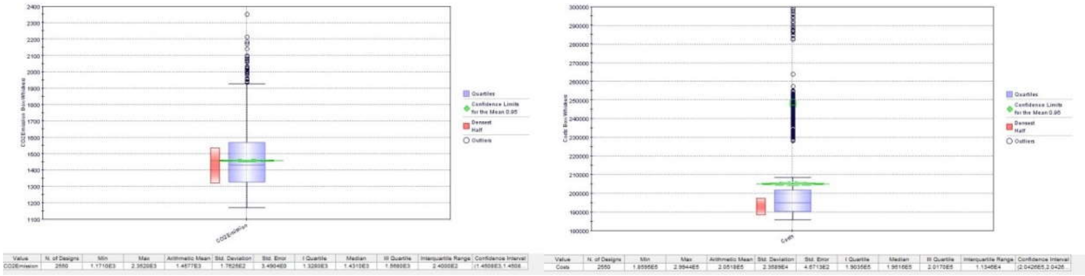
a. CO_2 emission **b. Costs**

Figure A.3.1-c. Probability density function; MOGAGAII



a. CO$_2$ emission **b. Costs**

Figure A.3.2-a. History plots; NSGAII

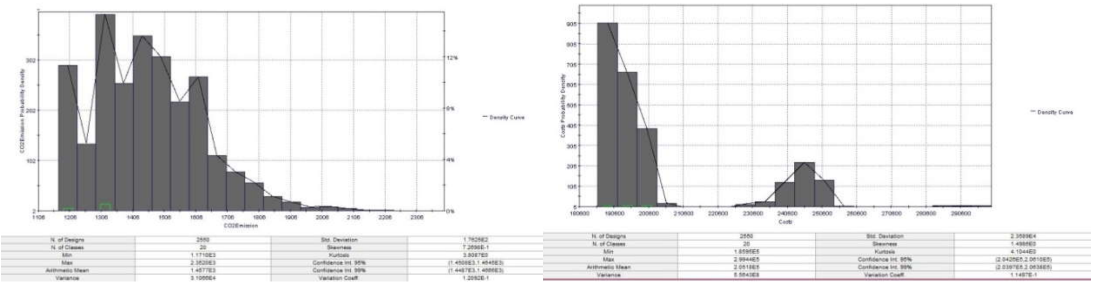


Value	N. of Designs	Min	Max	Arithmetic Mean	Std. Deviation	Std. Error	I Quartile	Median	III Quartile	Interquartile Range	Confidence Interval
CO2Emission	2550	1.1710E3	2.3520E3	1.4677E3	1.7626E2	3.4904E0	1.3290E3	1.4310E3	1.5680E3	2.4000E2	(1.4508E3,1.4508

Value	N. of Designs	Min	Max	Arithmetic Mean	Std. Deviation	Std. Error	I Quartile	Median	III Quartile	Interquartile Range	Confidence Interval
Costs	2550	1.8595E5	2.9944E5	2.0518E5	2.3589E4	4.6713E2	1.9035E5	1.9516E5	2.0170E5	1.1346E4	(2.0426E5,2.0426

a. CO$_2$ emission **b. Costs**

Figure A.3.2-b. Box Whiskers; NSGAII



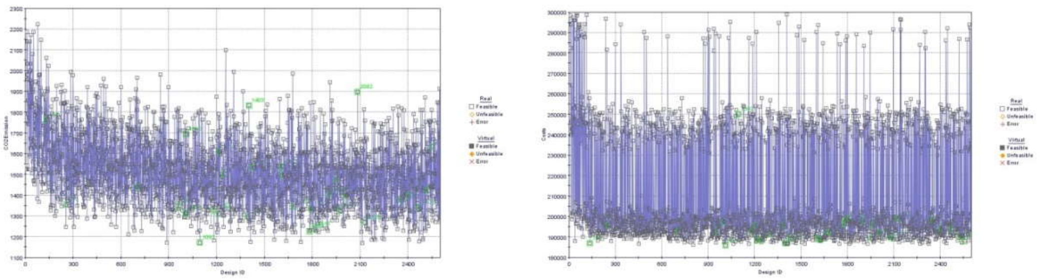
N. of Designs	2550	Std. Deviation	1.7626E2
N. of Classes	20	Skewness	7.2698E-1
Min	1.1710E3	Kurtosis	3.8087E0
Max	2.3520E3	Confidence Int. 95%	(1.4508E3,1.4646E3)
Arithmetic Mean	1.4577E3	Confidence Int. 99%	(1.4487E3,1.4686E3)
Variance	3.1066E4	Variation Coeff	1.2092E-1

