

Green Logistics Oriented Framework for the Integrated  
Scheduling of Production and Distribution Networks  
– A Case of the Batch Process Industry –

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*To the most precious people in my life;  
My adorable parents, sisters and brother,  
My husband and my little angel Hamza*

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## ABSTRACT

Nowadays, most consumable goods are produced and transported in batches. Within the globalized environment, the flow of these batches is raising dramatically to satisfy the recurrent demands of the increasing population. Planning the flow of these batches from suppliers to customers, through dynamic logistics systems, has a high degree of uncertainties on supply chain related decisions. In order to respond effectively and efficiently to these uncertainties, the supply chain network has to be redesigned, considering the economic and environmental requirements. To handle these requirements sustainably, green logistics is a promising approach. However, there is a lack of green logistics models which integrate both the production and distribution decisions within the batch process industries.

This research develops a green logistics oriented framework in the case of the batch process industry. The framework integrates the tactical and operational levels of planning and scheduling to generate the optimum production and distribution decisions. A two-stage stochastic programming model is formulated to design and manage batch supply chain. This is a mixed-integer linear program of the two-stage stochastic production-distribution model with economic-environmental objectives. The first stage is concerned with optimum schedules of the production and distribution of the required batches. The second stage subsequently generates the optimum delivering velocities for the optimal distribution routes which are resulted from the first stage. Carbon emissions under uncertainties are incorporated as a function of random delivery velocities at different distribution routes within the network of the supply chain.

To examine the applicability of the developed framework, the model is verified and validated through four theoretical scenarios as well as two real world case studies of multi-national batch process industries. The results of the analysis provide some insights results into supply chain costs and emissions. Based on the results, savings of about 43 percent of the total related economic and environmental costs were achieved compared to the actual situation at the case study companies. Cost savings mean long-term profitability, which is essential to sustain a worldwide competitive advantage. Furthermore, the stochastic and expected value solutions are compared in several

scenarios. The stochastic solutions are consistently better with respect to costs and emissions. Calculations indicate that up to 13 percent of total cost savings are achieved when a stochastic approach is used to solve the problem as opposed to an expected value approach. The proposed framework supports academic green logistics models and real world supply chain decision making in batch process industry. Building such a framework provides a practical tool which links being green and being economically successful.

# **ZUSAMMENFASSUNG**

## **EIN GREEN LOGISTICS FRAMEWORK FÜR DIE INTEGRIERTE ZEITPLANUNG VON PRODUKTIONS- UND DISTRIBUTIONSNETZWERKEN – AM BEISPIEL DER LOSFERTIGUNG**

Konsumprodukte werden heute vorrangig in Losen produziert und transportiert. Bedingt durch die Bedürfnisse der anwachsenden Weltbevölkerung nimmt die Menge der transportierten Konsumgüter deutlich zu. Die Planung der Warenströme von den Herstellern bis zu den Verbrauchern geht mit einem hohen Grad an Unsicherheit bezüglich der Entscheidungen einher, die hinsichtlich des Supply-Chain-Netzwerks zu treffen sind. Um auf diese Unsicherheiten effektiv und effizient reagieren zu können, ist eine Umgestaltung der Netzwerke unter Berücksichtigung der ökonomischen und ökologischen Anforderungen notwendig. Das Green-Logistics-Konzept stellt einen vielversprechenden Ansatz dar, um diese Anforderungen nachhaltig zu erfüllen. Aktuell existieren jedoch keine Green-Logistics-Modelle für die Losfertigung, welche sowohl produktions- als auch distributionsrelevante Entscheidungen berücksichtigen.

Im Rahmen dieser Arbeit wird daher ein Framework zur Umsetzung von Green Logistics-Konzepten in der Losfertigung entwickelt. Das Framework bietet integrierte taktische und operative Planungsebenen, um Produktions- und Distributionsentscheidungen zu optimieren. Weiterhin wird ein zwei-stufiges, stochastisches Programmiermodell umgesetzt. Hierbei handelt es sich um ein gemischtganzzahliges lineares Programm des zweistufigen Produktions-Distributions-Modells mit ökonomischen und ökologischen Zielen. Die erste Stufe behandelt die Ablaufplanung der Herstellung und Distribution der benötigten Lose. Die zweite Stufe generiert die optimale Distributionsgeschwindigkeit für die aus Stufe eins gewonnenen optimalen Distributionsrouten. Die Unsicherheiten bezüglich der entstehenden CO<sub>2</sub>-Emissionen werden durch eine Zufallsfunktion innerhalb des Supply-Chain-Netzwerks berücksichtigt.

Um die Anwendbarkeit des entwickelten Frameworks zu überprüfen, wurde das Modell anhand von vier theoretischen und zwei realen Fallstudien der multi-nationalen Losfertigung validiert. Die Ergebnisse der Analyse geben aufschlussreiche Einblicke

bezüglich der entstehenden Supply-Chain-Kosten und –Emissionen. Die Ergebnisse zeigen, dass für die Fallstudien Einsparungen in Höhe von ca. 43 Prozent der ökonomischen und ökologischen Kosten gegenüber der aktuellen Situation erreichbar sind. Kosteneinsparungen bedeuten langfristige Profitabilität, was essentiell ist, um einen weltweiten Wettbewerbsvorteil zu erhalten. Weiterhin wurden die stochastischen und erwartungswertbasierten Lösungen in verschiedenen Szenarien verglichen. Die stochastischen Lösungen sind hinsichtlich der Kosten und Emissionen durchgehend besser. Berechnungen zeigen, dass bis zu 13 Prozent der gesamten Kosteneinsparungen erreicht werden, wenn ein stochastischer anstelle eines erwartungswertbasierten Ansatzes zur Lösung des Problems genutzt wird. Die vorgestellte Struktur unterstützt wissenschaftliche Green-Logistics-Modelle und reale Supply-Chain-Entscheidungsfindung in der Losfertigung. Durch den Aufbau eines solchen Frameworks wurde ein praxistaugliches Werkzeug geschaffen, welches gleichzeitigen ökonomischen und ökologischen Erfolg ermöglicht.



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## LIST OF ABBREVIATIONS

<i>APS</i>	Advanced Planning System
<i>CO<sub>2</sub></i>	Carbon Dioxide
<i>CVRP</i>	Capacitated Vehicle Routing Problem
<i>EEA</i>	European Environment Agency
<i>EEV</i>	Expected result of using the Expected Value
<i>EOF</i>	Equivalent Objective Function
<i>ERP</i>	Enterprise Resources Planning
<i>EU</i>	European Union
<i>G</i>	Gram
<i>GDP</i>	Gross Domestic Product
<i>GHG</i>	Greenhouse Gases
<i>GIS</i>	Geographic Information System
<i>GSCM</i>	Green Supply Chain Management
<i>ICM</i>	Integrated Chain Management
<i>ILP</i>	Integer Linear Programming
<i>ISO</i>	International Organization for Standardization
<i>JIT</i>	Just In Time
<i>Mph</i>	Miles per hour
<i>MPS</i>	Master Production Schedule
<i>MRP</i>	Material Requirements Planning
<i>NP</i>	Nondeterministic Polynomial
<i>NSF</i>	National Science Foundation

<i>OECD</i>	Organization for Economic Co-operation and Development
<i>P</i>	Polynomial
<i>RP</i>	Recourse Problem
<i>SCM</i>	Supply Chain Management
<i>SCND</i>	Supply Chain Network Design
<i>SCOR</i>	Supply Chain Operations Reference Model
<i>SDSS</i>	Spatial Decision Support System
<i>SDSS</i>	Spatial Decision Support System
<i>SVRP</i>	Stochastic Vehicle Routing Problem
<i>UFI</i>	User Friendly Interface
<i>VRP</i>	Vehicle Routing Problem
<i>VSS</i>	Value of the Stochastic Solution

# CHAPTER 1 INTRODUCTION

This chapter introduces the research topic by defining the research problem and the motivation behind studying it. Then, the research objective and research questions analysis are stated. Furthermore, the contents of each chapter are presented.

## 1.1. Problem Definition and Motivation

Nowadays, due to the ever-growing population, the consumption of basic-need goods (such as fast moving consumer goods, beverages, cleaning products ...) is increasing dramatically. Thus, these goods constitute a large part of the consumers' budget. In companies, these goods are usually produced in batches due to their low unit volume. In order to fulfil this high consumption rate, batch products are transported highly frequently. It is therefore understandable to attempt to reduce the amount of money spent on production and distribution processes of batch products as well as to move towards effective and efficient management of these processes which thus leads to huge savings in absolute terms for both the companies and the consumers. Since logistics and production systems are acknowledged as complex systems, managing their processes is a crucial and hard task.

Within the global market from the companies to the consumers, the management of the flows of these batches is associated with high uncertainty in terms of production and distribution decisions. To manage these uncertainties in a dynamic and complex logistics environment, better results are achievable through the effective integration of production plans, inventory control and distribution policies throughout the supply chain. This is due to the fact that the entire concept of supply chain management (SCM) is predicated on integration. Therefore, the integration of production scheduling and distribution planning is a crucial issue in the batch process industry.

Furthermore, as one of top market concerns of today, companies should adapt all aspects of logistic in supply chain management to be green. This shift toward greening the supply chain through an environmentally friendly logistics network design is not only due to governmental regulations but also to meet the customers' expectations and social responsibilities. Improved environmental performance would induce cost savings and

increase sales and thus improve economic performance. Nowadays, the link between the environmental and economic performance is widely accepted after this concept has been widely debated for a long time [2].

Although there is a growing necessity of designing green logistics network for different industries, most of the exciting research being done mainly focuses on strategic decisions. Design for strategic level is necessary but not sufficient; therefore, there is a real need to design the tactical and operational decisions within the green logistics network. Traditional scheduling models of production and distribution planning either focus on the economic issues without considering the environmental ones or formulate production and distribution models separately.

Due to the aforementioned facts, integrated and well-designed green logistics production and distribution schedules must be developed so that the enterprise balances the economic and environment objectives in a cost-effective way. However, little has been done to integrate the scheduling of production and distribution planning for batch process industries; this is an interesting area to contribute towards. Limited literature on the integrated batch production and distribution scheduling is remarked in a research work published in 2015 [1]. Thus, a research gap exists and more research should be devoted to address this integration.

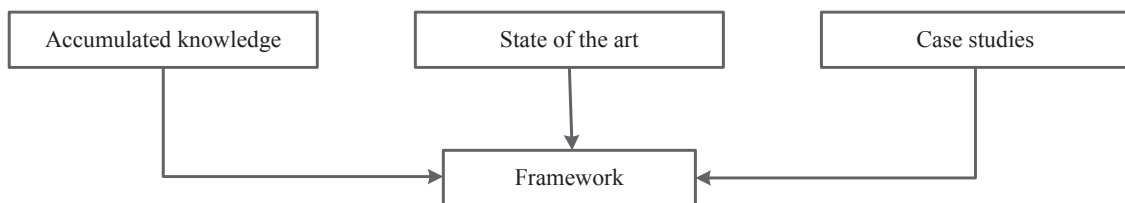
The research problem here can be defined as: The available production-distribution models for batch process industry are not sufficient to meet the economic-environmental requirements within the global markets. Accordingly, scheduling the production and distribution processes which consider the economic as well as the environmental objectives using a green logistics framework is required.