N. of Designs	2550	Std. Deviation	2.3589E4
N. of Classes	20	Skewness	1.4985E0
Min	1.8595E5	Kurtosis	4.1044E0
Max	2.9944E5	Confidence Int. 95%	(2.0426E5,2.0610E5)
Arithmetic Mean	2.0518E5	Confidence Int. 99%	(2.0397E5,2.0638E5)
Variance	5.5643E8	Variation Coeff	1.1497E-1

a. CO$_2$ emission **b. Costs**

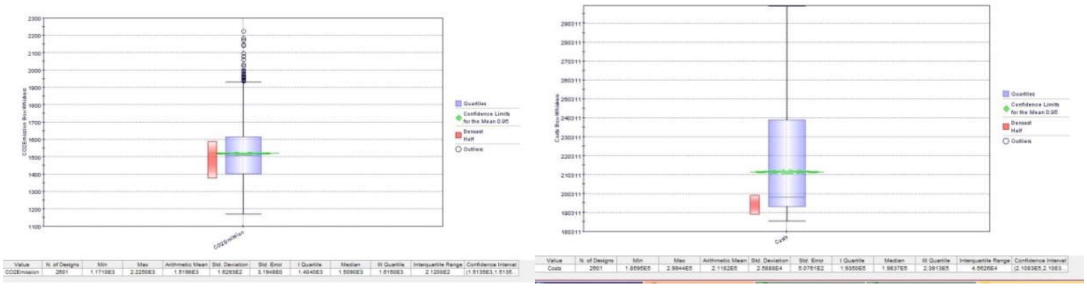
Figure A.3.2-c. Probability density function; NSGAII

B.4. History Plots, Box Whiskers, and Density Plots on total result designs for MOPSO



a. CO$_2$ emission **b. Costs**

A.4-a. History plots; NSGAII

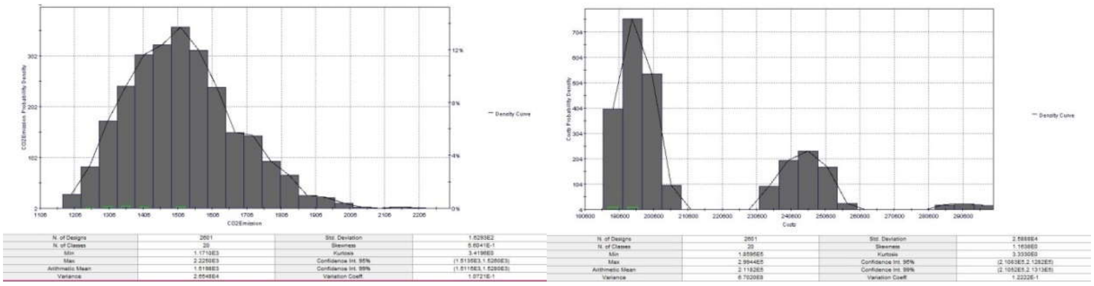


Value	N. of Designs	Min	Max	Arithmetic Mean	Std. Deviation	Std. Error	I Quartile	Median	III Quartile	Interquartile Range	Confidence Interval
CO2Emission	2601	1.1710E3	2.2260E3	1.5186E3	1.6293E2	3.1946E0	1.4040E3	1.5090E3	1.6160E3	2.1200E2	(1.5136E3,1.5136...

Value	N. of Designs	Min	Max	Arithmetic Mean	Std. Deviation	Std. Error	I Quartile	Median	III Quartile	Interquartile Range	Confidence Interval
Costs	2601	1.8596E5	2.9944E5	2.1182E5	2.5888E4	5.0761E2	1.9350E5	1.9837E5	2.3913E5	4.5626E4	(2.1083E5,2.1083...

a. CO$_2$ emission **b. Costs**

A.4-b. Box Whiskers; NSGAII



N. of Designs	2601	Std. Deviation	1.6293E2
N. of Classes	20	Skewness	5.6041E-1
Min	1.1710E3	Kurtosis	3.4196E0
Max	2.2260E3	Confidence Int. 95%	(1.5136E3,1.5260E3)
Arithmetic Mean	1.5186E3	Confidence Int. 99%	(1.5116E3,1.5280E3)
Variance	2.6548E4	Variation Coeff.	1.0721E-1

N. of Designs	2601	Std. Deviation	2.5888E4
N. of Classes	20	Skewness	1.1638E0
Min	1.8596E5	Kurtosis	3.3330E0
Max	2.9944E5	Confidence Int. 95%	(2.1083E5,2.1282E5)
Arithmetic Mean	2.1182E5	Confidence Int. 99%	(2.1052E5,2.1313E5)
Variance	6.7020E8	Variation Coeff.	1.2222E-1

a. CO$_2$ emission **b. Costs**

A.4-c. Probability density function; NSGAII

C.1. Total distances between DCs and retailers in types of roads

Table C.1. Total distance and the type of the road in each defined route between DCs and customers

Distribution Centres (DCs)	***Type of Road***	**DC to Customer Distance in each Type of Road *(km)***																					
		1.Drogheda	**2.Dundalk**	**3.Navan**	**4.Tullamore**	**5.Naas**	**6.Newbridge**	**7.Leixlip**	**8.Port Laoise**	**9.Bray**	**10.Arklow**	**11.Wicklow**	**12.Greystones**	**13.Clonmel**	**14.Waterford**	**15.Tramore**	**16.Kilkenny**	**17.Wexford**	**18.Enniscorthy**	**19.Dublin City**	**20.Dun Laoghari-**	**21.Fingal**	**22.South Dublin**
Dundalk	*Motorway*			51.1		30.8	128.0	38.2	166.0	117.0	166.0	85.9	126.0	255.0	248.0	261.0	216.0	226.0	140.6	81.5	91.9	69.1	99.5
	National Route				126.0	3.0													72.4				
	Regional& Local Roads	32.0				73.2		52.1				71.1											
	Built Up Areas		2.0																				
Total Distance (km)		**32.0**	**2.0**	**51.1**	**126.0**	**107.0**	**128.0**	**90.3**	**166.0**	**117.0**	**166.0**	**157.0**	**126.0**	**255.0**	**248.0**	**261.0**	**216.0**	**226.0**	**213.0**	**81.5**	**91.9**	**69.1**	**99.5**
Drogheda	*Motorway*				110.0	85.9			143.0	73.5	57.4	121.0	82.5	226.0	219.0	232.0	85.2	197.0			62.9		
	National Route						89.9				70.6								184.	28.8			
	Regional & Local Roads		33.5	25.8				47.5									82.8			20.9		29.0	61.5
	Built Up Areas	2.0																					
Total Average Distance (km)		**2.0**	**33.5**	**25.8**	**110.0**	**85.9**	**89.9**	**47.5**	**143.0**	**73.5**	**128.0**	**121.0**	**82.5**	**226.0**	**219.0**	**232.0**	**168.0**	**197.0**	**184.0**	**49.7**	**62.9**	**29.0**	**61.5**
Dublin City	*Motorway*		81.5		100.0				93.8					177.0	83.1	83.1	53.1	35.2				21.0	
	National Route	28.8		35.0		36.2	49.5	17.4		21.4	70.6		30.3		80.9	92.9	68.9	53.0	118.0		14.1		20.8
	Regional & Local Roads	20.9		15.4								63.0						42.8					
	Built Up Areas																			2.0			
Total Average Distance (km)		**49.7**	**81.5**	**50.4**	**100.0**	**36.2**	**49.5**	**17.4**	**93.8**	**21.4**	**70.6**	**63.0**	**30.3**	**177.0**	**164.0**	**176.0**	**122.0**	**131.0**	**118.0**	**2.0**	**14.1**	**21.0**	**20.8**
Tul-lamore	*Motorway*	109.0		83.8				86.0							45.4	45.4				100.0		115.0	29.6

	National Route		126.0						33.7	117.0	132.0	117.0	125.0	123.0	93.6	106.6	82.1	145.0	123.0	111.0			
	Regional & Local Roads					64.4	56.8																56
	Built Up Areas				2.0																		
Total Average Distance (km)		**109.0**	**126.0**	**83.8**	**2.0**	**64.4**	**56.8**	**86.0**	**33.7**	**117.0**	**132.0**	**117.0**	**125.0**	**123.0**	**139.0**	**152.0**	**82.1**	**145.0**	**123.0**	**100.0**	**111.0**	**115.0**	**85.6**
Bray	*Motorway*	73.5	117.0	75.5		21.7	27.6	37.2	104.0					187.0	181.0		70.8	30.1	38.2		10.1		17.7
	National Route				117.0	25.7	32.6				50.2					170.0	62.2		59.4	21.4		42.7	12.7
	Regional & Local Roads											43.6	6.4										
	Built Up Areas									2.0													
Total Average Distance (km)		**73.5**	**117.0**	**75.5**	**117.0**	**47.4**	**60.2**	**37.2**	**104.0**	**2.0**	**50.2**	**43.6**	**6.4**	**187.0**	**181.0**	**170.0**	**133.0**	**110.0**	**97.6**	**21.4**	**10.1**	**42.7**	**30.4**
Waterford	*Motorway*	219.0	248.0	4.8	45.4	133.0	126.0	159.0	44.2	181.0			109.0				51.7			83.1	45.7	187.0	71.2
	National Route				93.6				61.8		104.0			47.1				60.5	55.6	80.9			78.8
	Regional & Local Roads			187.2								122.0				11.8							
	Built Up Areas														2.0								
Total Average Distance (km)		**219.0**	**248.0**	**192.0**	**139.0**	**133.0**	**126.0**	**159.0**	**106.0**	**181.0**	**104.0**	**122.0**	**109.0**	**47.1**	**2.0**	**11.8**	**51.7**	**60.5**	**55.6**	**164.0**	**162.0**	**187.0**	**150.0**