## **1. 2. Objective and Research Methodology**

This doctoral thesis contributes to two main lines in the green logistics network design for the batch process industry: theoretical research field and practical decision-making. Correspondingly, the aim of this work has both theoretical and practical sides. Theoretically, this research aims to structure green logistics of the batch process industry as a research field. Practically, this work aims to gain a better understanding of green

logistics practices in a real world and supporting their decision-making processes. In order to achieve this aim, two sorts of inputs are employed: green logistics related literature and decision makers with expertise on this field. With these inputs, the aim is elaborated into specific objectives.

To develop an advanced logistics research, a research methodology with at least two different research methods is necessary [3]. In line with this conclusion, the research methodology that is followed in this work combined three basic research methods. The methodology used in this research for building-up the green logistics oriented framework is shown schematically in Figure 1-1. These sources review the existing scientific related literature, testing the case based scenarios method for real life application in two logistics operators in multinational companies and employ the knowledge accumulated during the entire PhD research.



**Figure 1-1 Methodological green logistics oriented framework data sources**

This three-phase methodologically research work is employed to design and evaluate a green logistics oriented framework in order to integrate the scheduling of production and distribution for the batch process industry. The first phase encompasses the current knowledge and ideas that have been established on the related research topics and their strengths and weaknesses. The second phase comprises the developing and modelling of a two-stage stochastic programming model using different mathematical programming tools. Finally, the third phase tests the validity of the mathematical formulation in a real world application. These phases are described in detail through chapters 3, 4 and 5 respectively.

In this thesis, we build a decision support tool which automatically generates the schedules of the production plans and distribution plans efficiently and effectively using

three main data sources. These sources are the literature review, mathematical modeling and the case studies of the real world batch processes industries.

### **1.3. Research Questions**

Although that the field of green logistics receives increasing attention, huge gaps exist in modelling the green supply chain networks. Since this new research field is expanding dramatically, several potential factors have to be improved. The need towards applicable designs for a sustainable network in the logistics area is crucial.

The current study helps in answering several questions arising in this context:

- What is the practical methodology used to manage the dynamics in logistics within the batch process industries?
- How to efficiently build a model that integrates the scheduling of production and distribution networks for the batch process industry while taking into consideration green logistics?
- How to present the economic and environmental terms, taking the interest of different factors into consideration?
- How to practically implement the developed network design in a batch process industry in a real world environment?
- How to model the stochasticity within the scheduling of this network?
- What are the parameters that affect the network design?
- What are the benefits of integrating production and distribution while designing the network?
- How to validate, verify and evaluate the developed framework?

In order to manage all of these challenges within the batch process industry, the aim of this PhD research is to contribute to the research in the area of the green logistics network design. Presented here is a green logistics oriented framework used for integrated scheduling of production and distribution networks for the batch process industry under uncertainty. This research is considering both production scheduling and vehicle routing decisions for batch products in the same framework. These operations are core operations

in the batch process industry. Additionally, production and distribution are mainly managed by the same decision maker.

Furthermore, this thesis contributes to better understanding how green logistics can be approached in the batch process industry. This research brings insights to green logistics decision-making as well as to the field of network design as a whole. It also aspires to enhance knowledge and information transfer between different levels in supply chains. The development of various green designs is an important step towards the broader adoption and development of sustainability which concerns not only the economic aspect but also the ecological and societal aspects as well. This model is applied to real world case studies in this industry for a multi-national company.

The main objective of this work is to integrate the production and distribution decisions in the batch process industry taking into consideration green issues under uncertainty. This objective is achieved by developing a two-stage programming model capable of solving practical, complicated industrial problems in the field of green logistics. It is driven by all the previously mentioned reasons and focuses on the integration between the production plan and distribution schedule. This model will consider:

- The global optimal solution for the described production environment. This solution optimizes the overall system's efficiency in both tactical and operational levels.
- Decisions related to planning and scheduling of the integrated production-distribution.
- The production related issues such as the maximum production capacity and multi period planning; the distribution related issues such as the optimum distribution routes and the distributed quantities; as well as the inventory related issues, such as the beginning amount of inventory stored from the previous production plan and the amount of safety stock required by the end of the current production plan from each batch type.
- The green related issues such as greenhouse gas emissions. The studied emissions are related to the velocities of the vehicles used for distribution which are uncertain due to the randomness associated with travel distances.



## 1. 4. Outline of the Dissertation

This research is texted into six main chapters. *Chapter One* provides several fundamentals relevant to the current studied work. There are vast set of topics which could elect to carry out this research. These topics include: network design, supply chain management, sustainability, inventory management, vehicle routing as well as other topics. Likewise, the special features of batch process industry for modelling a green logistics framework are studied. The developed framework targets to minimize economic and environmental related costs.

*Chapter Two* provides a background which covers and introduces all research related concepts and definitions. These concepts and definitions include the integrated scheduling of production and distribution planning managerial decisions, the interrelation between sustainability and green logistics and emission uncertainties. Furthermore, the proposed framework requirements and modelling issues are discussed. Afterwards, the various solution technologies used to provide optimal solutions are discussed. This chapter is closed by a review of the existing literature dealing with the integrated production-distribution models as well as applying green logistics in the batch processes industry.

*Chapter Three* presents the research methodology applied in this work. Moreover, the solution methodology and procedure for the proposed model are described. The use of exact algorithms to solve the suggested model is justified and then the detailed description of the solution tool is discussed. The developed model is solved at different instances of the problem until optimality using the LINGO<sup>®</sup> optimization package.

*Chapter Four* poses the main contribution of this research. It presents the research problem and the mathematical model. The model addresses related production as well as distribution characteristics considering the uncertain production environment. The model also provides an answer to many tactical and operational decisions in the production and distribution planning. The dynamics of the two-stage stochastic programming model function as follows: In the first stage, production, inventory and distribution decisions (i.e., choosing the routes for demand delivery to customers) are generated. These decisions are made to satisfy customer demand without exceeding any of the capacities

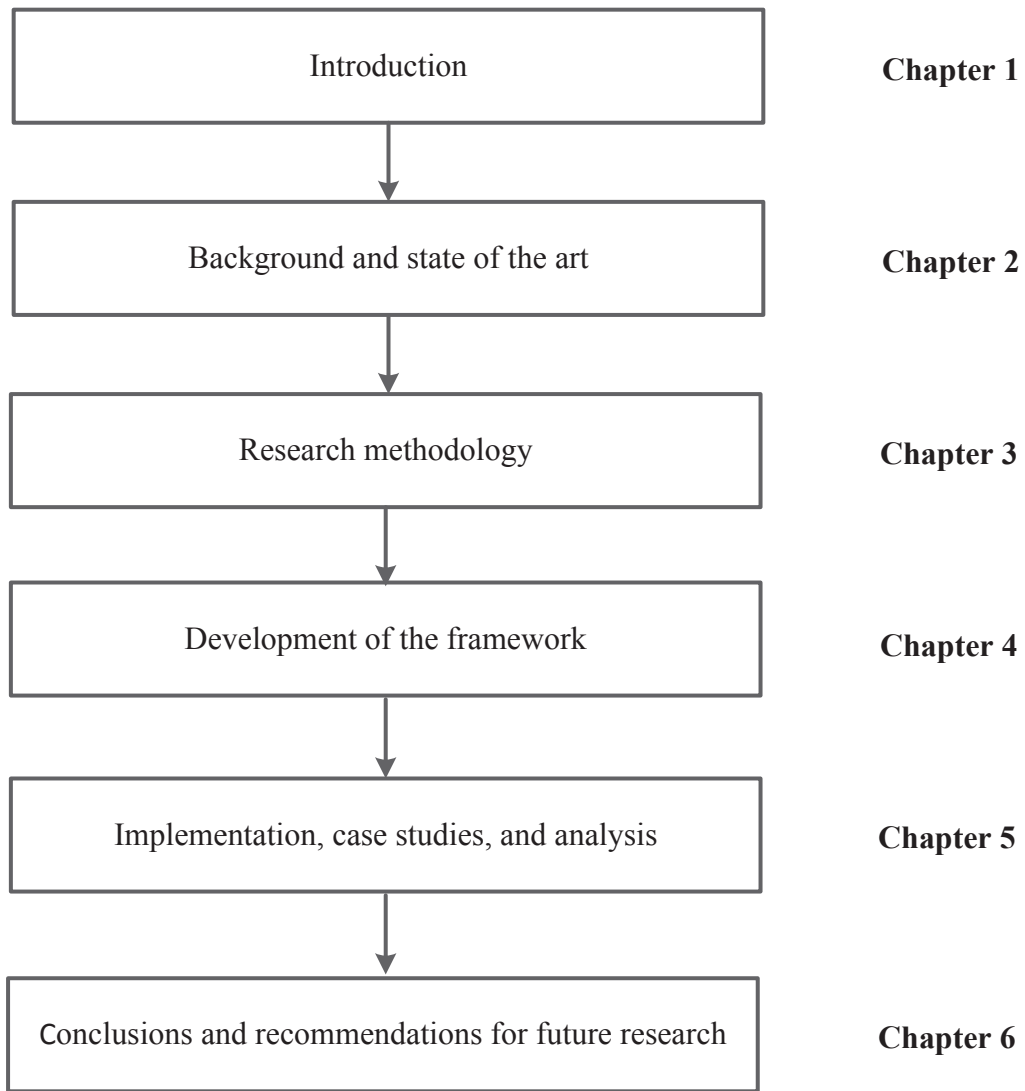
as well as minimizing the total costs of production, inventory, distribution and the expected costs of the second stage problem.

*Chapter Five* presents the evaluation of the system through its implementation into real life application for integrated production-distribution under uncertainty. The verification and testing of the model are conducted for different test models. A case study in the batch processes industry is presented. Moreover, the numerical results and computational analysis of the model outcomes are demonstrated. The modelled framework which is presented in Chapter Four is used successfully to provide a solution that is applied to design the company production and distribution schedule. Results emphasize the contribution of the proposed model and its efficient use.

In *Chapter Six*, the conclusions and recommendations for future research in this field are suggested. It is followed by the scientific contributions of this thesis.

A list of the 160 up-to-date references cited in this thesis is included. Finally, appendices are presented covering the input data for LINGO<sup>®</sup> software and the LINGO<sup>®</sup> code of the test models and the case study.

The dissertation outline is also presented schematically in Figure 1-2.



**Figure 1-2 Dissertation outline**

## **CHAPTER 2      GREEN LOGISTICS ORIENTED FRAMEWORK: STATE OF THE ART**

The objective of this chapter is to provide an overall understanding of green logistics by structuring the field. Specifically, a green logistics framework is developed, meaning a basic conceptual structure for green logistics is provided. This structure involves the identification of the related green logistics concepts and the terminology used in the scheduling of the production and distribution networks. Furthermore, a review of the current state of the art in the field of green logistics network design is presented. This review is attempted to structure the relatively new field and to identify modelling and solution techniques that have been applied by researchers so far. The main goal of the chapter is to provide the reader with a consistent overview of the work in this research topic and the progress made within this area throughout the past decades.