Last Updated: 05/12/2012; Source: Google Map

C.2. Total distances between retailers by the type of the roads

C.2. Total distance and the type of the road in each defined route between retailers

Distribution Centres (DCs)	*Type of Road*	DC to Customer Distance in each Type of Road *(km)*																					
		1.Drogheda	2.Dundalk	3.Navan	4.Tullamore	5.Naas	6.Newbridge	7.Leixlip	8.Port Laoise	9.Bray	10.Arklow	11.Wicklow	12.Greystones	13.Clonmel	14.Waterford	15.Tramore	16.Kilkenny	17.Wexford	18.Enniscorthy	19.Dublin City	20.Dun Laoghari-	21.Fingal	22.South Dublin
1.Drogheda	*Motorway*				110.0	85.9			143.0	73.5	57.4	121.0	82.5	226.0	219.0	232.0	85.2	197.0			62.9		
	National Route						89.9				70.6								184.	28.8			
	Regional & Local Roads		33.5	25.8				47.5									82.8			20.9		29.0	61.5
	Built Up Areas																						
Total Distance (km)		**-**	**33.5**	**25.8**	**110.0**	**85.9**	**89.9**	**47.5**	**143.0**	**73.5**	**128.0**	**121.0**	**82.5**	**226.0**	**219.0**	**232.0**	**168.0**	**197.0**	**184.0**	**49.7**	**62.9**	**29.0**	**61.5**
2.Dundalk	*Motorway*			51.1		30.8	128.0	38.2	166.0	117.0	166.0	85.9	126.0	255.0	248.0	261.0	216.0	226.0	140.6	81.5	91.9	69.1	99.5
	National Route				126.0	3.0													72.4				
	Regional& Local Roads	32.0				73.2		52.1				71.1											
	Built Up Areas																						
Total Distance (km)		**32.0**	**-**	**51.1**	**126.0**	**107.0**	**128.0**	**90.3**	**166.0**	**117.0**	**166.0**	**157.0**	**126.0**	**255.0**	**248.0**	**261.0**	**216.0**	**226.0**	**213.0**	**81.5**	**91.9**	**69.1**	**99.5**
3.Navan	*Motorway*		51.1		83.8	17.1		44.1	52.2	75.5	41.1	117.0	83.7	201.0	4.8	112.0	102.3				69.0		57.7
	National Route										82.9							182.0	159.0	35.0			
	Regional & Local Roads	25.8				45.3	74.1		52.8						187.2	104.0	53.7			15.4		40.5	
	Built Up Areas																						
Total Average Distance (km)		**25.8**	**51.1**	**-**	**83.8**	**62.4**	**74.1**	**44.1**	**105.0**	**75.5**	**124.0**	**117.0**	**83.7**	**201.0**	**192.0**	**216.0**	**156.0**	**182.0**	**159.0**	**50.4**	**69.0**	**40.5**	**57.7**
4.Tullamore	*Motorway*	109.		83.8				86.0							45.4	45.4				100.		115.	29.6
	National Route		126.						33.7	117.	132.	117.	125.	123.	93.6	106.	82.1	145.	123.	111.			

	Regional & Local Roads					64.4	56.8																56
	Built Up Areas																						
Total Average Distance (km)		**109.0**	**126.0**	**83.8**	**-**	**64.4**	**56.8**	**86.0**	**33.7**	**117.0**	**132.0**	**117.0**	**125.0**	**123.0**	**139.0**	**152.0**	**82.1**	**145.0**	**123.0**	**100.0**	**111.0**	**115.0**	**85.6**
5.Naas	*Motorway*	85.9	30.8	16.8					61.4	21.7			5.5	144.0	133.0	150.0	96.0		57.2		16.9	24.2	
	National Route		3.0					26.2		25.7			51.8					118.	48.8	36.2	25.6	29.8	18.6
	Regional & Local Roads		73.2	45.8			11.7				75.3	59.5											
	Built Up Areas																						
Total Average Distance (km)		**85.9**	**107.0**	**62.6**	**56.8**	**-**	**11.7**	**26.2**	**61.4**	**47.4**	**75.3**	**59.5**	**57.3**	**144.0**	**133.0**	**150.0**	**96.0**	**118.0**	**106.0**	**36.2**	**42.5**	**54.0**	**18.6**
6.Newbridge	*Motorway*		128.0						45.1	27.6			31.2	133.0	126.0	139.0	85.1	39.3	39.3		23.2	30.5	
	National Route	89.9						38.6		32.6			38.5					77.7	54.7	49.5	31.7	35.9	31.0
	Regional & Local Roads			74.1	56.8	11.7					78.1	62.5											
	Built Up Areas																						
Total Average Distance (km)		**89.9**	**128.0**	**74.1**	**56.8**	**11.7**	**-**	**38.66**	**45.1**	**66.2**	**78.1**	**62.5**	**69.7**	**133.0**	**126.0**	**139.0**	**85.1**	**117.0**	**94.6**	**49.5**	**54.9**	**66.4**	**31.0**
7.Leixlip	*Motorway*		38.2	44.1					82.9	37.2	37.4		46.4	166.0	159.0	172.0	117.0		57.2		31.6	34.1	
	National Route				86.0	24.8					49.3							98.4	69.8	17.4			
	Regional & Local Roads	47.5	52.1				38.3					73.8						48.6					15.9
	Built Up Areas																						
Total Average Distance (km)		**47.5**	**90.3**	**44.1**	**86.0**	**25.8**	**38.3**	**-**	**82.9**	**37.2**	**86.7**	**73.8**	**46.4**	**166.0**	**159.0**	**172.0**	**117.0**	**147.0**	**127.0**	**17.4**	**31.6**	**34.1**	**15.9**
8.Port Laoise	*Motorway*	143.0	166.0	52.2		61.4	45.1	82.9		104.0			114.0		44.2	45.4				93.8	98.7	110.0	74.8
	National Route				33.7									99.0	61.0	73.6	48.9	112.0	89.6				
	Regional & Local Roads			52.8							98.8	83.2											

	Built Up Areas																						
Total Average Distance (km)		**143.0**	**166.0**	**105.0**	**33.7**	**61.4**	**45.1**	**82.9**	**-**	**104.0**	**98.8**	**83.2**	**114.0**	**99.0**	**106.0**	**119.0**	**48.9**	**112.0**	**89.6**	**93.8**	**98.7**	**110.0**	**74.8**
9.Bray	*Motorway*	73.5	117.0	75.5		21.7	27.6	37.2	104.0					187.0	181.0		70.8	30.1	38.2		10.1		17.7
	National Route				117.0	25.7	32.6				50.2					170.0	62.2		59.4	21.4		42.7	12.7
	Regional & Local Roads											43.6	6.4										
	Built Up Areas																						
Total Average Distance (km)		**73.5**	**117.0**	**75.5**	**117.0**	**47.4**	**60.2**	**37.2**	**104.0**	**-**	**50.2**	**43.6**	**6.4**	**187.0**	**181.0**	**170.0**	**133.0**	**110.0**	**97.6**	**21.4**	**10.1**	**42.7**	**30.4**
10.Arklow	*Motorway*	57.4	166.0	41.1	132.0			37.4						144.0					22.2				
	National Route	70.6		82.9				49.3		50.2			45.3		104.0	119.0	94.2		25.1	70.6	59.5	92.0	
	Regional & Local Roads					75.3	78.1		98.8			7.6						60.2					74.6
	Built Up Areas											25.3											
Total Average Distance (km)		**128.0**	**166.0**	**124.0**	**132.0**	**75.3**	**78.1**	**86.7**	**98.8**	**50.2**	**-**	**32.9**	**45.3**	**144.0**	**104.0**	**119.0**	**94.2**	**60.2**	**47.3**	**70.6**	**59.5**	**92.0**	**74.6**
11.Wicklow	*Motorway*	121.0	85.9	117.0										35.9			26.4						
	National Route				117.0									105.1		138.0			69.8				
	Regional & Local Roads		71.1			59.5	62.5	73.8	83.2	43.6	7.6		42.5		122.0		65.8	94.3		63.0	52.2	84.7	59.0
	Built Up Areas										25.3												
Total Average Distance (km)		**121.0**	**157.0**	**117.0**	**117.0**	**59.5**	**62.5**	**73.8**	**83.2**	**43.6**	**32.9**	**-**	**42.5**	**141.0**	**122.0**	**138.0**	**92.2**	**94.3**	**69.8**	**63.0**	**52.2**	**84.7**	**59.0**
12.Greystones	*Motorway*	82.5	126.0	83.7		5.5	31.2	46.4	114.0						109.0		70.6	30.1	38.2			64.4	40.7
	National Route				125.0	51.8	38.5				45.3			189.0		164.0	71.4	28.0	53.8	30.3			
	Regional & Local Roads									6.4		42.5						46.9			18.9		