This chapter is structured as follows: First: an overview about the related concepts is given. Second: the different integrated production-distribution planning models are classified in section 2.2. Third: This is followed by looking at the green aspects during the production and distribution processes. The process characteristics of the batch process industry are studied in section 2.4. Forth: the related state of the art in the studied field is reviewed in sections 2.5. Finally, the chapter is concluded and the results from the literature review are discussed.

### **2. 1. Bridging the Gap: Overview**

Globalization of markets, diversity in consumer choices, raising media as well as consumers concern about safety and environment and other different drivers have pushed researchers to develop new generations of supply chains. Currently, companies are forced to address these environmental issues due to customer requirements and governmental regulations. Since the early 21<sup>st</sup> century, the European Union (EU) has become a highly influential proponent of green supply chains. The European Parliament views this concept as critical to the future of the EU and claims that current and future legislations must integrate sustainability into implementation orders.

Meanwhile, the batch process industry covers a wide portfolio of products including: fast moving consumer goods [4]; beverages; personal care; household and cleaning products; apparel industry; food processing; chemical manufacturing; and pharmaceutical industries products [5]. Batch processes are economically desirable due to their high turnover rate and their contribution to the GDP [6]. In the batch process industry, large numbers of products are typically processed using similar production paths. Furthermore, these goods possess low unit volumes and require frequent purchasing and consequently, frequent transport. Generally, well-established distribution networks are available to transport these batches of goods.

Companies are required to address the environmental aspects, such as emissions of greenhouse gases (GHG). Recently, carbon emissions are increasingly gaining attention by governmental and private companies [7]. Since green logistics implies an environmentally friendly and efficient transport distribution system [8], [9], [10], it is crucial to optimize the total supply chain costs and environmental impacts concurrently [11].

Within management in general and logistics in particular, supply chain management SCM is one of the most successful concepts. Thus, a better utilization of these resources becomes more and more important. Efficient planning leads to the direct reduction in the number of resources needed to provide customers' demands as well as to a better utilization of the supply network by reducing transporting movements.

In today's global environment, effective supply chain planning is essential not only for competitive position but also for the successful performance of the entire network. Supply chain planning is one of the two major categories of supply chain management (SCM) processes (beside supply chain design).

Production and distribution operations are key functions in today's supply chains. To achieve optimal operational performance in supply chains, it is critical to jointly integrate the planning of these two functions and minimize their costs simultaneously [12]. In the existing networks, these decisions are related to the required facilities such as locations, numbers and capacities [13].

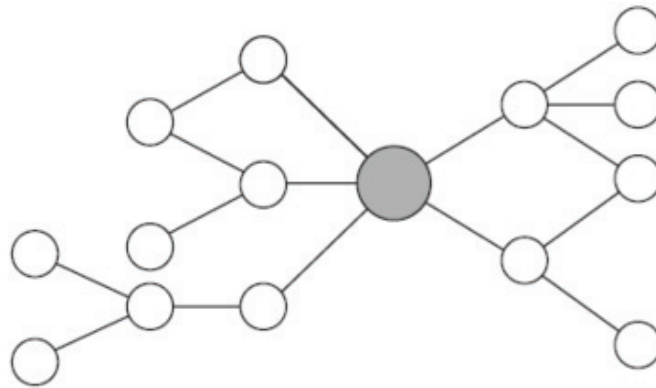
On the one hand, the product batches are for the most part transported using smaller packaging and joint distribution which mitigate the carbon footprint [14]. Due to these characteristics, products which are distributed in batch forms could be considered environmentally friendly. This advantage is commercially highlighted by enterprises and appreciated by consumers.

Developing production-distribution models while involving green logistics issues are required at the tactical-operational levels. According to the conclusions in the National Science Foundation (NSF) Symposium report [15], more research is needed to address this problem in the context of supply chains and logistics systems which has been tackled in the present study. Furthermore, there is a lack of applications and case studies that aim at validating theories and perspectives, particularly in the batch process industry [16].

## **2. 2. Network Design and its Related Concepts**

The term network is associated with numerous problems in various research fields. A network of connected and interdependent organizations is working together to control, manage and improve the flow of materials and information from the supplier to the end users [17]. As shown in Figure 2-1, a firm is the centre of a network composed of both the supplier and the customers.

The network design problem has attracted the interest of researchers for decades. In the network design phase, long-term decisions are made. These decisions are mainly to determine plant locations and to configure their systems of production. Mid-term decisions are made in the supply network planning phase. During this phase, the primary requirements for the final products to be produced at individual plants on the basis of demand planning data are provided. The short-term allocation of individual production resources to the production of the primary requirements is performed during the detailed production scheduling phase [18].



**Figure 2-1 Diagram for a network [17]**

Decisions within the supply chain network design (SCND) are made to satisfy customer demands while minimizing the sum of strategic, tactical and operational costs or maximizing the profit. Due to the high interaction between these decisions, treating the network as a whole and considering its various components simultaneously generates important benefits such as minimizing the total network cost [19].

Setting up a logistics network is a crucial task for ensuring the efficient operation of the supply chain. In this thesis, the term signifies the design of a green logistics network. This section investigates all the related concepts. These concepts involve the definitions of supply chain, supply chain management, logistics and their decisions.

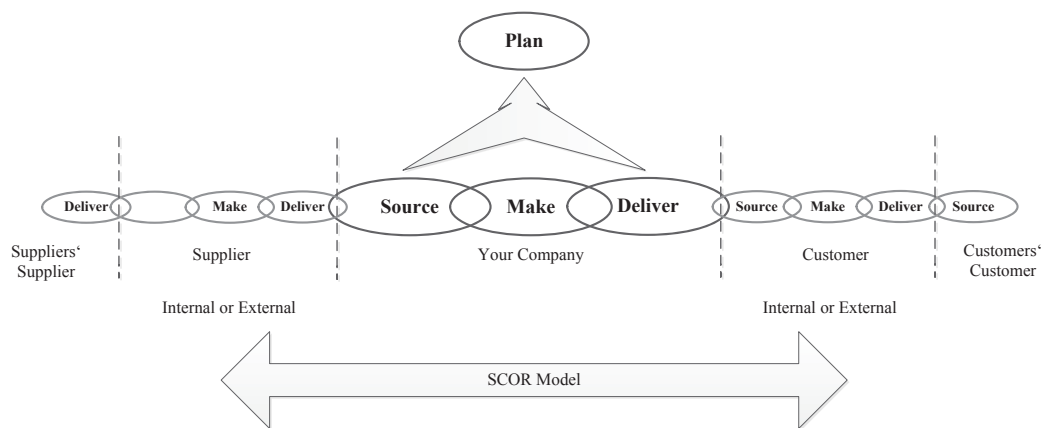
Additionally, both the green logistics and the green supply chain management are studied in terms of their interlinking relationship with sustainability. The three dimensions of sustainability are described. Furthermore, the integrated scheduling of production and distribution planning is presented. Last but not least, the production and distribution planning managerial decisions are shown.

### **2. 2. 1. Supply Chain, Supply Chain Management and Logistics**

The supply chain concept is referred to as an integrated system which synchronizes a series of inter-related business processes. This integration is established in order to get a supply of raw materials and parts, transform them to finished products, add values to these products and distribute them to either retailers or customers. In addition, it helps to facilitate information exchange among various entities or stages of the supply chain

network (e.g. suppliers, manufacturers and distributors). The main objective of any supply chain is to enhance the operational activity and profitability [5].

Supply Chain Management (SCM) is the set of functions that controls the flow of material and information through the supply chain [20]. The Supply Chain Management Council [21] introduced a model that defines the different issues encountered within SCM. The model is called ‘Supply Chain Council and Supply Chain Operations Reference Model’ (SCOR). This model is illustrated in Figure 2-2. The SCOR model is a process reference model which has been developed and endorsed by the Supply Chain Council as the cross-industry standard diagnostic tool for the SCM. The SCOR model enables users to address, improve and communicate supply chain management practices within and between all interested parties. Although the SCOR model provides a common supply chain framework, it is only a framework. This means that the implementation process of the SCOR model is still in question [22].

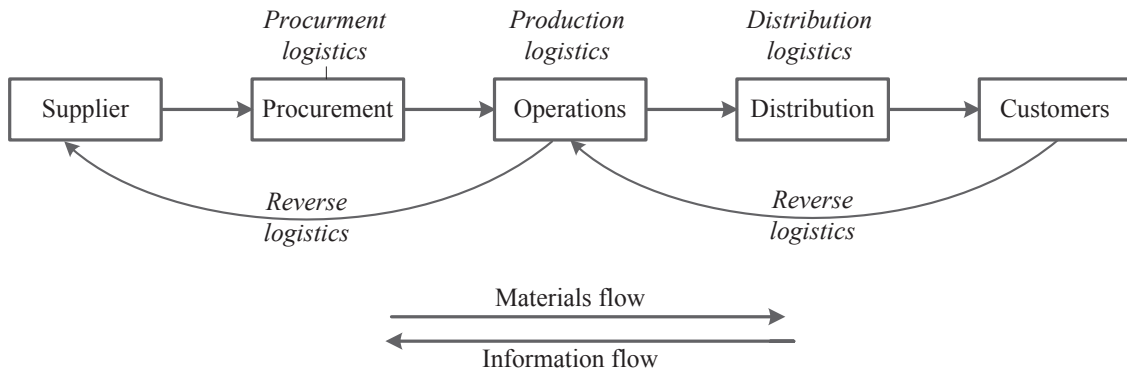


**Figure 2-2 The SCOR model [21]**

Due to the growing complexity of coordinating the supplement of materials and shipment of products in global supply chain networks, logistics as a business concept was first evolved in the 1950s [23]. Logistics management is one of the supply chain disciplines that plans, organizes, implements and controls the flow of resources (goods, services and related information) from the point of origin to the point of consumption in a way that meets customers’ requirements efficiently and effectively [24], [25]. In each supply chain, logistics processes are classified into four different types: procurement (inbound)



logistics, production logistics, distribution (outbound) logistics and reverse logistics [27]. The relation between these logistics processes in a supply chain is shown in Figure 2-3.



**Figure 2-3 Logistics processes in a supply chain [17], [27]**

Logistics involves an integrated approach of information, transportation, inventory, warehousing, material handling, packaging and recently added security. Within these logistic activities, transportation is considered as the major component of most logistics services [26]. Production logistics include all transport and storage processes within a company that add value in production. Typical goods are raw materials, auxiliary materials, operating materials, purchased items, semi-finished and finished products or spare parts. All inbound logistics processes are combined to procurement logistics. Procurement logistics typically comprises all materials transported in production logistics. Semi-finished and finished products, merchandise and spare parts are goods that are transported and stored in distribution logistics. Reverse logistics comprise residues (secondary raw materials and waste) such as used and worn products, rebuilt units, returns, empties and packaging [27].

Industrial production and trade require an efficient and reliable supply network. The goal of logistics is to deliver the right objects in the right quantity to the right place at the right time in the right quality for the right costs. With the fast development of information technology and the global market, collaboration between different functional units in a supply chain plays an important rule to manage the global rapid changes of customer needs. A successful collaboration increases the efficiency of the whole supply chain [28].

To ensure the effectiveness of SCM, different decisions at different managerial levels must be taken. This is shown in the following section.

### 2. 2. 2. Supply Chain Decisions

Efficient management of the supply chain network necessitates taking into account different decisions at different levels. The Supply Chain Planning Matrix [29], as shown in Figure 2-4, classifies the planning decisions in the two dimensions “planning horizon” and “supply chain process”. These decisions which lead to effective design and management of supply chain networks are categorized into the three main management levels: strategic, tactical and operational planning.

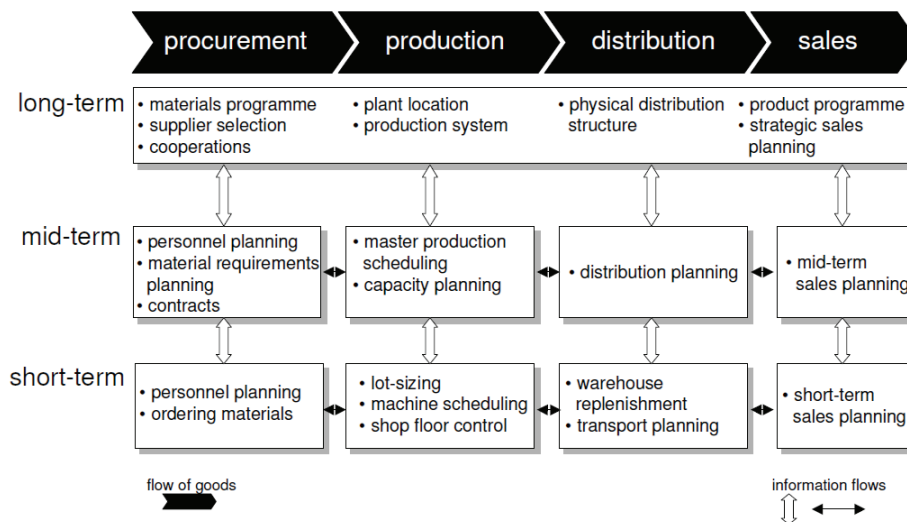


Figure 2-4 The supply chain planning matrix [29]

- Strategic Planning Decisions

The time frame of these decisions is several years. Thus, firms should consider the market changes and uncertainties. The scope of this phase is concerned with resource planning. These decisions are referred to as supply chain strategy.

Decisions made in this scope are about the location and capacity of both the production (manufacturing) and warehousing facilities. Other strategic decisions include the modes of transportation, new product development, outsourcing, supplier selection, information technology selection and pricing. Decisions in this phase include: production system type;

production scale from a cost perspective; quality; delivery; flexibility to compete; facility location; process selection; and long range choices concerning raw materials.

- Tactical Planning Decisions

In the tactical or medium range plans the time frame ranges from a quarter to two years into the future. This phase focuses on resource assignments. These decisions are referred to as supply chain planning.

The inputs of the tactical planning decisions are covering the basic physical production capacity constraints and demand pattern established by a long range plan. Medium range planning often involves making decisions on the Master Production Schedule (MPS), Material Requirements Planning (MRP), establishing production quantities or lot sizing over the planning period [30] and generating detailed production schedules over a specific interval of time [29].

The generated outcomes include demand allocation; distributing the demand of each customer to certain production and warehousing plant(s). It also involves the inventory control decisions, production/distribution coordination and equipment selection. A decision in this phase implies the following values: the work force size; the regular time; overtime; and subcontracting units utilized by the facility.

- Operational Planning Decisions

Short range activities have a typical one-day time horizon. The scope of this phase is concerned with the utilization of resources.

Decisions are mainly for firm individual customer orders and include: vehicle routing/scheduling, workforce scheduling; recordkeeping; order picking timings; and packaging. In most cases, operational decisions are drawn up into detailed schedules for one week, one day and one shift. These schedules involve: product/job assignment; loading; sequencing; and the routing of orders through the facility or the workforce.

Many researchers have modelled systems which deal with green supply chain designs [31]. Existing models handle different aspects of production-distribution functions at

many levels such as: aggregate production planning at the tactical level [32][33]; transportation at the operational level [34]; transportation and inventory at the tactical and operational levels [11]; as well as facility location and supply chain planning at the strategic level [35]. However, new models are required to address many other decisions [36]; specifically, production-distribution models at the tactical-operational levels are required since they are rarely dealt with in the literature.

### **2. 2. 3. Green Supply Chain Management and Green Logistics**

Since the applications of logistics are generally positive for the efficiency of transport systems, it has been suggested that logistics is environment friendly, thus, the concept of “green logistics” has emerged [37]. Green logistic trends have been important to logistics management in terms of the environment [38]. Greening supply chains aim to balance the market requirements with environmental issues. To meet challenges such as energy conservation and pollution abatement, enterprises have tried to green their supply chains, in other words, to create networks of suppliers to purchase environmentally superior products or to build common approaches to waste reduction and operational efficiencies [9]. This concept is shown in Figure 2-5.

Green Supply Chain Management (GSCM) addresses, simultaneously, the environmental issues and the operational processes of supply chain management. Correspondingly, all the solutions, including logistics management, should be integrated in a more comprehensive supply chain procedure. With the growing concern for the environment, a new perspective is added to supply chains – their environmental management [39]. Environmental issues can be handled in an integrated fashion within the achievement of business operational goals [40].

GSCM is a multifaceted problem, which comprises economic, social and environmental elements. The motivation for the introduction of GSCM may be ethical (e.g. reflecting the values of managers) and/or commercial (e.g. gaining a competitive advantage by signalling environmental concern) [41]. Wolf and Seuring (2010) stated that the body of literature on the GSCM is growing and expanding over the past few years [42].

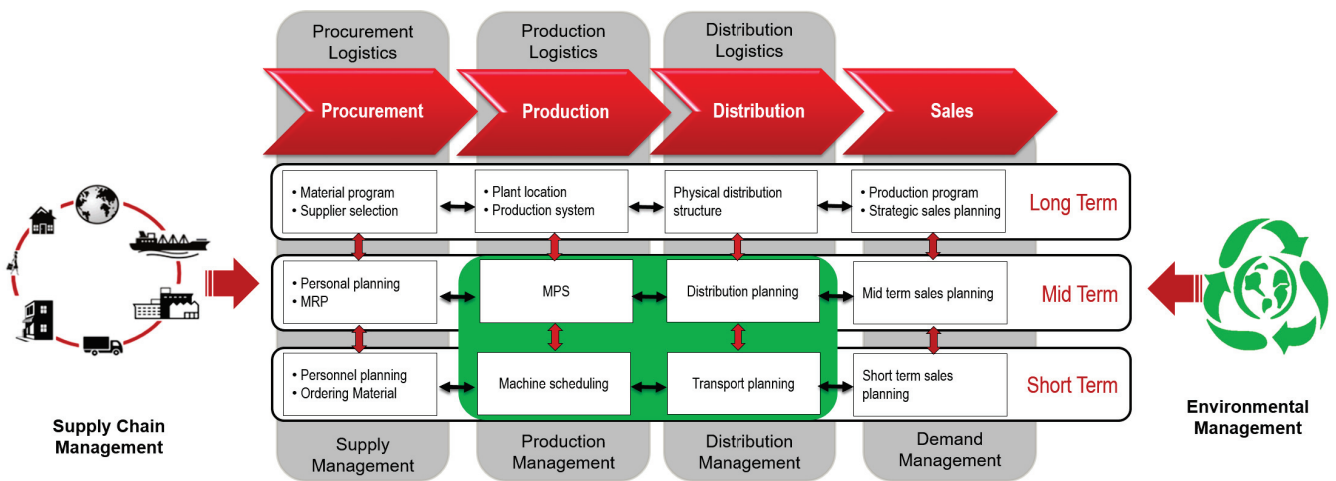


Figure 2-5 Green Supply Chain Management (GSCM) concept [25]

Today, many companies are required to address these environmental issues due to both regulatory and non-regulatory conditions [39]. Companies operate between two opposing poles: on the one hand, there are societal risks which arise from their business activities, while, on the other hand, there is the active involvement in society. As a result of increasing global activities which influence ways of life and consumer preferences, the balance between a business case for sustainable development as well as natural and societal concerns should be considered [43].

At the same time, delivering products to customers faster, more reliable and greener than competitors has become a requirement rather than a competitive advantage. Customers take the environmental issues more and more into account. These trends are overlapping; companies must satisfy the needs of their customers and even exceed the environmental expectations of their governments [44]. Hence, green logistics is the most dominant theme of GSCM research [45]. The importance of green logistics is motivated by the fact that the current production and distribution logistics strategies are not sustainable in the long term [46].

The environmental, economic and social demands caused by the government, manufacturing services as well as none and for profit organizations will continue to exist. The source and management of these environmental and social burdens are not the sole responsibility of one organization; entire supply chains and their networks must be involved. Research efforts must be augmented to understand the roles, management, tools and mechanisms for sustainable supply chains in order to help meet these challenges [47].

Green logistics is one of the hot research topics which interlink the economic, environmental and social aspects. However, in many cases, it is difficult to strike a balance between the varying requirements due to the multifaceted nature of the logistics discipline. Nowadays, sustainable development as well as greening aspects appear as key issues facing logistics activities. To consider wider objectives and issues within supply chains, researchers study both sustainable supply chain management and green logistics which lead to new methods of executing the logistics activities.

Nevertheless, enterprises are facing new challenges while applying these methods which require quick responses to the changes of the customer's needs. Additionally, the entire

supply chain has become more dynamic than ever before due to the many challenges they face compared with their predecessors. These challenges include shorter life cycles of products as well as an increased number of product variants and the dependence of supply chain functional units. Moreover, global enterprises require higher attention on the environmental effects of their logistics activities.

In sum, the green SCND consists of all the network design questions issues which benefit the environment. Particularly, it is the adoption and development of sustainability which concerns the economic, environmental and social aspects. The interrelation between sustainability and green logistics in logistics enterprises will be researched in the next chapter.

#### **2. 2. 4. The Integrated Scheduling of Production and Distribution Planning**

Within any supply chain, there are three fundamental elements as shown in Figure 2-4: procurement, production and distribution. These decisions were traditionally made separately; however, their integration can have a significant impact on the overall system and service performance [48]. The more integrated a supply chain, the higher the performance will be [49]. The supply chain is not just a chain of business on a one-to-one, business-to-business relationship but rather a network of multiple business relationships in order to gain synergy of intra-company and inter-company integration and management [49].

Production and distribution operations are the two key functions in the supply chain. It is critical to integrate these two functions, plan and schedule them jointly in a coordinated manner [50]. To achieve this integration in a logistic system, efficient design of the production and distribution logistics should be established. Within global supply chains, only an integrated scheduling of production and distribution operations can materialise the competitive advantage of such a supply chain in terms of total cost and on time delivery reliability [51]. When integrated chain management is realized, materials are used more efficiently and resources are conserved.