		13.Clonmel					**14.Waterford**					**15.Tramore**					**16.Kilkenny**			
Built Up Areas	**Total Average Distance (km)**	*Motorway*	*National Route*	*Regional & Local Roads*	*Built Up Areas*	**Total Average Distance (km)**	*Motorway*	*National Route*	*Regional & Local Roads*	*Built Up Areas*	**Total Average Distance (km)**	*Motorway*	*National Route*	*Regional & Local Roads*	*Built Up Areas*	**Total Average Distance (km)**	*Motorway*	*National Route*	*Regional & Local Roads*	*Built Up Areas*
	82.5	226.0				**226.0**	219.0				**219.0**	232.0				**232.0**	85.2		82.8	
	126.0	255.5				**255.5**	248.0				**248.0**	261.0				**261.0**	216.0			
	83.7	201.0				**201.0**	4.8		187.2		**192.0**	112.0				**216.0**	102.3		53.7	
	125.0		123.0			**123.0**	45.4	93.6			**139.0**	45.4	106.6			**152.0**		82.1		
	57.3	144.0				**144.0**	133.0				**133.0**	150.0				**150.0**	96.0			
	69.7	133.0				**133.0**	126.0				**126.0**	139.0				**139.0**	85.1			
	46.4	166.0				**166.0**	159.0				**159.0**	172.0				**172.0**	117.0			
	114.0		99.0			**99.0**	44.2	61.8			**106.0**	45.4	73.6			**119.0**		48.9		
	6.4	187.0				**187.0**	181.0				**181.0**		170.0			**170.0**		62.2		
	45.3	144.0				**144.0**		104.0			**104.0**		119.0			**119.0**		94.2		
	42.5	35.9	105.1			**141.0**			122.0		**122.0**		138.0			**138.0**	26.4		65.8	
	-		189.0			**189.0**	109.0				**109.0**		164.0			**164.0**	70.6	71.4		
	189.0					**-**		47.1			**47.1**		17.8	35.2		**53.0**		50.1		
	109.0		47.1			**47.1**					**-**			11.8		**11.8**	51.7			
	164.0		17.8	35.2		**53.0**			11.8		**11.8**					**-**	64.2			
	142.0		50.1			**50.1**	51.7				**51.7**	64.2				**64.2**				
	105.0		102.0			**102.0**		60.5			**60.5**		76.7			**76.7**		34.5	42.6	
	92.0		96.8			**96.8**		55.6			**55.6**		71.9			**71.9**			57.7	
	30.3	177.0				**177.0**	83.1	80.9			**164.0**	83.1	92.2			**176.0**	53.1	68.9		
	18.9	59.4	116.6			**176.0**	45.7				**162.0**		178.0			**178.0**	63.2	64.8		
	64.4	193.0				**193.0**	187.0				**187.0**	199.0				**199.0**	145.0			
	40.7	158.0				**158.0**	71.2	78.8			**150.0**	83.2	78.8			**162.0**	51.5	55.5		

Total Average Distance (km)		**168.0**	**216.0**	**156.0**	**82.0**	**96.0**	**85.1**	**117.0**	**48.9**	**133.0**	**94.2**	**92.2**	**142.0**	**50.1**	**51.7**	**64.2**	**-**	**77.1**	**57.7**	**122.0**	**128.0**	**145.0**	**107.0**
17.wexford	*Motorway*	197.0	226.0				39.3			30.1			30.1							35.2	37.6		
	National Route			182.0	145.0	118.0	77.7	98.4	112.0	35.0			28.0	102.0	60.5	76.7	34.5		23.4	53.0	37.1		
	Regional & Local Roads							48.6		44.9	60.2	94.3	46.9				42.6			42.8	44.3	165.0	136.0
	Built Up Areas																						
Total Average Distance (km)		**197.0**	**226.0**	**182.0**	**145.0**	**118.0**	**117.0**	**147.0**	**112.0**	**110.0**	**60.2**	**94.3**	**105.2**	**102.0**	**60.5**	**67.7**	**77.1**	**-**	**23.4**	**131.0**	**119.0**	**165.0**	**136.0**
18.Enniscorthy	*Motorway*		140.			57.2	39.3	57.2		38.3	22.2		38.2								45.7		
	National Route	184.0	72.4	159.0	123.0	48.8	54.7	69.8	89.6	59.4	25.1	69.8	53.8	96.8	55.6	71.9		23.4		118.0	62.3	143.0	106.0
	Regional & Local Roads																57.7						
	Built Up Areas																						
Total Average Distance (km)		**184.0**	**213.0**	**159.0**	**123.0**	**106.0**	**94.6**	**127.0**	**89.6**	**97.6**	**47.3**	**69.8**	**92.0**	**96.8**	**55.6**	**71.9**	**57.7**	**23.4**	**-**	**118.0**	**108.0**	**143.0**	**106.0**
19.Dublin City	*Motorway*		81.5		100.				93.8					177.	83.1	83.1	53.1	35.2				21.0	
	National Route	28.8		35.0		36.2	49.5	17.4		21.4	70.6		30.3		80.9	92.9	68.9	53.0	118.		14.1		20.8
	Regional & Local Roads	20.9		15.4								63.0						42.8					
	Built Up Areas																						
Total Average Distance (km)		**49.7**	**81.5**	**50.4**	**100.0**	**36.2**	**49.5**	**17.4**	**93.8**	**21.4**	**70.6**	**63.0**	**30.3**	**177.0**	**164.0**	**176.0**	**122.0**	**131.0**	**118.0**	**-**	**14.1**	**21.0**	**20.8**
20.Dun Laogharire /Rathdawn	*Motorway*	62.9	91.9	69.0		16.9	23.2	31.6	98.7	10.1				59.4	45.7		63.2	35.2				32.3	27.2
	National Route				111.0	25.6	31.7				59.5			116.6	116.3	178.0	64.8	53.0	118.0	14.0			
	Regional & Local Roads											52.2	18.9					42.8					
	Built Up Areas																						
Total Average Distance (km)		**62.9**	**91.9**	**69.0**	**111.0**	**42.5**	**54.9**	**31.6**	**98.7**	**10.1**	**59.5**	**52.2**	**18.9**	**176.0**	**162.0**	**178.0**	**128.0**	**131.0**	**118.0**	**14.1**	**-**	**32.3**	**27.2**
21.Fingal	***Motorway***		69.1		115.0	24.2	30.5	34.1	110.0				64.4	193.0	187.0	199.0	145.0			21.0	32.3		39.5