The complexity of today's logistics systems drives the central planning and control of the logistic processes into becoming increasingly difficult. Moreover, in order to achieve sustainable logistics of the system, complex systems of supply chains need to be integrated [52]. Keeping up the integrated framework to obtain the benefits of optimizing the total logistics system should be considered. In general, integration is the process of obtaining multiple individual elements into one. Economically, it refers to creating a large value composed of many multiple small units [53].

The integration process is the centre of performing logistics tasks [53]. Many research papers address the relationship between integration and performance. There is far less research on how to achieve integration across a plant [54]. Furthermore, the execution of planning this task is challenging for both the supply chain professionals and scientists, since the underlying planning problem is NP-hard [51].

Many companies now realize that greater value can be offered to their customers by effectively integrating logistics management and product availability to improve the timeliness and consistency of delivery. Firms are moving from decoupled decision making processes, when they have been managed independently, towards a more coordinated and integrated design [55]. Using integrated approaches to optimize the logistics systems has a positive impact not only from the economic perspective but also from an environmental view. This integration leads to potential reduction in the total costs and increases the efficiency, flexibility and profitability of the supply chain [56]. In addition, the lack of coordination between the supply chain functions has a negative impact. This lack is one of the main causes of the higher carbon emissions among the supply chain [14].

Therefore, an integrated supply chain model is an important tool in order to maintain the sustainability within the dynamic, uncertain global environment [56]. The major difference between the objectives of the integrated chain management (ICM) and SCM is that the ICM targets to reduce environmental impacts as well as improving chain performance which is the only focus of the SCM [57].



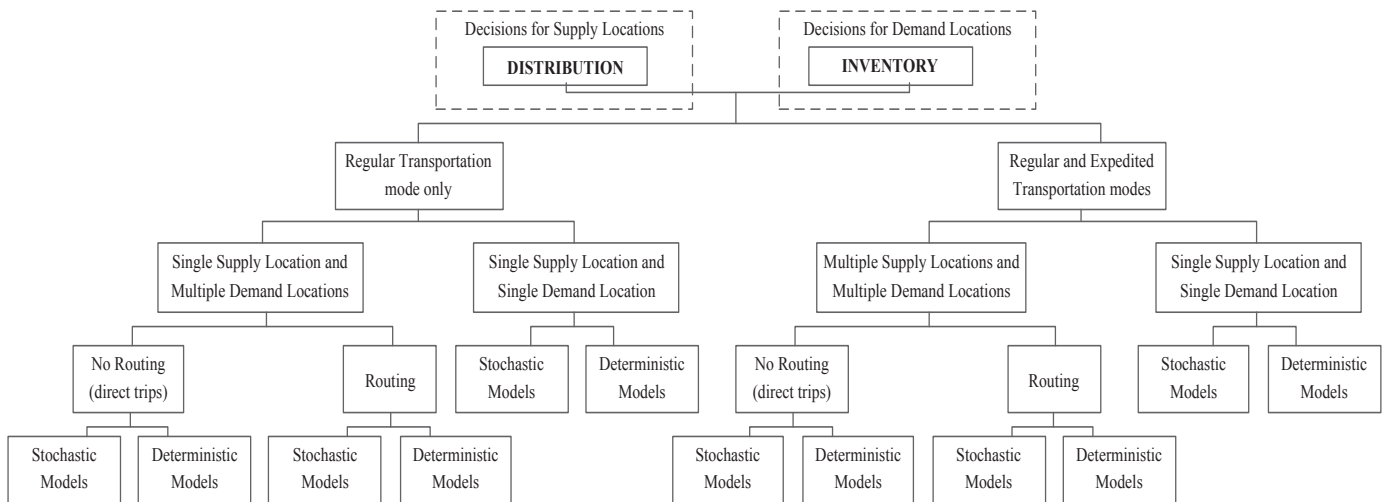
### **2. 2. 5. Production and Distribution Managerial Decisions**

Production and distribution management is concerned with the different decisions that should be considered in the phases of the supply chain. It requires generating production and distribution plans. These plans define: the quantities to be produced from each product; quantities to be delivered from each product to every location; the amount of inventory to be stored in the plant from each product; the accumulated quantities to be delivered up to the customers in each planning period, number of routes and vehicles; as well as the optimal routing sequence of customers.

Evidently, design and management of supply chain activities is a primary factor in promoting environmental impact. The process of designing, sourcing, producing and distributing products in the global market plays a central role in the SCND [58]. This target is achieved while total cost elements include: the production cost; the inventory holding cost; the environmental impact cost; as well as the fixed and variable transportation costs. This objective is achieved by considering the different production and distribution parameters such as: the number of vehicles and the distribution routes of customers; the production capacity of the plant; the order quantity of the customers; the plant storage limitations; the multiple planning periods; and the multi-commodity production and distribution [59].

### **2. 3. Classification of the Integrated Production-Distribution Planning Models**

The integrated production-distribution planning systems were classified by Sarmiento and Nagi [59] into three main categories: integrated analysis of distribution-inventory planning; inventory-distribution-inventory planning; and inventory-production-distribution-inventory models. The authors reviewed, categorized and classified more than 50 research works under many parameters such as transportation mode, supply demand location, time horizon, etc. as presented in Figure 2-6, Figure 2-7 and Figure 2-8.



**Figure 2-6 Classification of distribution-inventory models [59]**

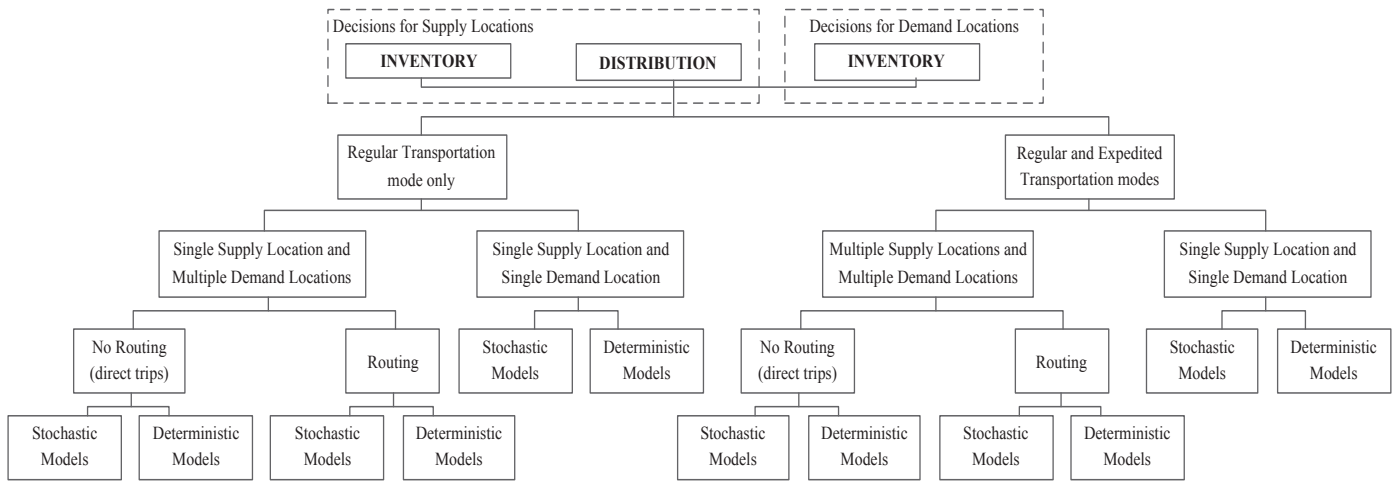


Figure 2-7 Classification of inventory-distribution-inventory models [59]

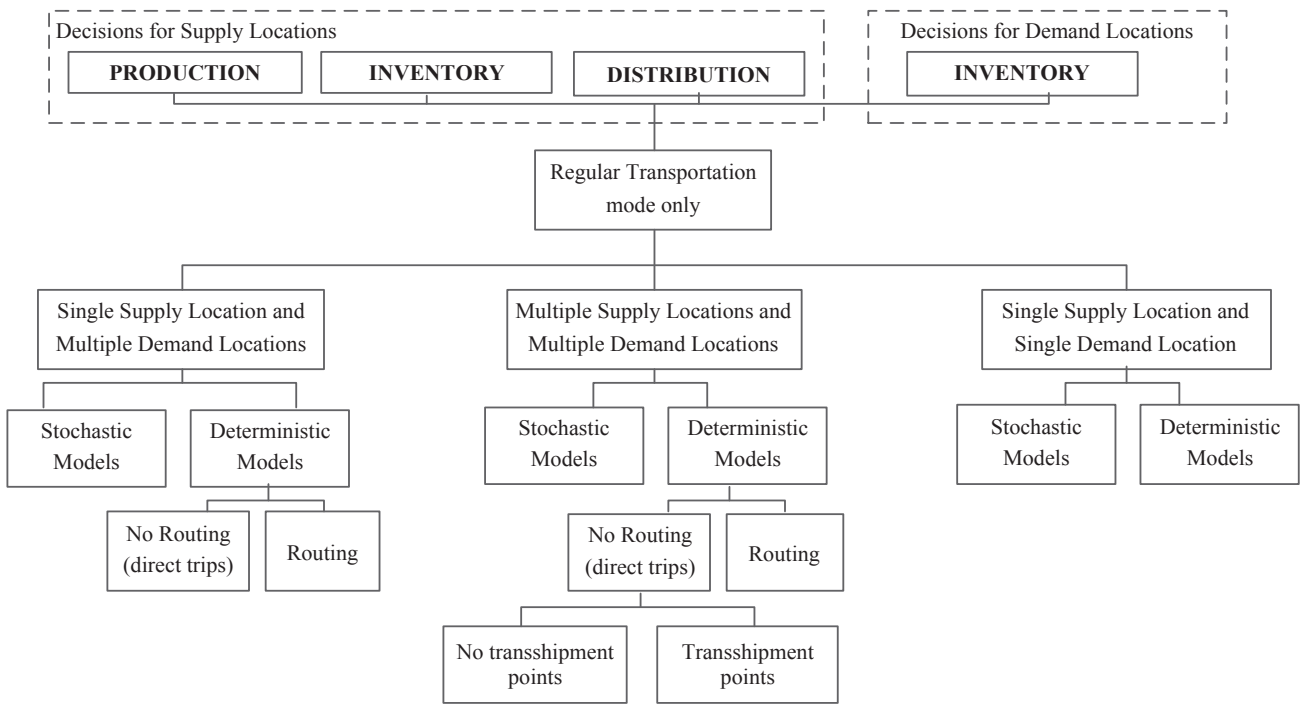


Figure 2-8 Classification of production-inventory-distribution-inventory models [59]

A clear classification of the inventory-distribution and production-distribution problems is difficult to develop, given the diversity and number of assumptions that can be taken into consideration in such problems [59].

Another review published by Chen [50] used three dimensions as the basis of the classification for the models. These dimensions are the decision level, integration structure and problem parameters. The author classified problems which were studied in the research into five classes as follows: the first class is production-transportation problems; the second class is joint lot sizing and finished product delivery problems; the third class is joint raw material delivery and lot sizing problems; the fourth class is general tactical production-distribution problems; and the fifth class is joint job processing and finished job delivery problems. The author concluded that, although a large amount of research has been conducted, this is still a relatively new area. As direction for future research, he recommended the inclusion of more parameters and related topics.

#### **2.4. Relationship between Production, Distribution and the Environmental Issues**

According to one of the most comprehensive reviews of the GSCM, there are two types of greenness: green design for products and green operations [60]. Among the green operations, the way products have been ordered, produced and transported has an environmental impact. Taking into account the environmental issues during the planning of supply chain operations, some production processes are much environmental friendlier than others in terms of their carbon footprints [36].

Governments over the world have been trying to control the amount of the carbon-emission officially. Moreover, companies are now paying much more attention to their carbon footprint. Under these schemes, the manufacturer gets motivated to develop or improve their manufacturing technology to comply with the regulations [61]. Likewise, many researchers investigated the ways to mitigate the Greenhouse Gas (GHG) emissions from the production and distribution phases. They introduced some common actions to reduce or eliminate these emissions such as investing in carbon efficient reduction technologies [56].

Greenhouse gases (GHG) include water vapour; methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), ozone (O<sub>3</sub>) and carbon dioxide (CO<sub>2</sub>) which represent by mass more than 99 percent of all the gaseous components of exhaust [62]. The EU sets GHG emissions rate standards and has mandated a decrease in emissions rates of about 20 percent from 2009 to 2015; as in the United States, further decreases are expected through 2020 [63]. So far, the estimation of the total emitted CO<sub>2</sub> by each distribution vehicle are not possible before planning the routes [34].

### **2. 4. 1. Green Production**

In today's competitive environment, manufacturers aim at improving their public image by producing environmentally friendly products. This aim should be considered during production planning as well as manufacturing phases. Green production improves sustainability performance by reducing waste and therefore, production related costs. This sustainability is the result of using appropriate materials and innovative environmental technologies. Other intended benefits by instilling green production methods include savings in raw material costs, production efficiency gains and reduced environmental expenses [61]. Correspondingly, green production is not only beneficial to consumers but also beneficial to the manufacturer in the long run.

During the production planning, researchers have introduced some principles to apply environmental protection and energy conservation concepts. These concepts are now well known as just-in-time (JIT) [36], lean manufacturing [59], [64] and green production [65]. Furthermore, carbon emissions can be eliminated by improving demand forecasting accuracy [14]. Within the manufacturing operations, carbon emissions can be eliminated by rationalizing the usage of material [14].

In the batch process industry, the ordering of batches has also had an environmental impact. In most cases, customers ordered their demand quantities as a number of pieces or items. These numbers are then converted to the number of batches at the production facility. Typically, companies offer quantity discounts to encourage customers to order more. A producer intends to discount the unit production cost if the amount of production is large [32]. The ordering quantities discount policy should not only be offered based on economic reasoning but based on environmental reasoning as well.

Furthermore, all types of inventory have an environmental impact. Mainly, there are four types of inventories: raw materials, work-in-progress, finished goods and packing material. The environmental storage footprint consists of refrigerated storage (food storage for example), heated storage (in the case of some oils for example) and evaporation during storage [36]. These types should be considered in the planning during both the production and distribution processes.

### **2. 4. 2. Green Distribution**

The green distribution process contains many activities that need to be planned in an environmentally friendly way. These activities involve packaging, transportation and logistics. In the literature, green packages can be made using environmentally friendly, recycled materials with improved packaging designs and techniques help companies to reduce waste and costs. Using smaller packaging and joint distribution are both recommended to eliminate GHG emissions [36], [67]. Joint distribution not only reduces fuel consumption but also reduces noise and pollution during transportation.

Distribution planning plays a vital role by generating the optimum routes, minimizing the total transportation costs as well as saving energy and, respectively, GHG emissions. While loading orders, the main actions that can be taken to minimize the carbon emissions during the distribution operations are maintaining full truckloads and a selection of the optimum distribution routes [68].

The trade-off between central and non-central storage decisions plays a vital economic as well as environmental role in supply chain planning. Economic cost element is mainly about the number of storage areas to be either rented or bought, while the environmental cost element is related to the heating/cooling energy cost. Thus, there are two choices to manage this issue; the first choice is to have a central storage area with high associated transportation costs. The other option is to have a non-central storage with low transportation costs [36].

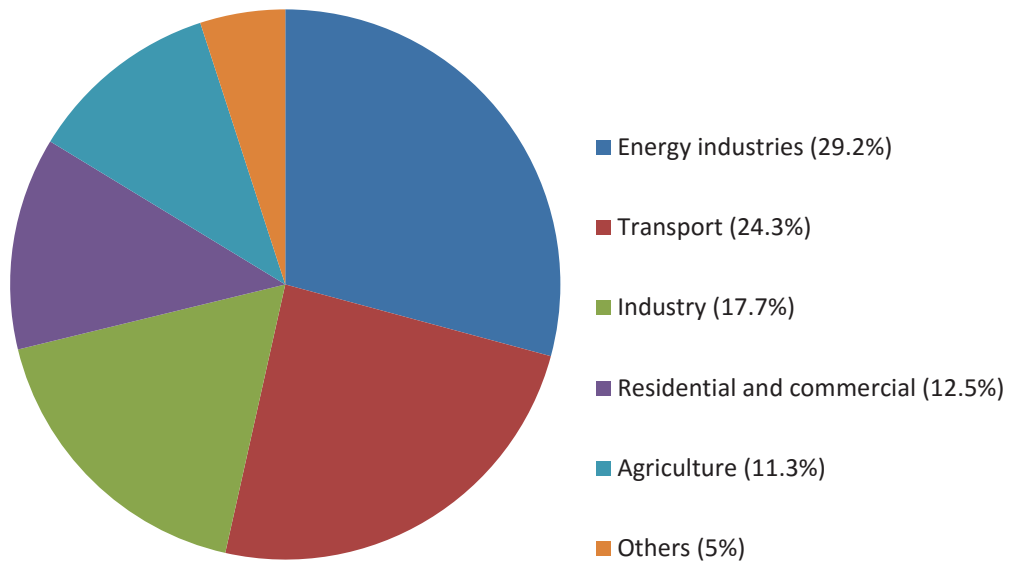
Transportation is the most visible aspect of supply chains [36]. The transportation sector was the second largest emitter accounting for 19 percent in 1995 and will remain in the same place in 2020 with 24 percent of the total EU emissions [36], [69], [70]. Based on

Buehler and Pucher [138], transport is responsible for about a third of all GHG emissions in the USA and one fifth of worldwide GHG emissions, mainly in form of CO<sub>2</sub> in 2011.

Road-based transport is the largest contributor of emissions [36]. More than two thirds of transport-related greenhouse gas emissions are from road transport; it accounts for approximately 70 percent of the total transportation emissions, according to the Organization for Economic Cooperation and Development (OECD) [62] and European Environment Agency (EEA) reports [71]. More details together with these values are shown in Figure 2-9 and Figure 2-10.



### EU GHG emissions by sector



### EU GHG emissions from transport by mode

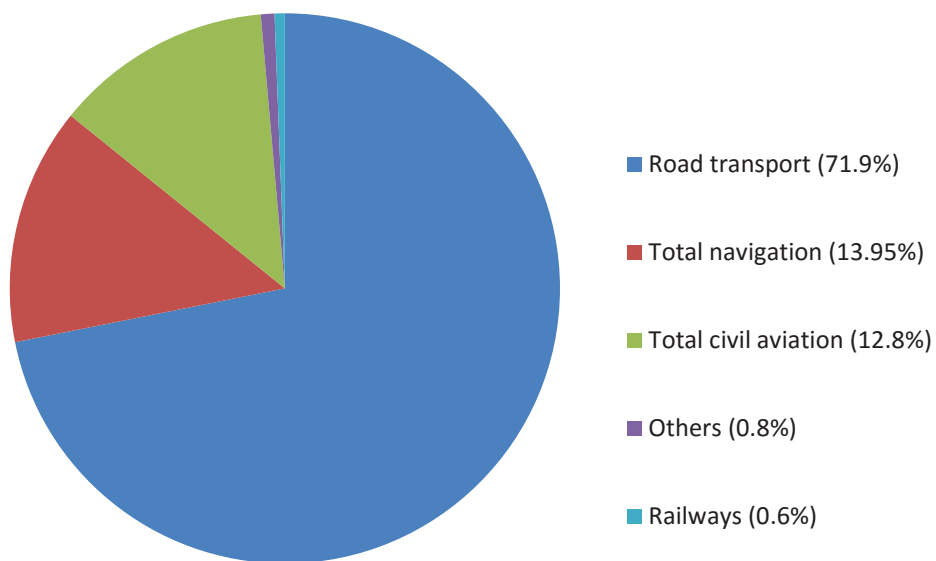
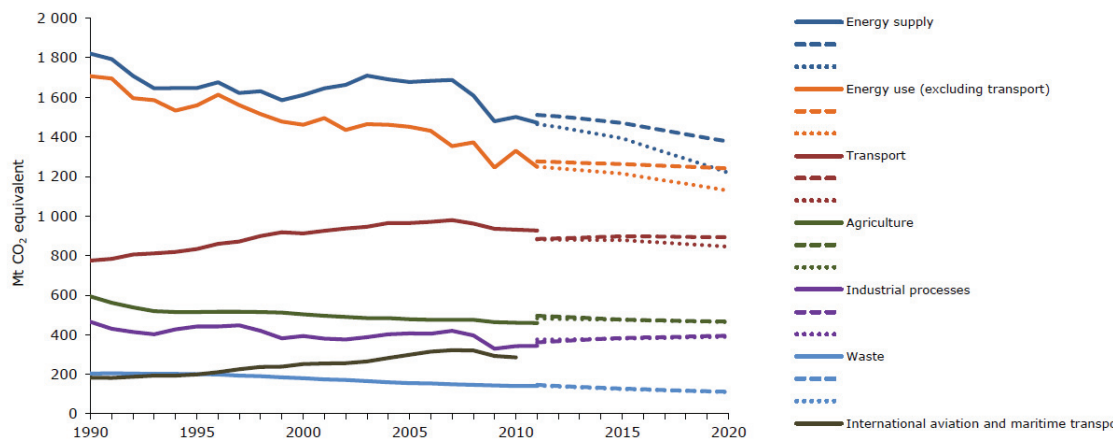


Figure 2-9 EU greenhouse gas emissions by sector and mode of transport, 2012 – adapted from EEA [71]



Note: GHG emission projections are representing either through dashed lines (with existing measures) or dotted lines (additional measures).

Source: National GHG inventory report, 2012; EEA proxy estimate of 2011 GHG emissions; national GHG projection data submitted in 2011.

**Figure 2-10 EU greenhouse gas emissions trends and projections 1990-2020 – adapted from EEA [71]**

In most of the industrialized countries, road-based transports are the main freight carrier even with the presence of very dense and modern railway systems. Their share is between 75 and 100 percent in several industrialized countries and developing countries respectively. This is due to their flexibility to deliver over short distances, their efficiency in terms of just-in time freight deliveries as well as increasing demand for door-to-door services. Therefore, more road transport models should be developed in order to forecast the increased customer's demands and the generated GHG emissions during the distribution of these demands [62]. Reducing the amount of CO<sub>2</sub> emissions leads to reducing costs [72].