	National Route					29.8	35.9			42.7	92.0								143.				
	Regional & Local Roads	29.0		40.5								84.7						165.					
	Built Up Areas																						
Total Average Distance (km)		**29.0**	**69.1**	**40.5**	**115.0**	**54.0**	**66.4**	**34.1**	**110.0**	**42.7**	**92.0**	**84.7**	**64.4**	**193.0**	**187.0**	**199.0**	**145.0**	**165.0**	**143.0**	**21.0**	**32.3**	**-**	**39.5**
22.South Dublin	*Motorway*		99.5	57.7	29.6				74.8	17.7			40.7	158.0	71.2	83.2	51.5				27.2	39.5	
	National Route					18.6	31.0			12.7					78.8	78.8	55.5		106.0	20.8			
	Regional & Local Roads	61.5			56.0			15.9			74.6	59.0						136.0					
	Built Up Areas																						
Total Average Distance (km)		**61.5**	**99.5**	**57.7**	**85.6**	**18.6**	**31.0**	**15.9**	**74.8**	**30.4**	**74.6**	**59.0**	**40.7**	**158.0**	**150.0**	**162.0**	**107.0**	**136.0**	**106.0**	**20.8**	**27.2**	**39.5**	**-**

Last Updated: 05/12/2012; Source: Google Map

C.3. CO$_2$ emission and cost estimations from transporting products between retailers

TableC.3 CO$_2$ emission estimations and costs of serving routes by HGVs in between retailers

Distribution Centres (DCs)	1.Drogheda		2.Dundalk		3.Navan		4.Tullamore		5.Naas		6.Newbridge	
Type of Road	*CO2 Emission from Fuel Burnt* p_{jk}	*Cost of Serving Path (€)* c_{jk}	*CO2 Emission from Fuel Burnt* p_{jk}	*Cost of Serving Path (€)* c_{jk}	*CO2 Emission from Fuel Burnt* p_{jk}	*Cost of Serving Path (€)* c_{jk}	*CO2 Emission from Fuel Burnt* p_{jk}	*Cost of Serving Path (€)* c_{jk}	*CO2 Emission from Fuel Burnt* p_{jk}	*Cost of Serving Path (€)* c_{jk}	*CO2 Emission from Fuel Burnt* p_{jk}	*Cost of Serving Path (€)* c_{jk}
DC to Customer Distance in each Type of Road *(km)*												
1.Drogheda	2	2	30	26	24	20	101	72	79	56	83	61
2.Dundalk	30	26	2	2	47	33	116	86	99	58	118	83
3.Navan	24	20	47	33	2	2	77	54	58	35	68	50
4.Tullamore	101	72	116	86	77	54	2	2	59	49	52	43
5.Naas	79	56	99	58	58	35	59	49	2	2	11	9
6.Newbridge	83	61	118	83	68	50	52	43	11	9	2	2
7.Leixlip	44	32	83	53	41	29	80	56	24	18	36	26
8.Port Laoise	132	93	153	108	97	63	31	23	57	40	42	29
9.Bray	68	48	108	76	70	49	108	79	44	26	61	37
10.Arklow	118	74	153	108	115	71	122	90	70	58	72	60
11.Wicklow	112	79	145	98	108	75	108	79	55	46	58	48
12.Greystones	76	54	116	82	77	54	115	85	53	31	64	39
13.Clonmel	209	147	236	166	186	131	114	84	133	94	123	86
14.Waterford	202	143	229	161	177	105	128	80	123	86	116	82
15.Tramore	214	151	241	168	200	142	140	74	139	98	128	90
16.Kilkenny	155	100	200	140	144	96	76	56	89	62	79	55
17.Wexford	182	128	209	147	168	124	134	99	109	80	108	67
18.Enniscorthy	137	125	197	129	147	108	114	84	98	61	87	54
19.Dublin City	46	28	75	53	47	28	92	65	33	25	46	32
20.Dun Laoghari-	58	41	85	60	64	45	103	75	39	23	51	31
21.Fingal	27	22	64	45	37	31	106	75	50	30	61	37
22.South Dublin	57	47	92	65	53	37	79	50	17	13	29	21

15.Tra more	14.Waterford		13.Clonmel		12.Greystones		11.Wicklow		10.Arklow		9.Bray		8.Port Laoise		7.Leixlip	
CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}
214	143	202	147	209	54	76	79	112	74	118	48	68	93	132	32	44
241	161	229	166	236	82	116	98	145	108	153	76	108	108	153	53	83
200	105	177	131	186	54	77	75	108	71	115	49	70	63	97	29	41
140	80	128	84	114	85	115	79	180	90	122	79	108	23	31	56	80
139	86	123	94	133	31	53	46	55	58	70	26	44	40	57	18	24
128	82	116	86	123	39	64	48	58	60	72	37	56	29	42	26	36
159	103	147	108	153	30	43	56	68	49	80	24	34	54	77	2	2
110	61	98	67	91	74	105	64	77	76	91	68	96	2	2	54	77
157	118	167	122	173	5	6	33	40	34	47	2	2	68	96	24	34
110	71	96	94	133	31	42	19	30	2	2	34	47	76	91	49	80
127	93	113	81	130	32	39	2	2	19	30	33	40	64	77	56	68
151	71	101	128	175	2	2	32	39	31	42	5	6	74	105	30	43
48	31	43	2	2	128	175	81	130	94	133	122	173	67	91	108	153
11	2	2	31	43	71	101	93	113	71	96	118	167	61	98	103	147
2	9	11	30	48	111	151	94	127	81	110	115	157	68	110	112	159
59	34	48	34	46	83	131	53	85	64	87	60	123	33	45	76	108
71	41	56	69	94	57	97	72	87	46	56	78	102	76	103	90	136
66	38	51	66	89	52	85	47	64	26	44	55	90	61	83	74	117
163	97	151	115	164	21	28	48	58	48	65	14	20	61	87	12	16
164	94	150	104	163	14	17	40	48	40	55	7	9	64	91	21	29
184	122	173	126	178	42	59	65	78	62	85	29	39	72	102	22	31
150	88	139	103	146	26	38	40	54	57	69	17	28	49	69	12	15

22.South Dublin		21.Fingal		20.Dun Laogharire /Rathdawn		19.Dublin City		18.Enniscorthy		17.Wexford		16.Kilkenny		
Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}	CO2 Emission from Fuel Burnt p_{jk}	Cost of Serving Path (€) c_{jk}
47	57	22	27	41	58	28	46	125	137	128	182	100	155	151
65	92	45	64	60	85	53	75	129	197	147	209	140	200	168
37	53	31	37	45	64	28	47	108	147	124	168	96	144	142
50	79	75	106	75	103	65	92	84	114	99	134	56	76	74
13	17	30	50	23	39	25	33	61	98	80	109	62	89	98
21	29	37	61	31	51	32	46	54	87	67	108	55	79	90
12	15	22	31	21	29	12	16	74	117	90	136	76	108	112
49	69	72	102	64	91	61	87	61	83	76	103	33	45	68
17	28	29	39	7	9	14	20	55	90	78	102	60	123	115
57	69	62	85	40	55	48	65	26	44	46	56	64	87	81
40	54	65	78	40	48	48	58	47	64	72	87	53	85	94
26	38	42	59	14	17	21	28	52	85	57	97	83	131	111
103	146	126	178	104	163	115	164	66	89	69	94	34	46	30
88	139	122	173	94	150	97	151	38	51	41	56	34	48	9
96	150	129	184	121	164	105	163	49	66	52	71	42	59	2
61	99	94	134	74	118	71	113	44	53	45	71	2	2	42
104	126	126	150	65	110	72	121	16	22	2	2	45	71	52
72	98	97	132	62	100	80	109	2	2	16	22	44	53	49
14	19	14	19	10	13	2	2	80	109	72	121	71	113	105
18	25	21	30	2	2	10	13	62	100	65	110	74	118	121
26	36	2	2	21	30	14	19	97	132	126	150	94	134	129
2	2	26	36	18	25	14	19	72	98	104	126	61	99	96

Last Updated: 07&08/12/2012; Source: Google Map