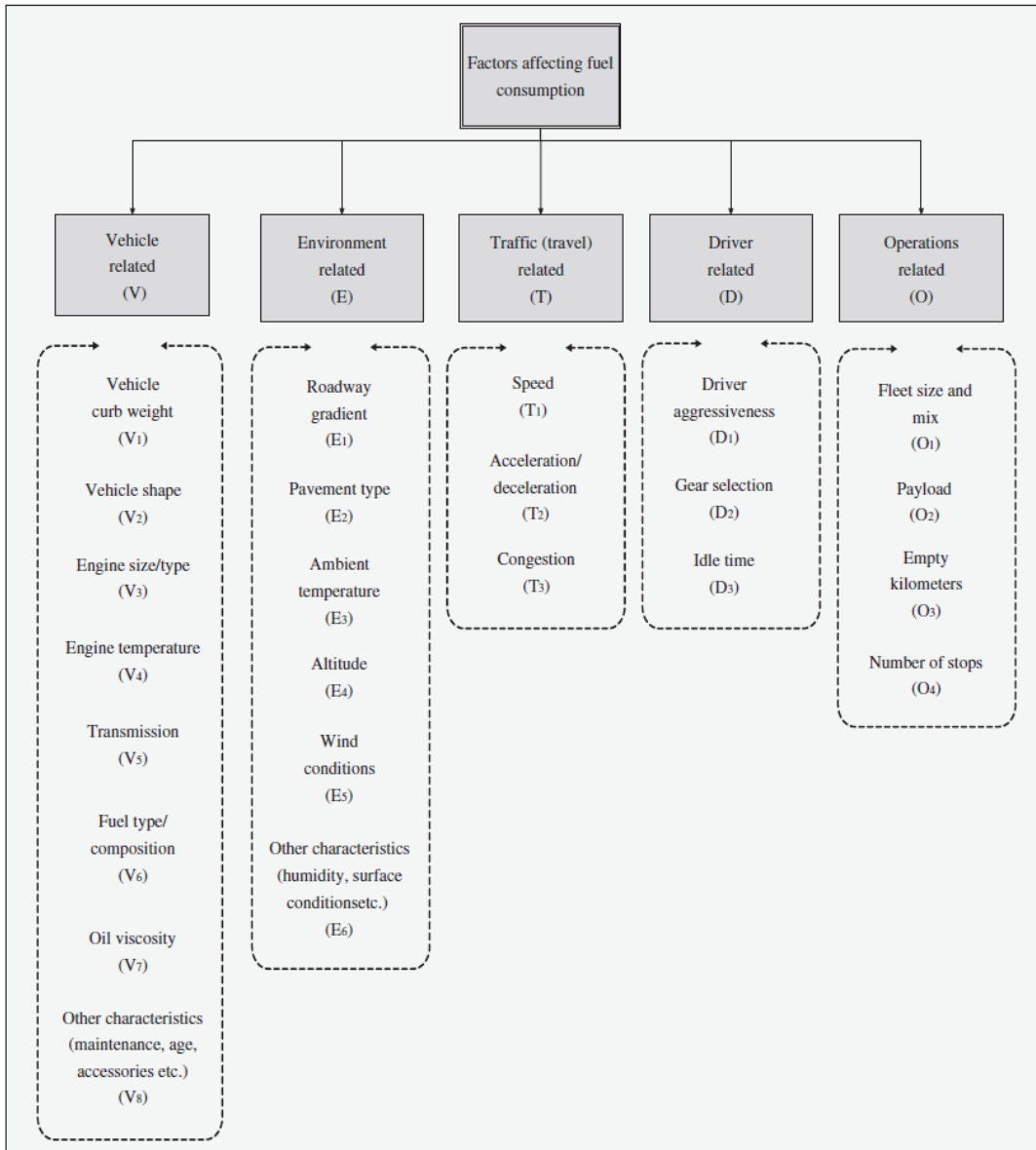
The total emissions produced by road vehicles are the sum of hot emissions, cold emissions and evaporation emissions. Hot emissions are produced when the engine is hot, whereas a cold engine generates cold emissions. The emissions caused by evaporation are the losses while refuelling, diurnal-breathing losses; hot soak losses and running losses [73].

Currently, there are two ways to calculate CO<sub>2</sub> emissions: fuel-based or distance-based methodology [74]. While the fuel-based method is more reliable, the distance-based method is simpler to use due to the type of the data required for each method. Using the

distance-based method requires knowing the distance travelled and fuel consumption by vehicles. In addition to this data, fuel-based method requires knowing the heating values which are very hard to get. Therefore, the common method to estimate the CO<sub>2</sub> emissions is the distance-based method. In this approach, the distances travelled by the vehicle, the vehicle type and the fuel type are collected. The vehicle type and fuel type are converted to the emissions factors (there are many formulas such as [34], [75], [76]). The vehicle estimated CO<sub>2</sub> emissions are calculated by multiplying distance travelled by the emission factor.

### **2.4.3. Effect of Delivering Velocity on the Generated Emissions**

The factors influencing fuel consumption can be divided into five categories: vehicle, environment, traffic, driver and operations as shown in Figure 2-11. In a review of recent research on green road freight transportation, vehicle velocity (speed) is shown to be the most important factor which affects fuel consumption. Speed has a significant effect in fuel consumption. Optimum driving speed lead to remarkable reduction of the emitted CO<sub>2</sub>. It is quite crucial to travel at a speed that leads to minimum fuel consumption for a given routing plan. The driver who controls vehicle speed plays a significant role that affects the fuel consumption. A difference in fuel consumption between the best and worst drivers can be as much as 25% [77].



**Figure 2-11 Factors affecting fuel consumption [77]**

The fuel economy of a vehicle varies with the vehicle's velocity. The fuel economy of current vehicles is maximized between 50 and 90 kilometres per hour. The fuel required to keep the engine running is greater for vehicles moving at lower velocities. On the other hand, when vehicles move at higher velocities, the fuel economy reduces as a result of increasing of the aerodynamic forces [78]. High and wide spectrum of velocities leads to more emissions, accidents, noise and congestion. Thus, controlling speed limits reduces fuel consumption and consequently CO<sub>2</sub> emissions. CO<sub>2</sub> emissions reduction by 10 and

20 percent respectively can be achieved at a 120 and 100 kilometres per hour speed limit according to a study conducted by the German Umweltbundesamt [79].

The amount of CO<sub>2</sub> emissions is proportional to the amount of fuel consumed which is depends on the travelling speed [74]. Thus, calculating emissions under constant speed assumption could be misleading. With this assumption, differences of up to 20 percent in CO<sub>2</sub> emissions on an average day for gasoline vehicles and 11 percent for diesel vehicles are calculated [78]. During congested periods of the day these differences rise 40 percent [78].

Until recently, the scientific literature related to fuel reduction in road freight transportation by means of operations research techniques has mainly focused on cost minimization [77]. Stochastic velocities are usually neglected in the literature, though these parameters are frequently used to describe the dynamic environment [73]. Vehicle's velocity as well as acceleration is highly correlated with their rate of GHG emissions [76], [78], [80]. However, many researchers (for example, [81], [82]) developed dynamic mathematical models to estimate the emissions and fuel consumption as a function of instantaneous speed and acceleration. More efficient and applicable models are, therefore, required to get closer to the real life environment. In this research, the delivery velocities have been involved in order to bridge the existing gap between traditional distribution planning models and environmental impact models particularly in terms of their strong relationship with emissions.

## **2.5. Processes Characteristics: Batch Process Industry**

There are four broad classes of production processes: job shop, batch flow, assembly line and continuous process. The differences among them have important implications on the choice of the production planning and scheduling system [83]. This research work aims at studying a selected case of the batch process industry.

For many years, continuous operations have been the most prevalent mode of processing. However, in recent years there is renewed interest in batch processes for a variety of reasons. The most appealing feature of the batch process is their flexibility in producing multiple products in a single plant through the sharing of process equipment [18], [84].

The batch operations are economically desirable, especially when small amounts of complex or even a large number of products are made using similar production paths [6]. Economic benefits can ensure the reduction of the number of setups through a more efficient use of production and other resources [85].

Features of the batch process industry motivate researchers to study their nature, not only because they can be produced in vast types within limited variations of production lines, but also because they are usually used by end consumers. Another motivation is that the batching of items for transportation between machines may improve machine utilization [86]. The goal is to minimize the scheduled workload by batching deals through converting the primary requirements for products into sets of batches for each task [18].

A batch process is frequently found in the fast moving consumer goods industry [87], food processing [86], [88], [89], chemical manufacturing [86], [90], oil refining [91], fertilizer industries [86] and pharmaceutical industries [18], [92]. Batching is the process of transforming a component or mix of components on a machine into different products [5].

Batches of various products are produced by scheduling a set of processing tasks or operations (called production stages) such as reacting, mixing, filling or packaging multiple pieces of equipment and/or machines. The process plan provides the sequence of stages (the route) that a batch should follow. There is a predefined quantity of similar products that together form one batch. The batch size is the amount of the products processed by a single machine operation and/or job [93]. Jobs may be batched if they share the same setup on a machine. This is another reason why batching occurs when a machine can process several jobs simultaneously [94].

In a batch manufacturing environment, products are released to the production system in groups of one or more parts. In other words, these parts are grouped into a family. For each batch, the production sequence and processing time at each workstation in the sequence are known. Thus, the production cost is substantially reduced relative to independent scheduling [95]. Batches need to be scheduled on equipment with various batch sizes during a short period of time. For each stage, ready usage time is known. This time usually involves the cleaning time, the setup time for the tools and the pre-running

time. In addition, the total production time of each batch is the summation of its setup and processing time.

When a production is completed, batches are ready to be distributed to the customers, based on their demand. Scheduling most of the distribution plans is based on the vehicle routing problem (VRP) [96]. The VRP is a classical combinatorial optimization problem that has become a key component of distribution and logistics management. It is defined that multiple vehicles initially located at a depot are to deliver discrete quantities of goods to a set of customers [97]. The classical VRP aims to find a set of routes, at a minimal cost for a well-known demand for each set of nodes, which all begin and end in the depot. Each node is visited only once, by only one vehicle and each vehicle has a limited capacity [98]. The total demand of each route cannot exceed the vehicle capacity. Each vehicle route satisfies some side constraints, e.g., duration and time window constraints [99].

Minimizing cost through the VRP can be achieved via many parameters but mainly by considering distance and time. Since the VRP introduction in 1959 by Dantzig and Ramser, different extended versions of the VRP have been studied to model real life applications [99]. A recent paper published in 2014, Lin et al. [46], reviewed and analyzed the articles which are related to all the VRP variants. Since 1969, Stochastic Vehicle Routing Problems (SVRP) has been introduced as one of the traditional VRP extensions. The SVRP arise whenever some elements of the problem are random. Common examples are stochastic demands, stochastic travel times and/or stochastic customers [100].

The reduction in total travelled distance by itself provides environmental benefits, not only due to the reduction in fuel consumption and the consequent pollutants, but also because it will trim unpredictable fuel prices and long lead times. Minimizing the distance travelled is a key step in network optimization because it reduces both emissions and the total supply chain cost [101]. Due to lack of information about the GSCM best practice, researchers are required to develop methods for evaluating the values of the real GHG emissions. Involving emissions values within the modelling of distribution plans is essential in order to achieve a sustainable balance between economic and environmental objectives [102].

## 2. 6. Overview of the Related State of the Art

In order to maximize the benefits and minimize the total cost for many enterprises, the enterprises tend to consider production and distribution decisions comprehensively rather than separately. The potential savings generated by the integration of production and distribution is addressed by Geotschalckx et al. in their review paper [103]. Researchers had developed multiple models, such as the study of Glover et al., to achieve this goal [104]. In their research, a production, distribution and inventory planning system for a batch process industry are presented and applied in a chemical company.

Hall and Potts considered a variety of scheduling, batching and delivery problems in their work. Depending upon the scheduling objective, they demonstrated a reduction by at least 20% and up to 100% in the total system cost due to the cooperation between the supplier and manufacturer [105].

More models were introduced afterwards such as the integrated model of Chandra and Fisher [106] which coordinated the production and inventory of multi-products over several time periods and furthermore the distribution of a fleet of vehicles to a number of retail outlets. They showed the economic value of using an integrated approach compared to solving each problem separately. An example of a more recent model is the one developed by Bonfill et al. [107]. Their model integrated production and distribution at the operational level for a multi-site supply chain. They presented two case studies and illustrated the benefits of using their integrated approach.

Despite the various researches in this area, Fahimnia et al. [108] pointed out the necessity of developing integrated optimization models that includes more elements of production and distribution costs. One of these cost elements which plays an important role nowadays is the environmental impact [59]. Several recent papers focused on including different green supply chain aspects in the production-distribution modelling at different levels. Sheu et al. [40] formulated a linear multi-objective programming model that optimizes the integrated operational logistics and the used-product reverse logistics in some green supply chains.



Some other researchers studied green transportation aspects at the operational level as Ubeda et al. [34]. They proposed several green changes within the VRP through a case study at one of the leading distribution companies in Spain. They showed that logistics managers are able to conduct green practices while meeting efficiency objectives at the same time. Pishvae et al. [109] developed a bi-objective fuzzy mathematical programming model for green logistics design under uncertain conditions. Their model integrated the transportation and production strategic decisions and was applied in an industrial case study.

Al-e-hashem et al. [32] formulated a model for aggregate production plans that considered uncertainty in customers' demands. Their model generates tactical related decisions in a green supply chain. Some models deal with the facility location and supply chain planning at the strategic level. For instance, Jouzdani et al. [35] presented a facility location model under demand uncertainty and traffic congestion. They applied their work on a case study of a milk and dairy products facility and measured both the economic and environmental costs.

At the operational level, Zhang and Xu [33] modelled a production planning optimization problem which included both production and carbon trading decisions. Last but not least, the transportation and inventory decisions at tactical and operational levels as well as the environmental impacts were the main focus of the model presented by Sazvar et al. [11]. Their objective was to strike a balance between the financial and environmental criteria under uncertain demand. None of these models integrated the green aspect of carbon emissions with the tactical-operational supply chain planning. The current work integrated these issues in the newly presented model.

As one application of the batch process industry, Chen et al. [110] considered the stochastic nature of demands and consequently, the suppliers' revenue. They proposed a mixed integer nonlinear mathematical model to integrate the production scheduling and vehicle routing with time windows for food products. Then, the model is decomposed into two sub-problems at the tactical level. Their formulation computational results indicate that their algorithm is effective and efficient. In this formulation, only the economic objective was taken into account.

Another integrated production and transport scheduling problems are studied by Ehm et al. [51]. In their work, they presented a reformulation of the scheduling problem as a shortest path problem based on graph-based scheduling heuristic for each job. The proposed method is applied to a supply chain scenario which contains a manufacturing facility in Brazil and shipments to customers in Germany. The obtained results show that the approach is suitable for the scheduling of large-scale problems and can be flexibly adapted to different real-world scenarios. Only economic objectives are considered in this research.

Recently, several researchers incorporated uncertainty in their integrated models (for example [18], [111], [112], [113]). Their investigation is concerned with the different supply chain costs and customer demands. However, the current study focuses on different sources of uncertainty which is related to the travel distances, the permissible velocities of vehicles and the emitted carbon values generated during demand deliveries. These sources are incorporated in the developed integrated green production-distribution model. Thus, a new integrated model will be added to the literature, examining the uncertainty in the green aspects of the supply chain, rather than the exploitation of the production and distribution operations. The applicability is examined of the developed framework in a real world batch processes industry.

In a recent research paper, Gao et al. [1] concluded that there is a shortage in the integrated batch production and the distribution scheduling models. They proposed a mixed integer programming formulation to minimize the completion time of the scheduling. They explored the solution to the general problem and propose a heuristic with a guaranteed performance. Only the economic dimension of the integrated problem is considered here.

A review of the models which considered the scheduling of production-distribution networks can be seen in Table 2-1. It is noteworthy to state that the available supply chain models do not cover the specific characteristics of the batch process industry.

**Table 2-1 The review of dealing with production-distribution models**

<b>Researcher, Article Date</b>  <b>and</b>  <b>Reference Number</b>	<b>Level of Integrity</b>		<b>Related Issues</b>		<b>Research Methodology</b>			<b>Production Processes Characteristics</b>				
	Production Planning	Distribution Planning	Economical issue	Environmental issue	Descriptive analysis	Mathematical modelling	System simulation	Job shop	Assembly line	Continuous process	Batch process	Undefined
Gao et al., 2015 [1]	•	•	•			•					•	
Stankovic and Bakic, 2006 [6]	•		•			•					•	
Zhu and Cote, 2004 [9]			•	•	•					•		
Pinto-Varela et al., 2011 [10]	•	•	•	•		•						•
Sazvar et al., 2014 [11]		•	•	•		•					•	
Ji et al., 2014 [14]	•	•	•	•	•							•
Bidhandi and Rosnah, 2011 [19]	•		•			•						•
Wang et al., 2011 [31]	•		•	•		•						•
Al-e-hashem et al., 2013 [32]			•	•		•					•	
Zhang and Xu, L., 2013 [33]	•		•	•		•				•		
Ubeda et al., 2011 [34]		•	•	•		•					•	
Jouzani et al., 2013 [35]		•	•		•					•		
Sheu et al., 2005 [40]	•	•	•	•		•						
Walton et al., 1998 [44]					•							
Nananukul, 2008 [48]	•	•	•			•		•				
Ehma et al., 2015 [51]	•	•	•			•						•
Deif, 2011 [61]	•	•	•	•	•							•
Burkard et al., 2002 [84]	•		•		•							•
Giannelos and Georgiadis, 2003 [87]	•		•			•						•

Researcher, Article Date  and  Reference Number	Level of Integrity		Related Issues		Research Methodology			Production Processes Characteristics				
	Production Planning	Distribution Planning	Economical issue	Environmental issue	Descriptive analysis	Mathematical	System simulation	Job shop	Assembly line	Continuous process	Batch process	Undefined
Jia and Ierapetritou, 2003 [91]	•					•				•		
Mockus et al., 2002 [92]	•		•				•				•	
Damodaran and Srihari, 2004 [93]	•		•			•		•				
Park, 2005 [96]	•		•		•							•
Al-fazary et al., 2010 [97]	•	•	•		•						•	
Li et al., 2010 [99]		•	•			•						•
Bonfill et al., 2008 [107]	•	•	•			•					•	
Pishvae et al., 2012 [109]	•	•	•	•		•	•					•
Georgiadis et al., 2011 [112]	•	•	•			•						•
Long and Zhang, 2014 [113]	•	•	•		•	•						•
Jung and Jeong, 2005 [114]	•	•	•			•	•					
Armentano et al., 2011 [115]	•	•	•				•					
Romano et al., 2007 [116]	•	•	•				•					
Scholz-Reiter et al., 2008 [117]	•						•	•				
Bilgen and Günther, 2010 [118]	•	•	•			•					•	
Puigjaner and Guillén, 2008 [119]	•	•	•			•	•				•	
Stewart, 1997 [120]	•	•	•		•							
Chen and Lee, 2008 [121]	•	•	•			•		•				
Scholz-Reiter et al., 2011 [122]	•	•	•			•					•	
Scholz-Reiter et al., 2010 [123]	•	•	•		•	•		•				
Taş et al., 2013 [124]		•	•		•							•
<b>The proposed Model</b>	•	•	•	•	•	•					•	

## 2. 7. Closing Remarks

Due to the aforementioned reasons, a design of an integrated framework for scheduling production-distribution green logistics system for the batch process industry, which fulfils the listed requirements, is of essential need in order to cover the research gap. The development of a sustainable, efficient, effective and robust model that addresses both the economic and the environmental aspects to manage the uncertainty of the dynamics in supply chain operations is required.

Many comprehensive reviews were introduced in the research area of integrated production-distribution planning and helped in classifying and categorizing the different levels of the production-distribution problems [125]. The challenge of integrating the production planning decisions with production distribution decisions through the supply chain is a combination of internal and external logistics due to economic issues [123]. Furthermore, there is a growing need for integrating environmentally sound choices into supply chains, because it is one of the schemes that support the total optimization besides the economic considerations [121]. In 2014, Lin et al. [46] concluded that these models are largely neglected in the literature.

The main objective of the proposed logistical research activities is to develop a production-distribution green logistics system for the batch process industry under uncertainty. In this research, the basic decisions and related issues of supply chains for the batch process industry are analyzed. The core of this integrated planning framework considers the optimal production and distribution decisions regarding the logistics of batch process products. This plan considers different managerial aspects related to the production and distribution logistics beside the economic and environmental issues. The model simulates the standard processes for the batch process logistics.

The output is the integrated production and distribution plans in the first stage. These plans include: the quantities to be produced for each product; the quantities to be delivered for each product to every location; the amount of inventory to be stored in the plant for each product; the accumulated quantities to be delivered up to each location; the number of routes needed; and the optimal routing sequence of customers in planning each period for the given input parameters.

In the second stage output, the optimum delivering velocities on the optimum routes are generated. These velocities present the optimal values which minimize the total emissions. Within the first stage, values of these velocities are ranged between a minimum and maximum random values. Emissions under uncertainties during distribution are incorporated in the presented model as a function of delivering velocities at different distribution routes.

## CHAPTER 3 RESEARCH METHODOLOGY

This chapter has five parts, first: the description of the research paradigm and its research methodologies to solve problems are presented. The research methodology that is followed in this thesis is described. Second: the combination of quantitative and qualitative methodologies for the proposed framework is presented respectively in sections 3.2. and 3.3.. Third: the review of all the required models and issues related to the solution methodology are termed. Forth: the key reference models which are required to formulate the framework are reviewed. Finally: the modelling requirements and issues in the framework are studied.

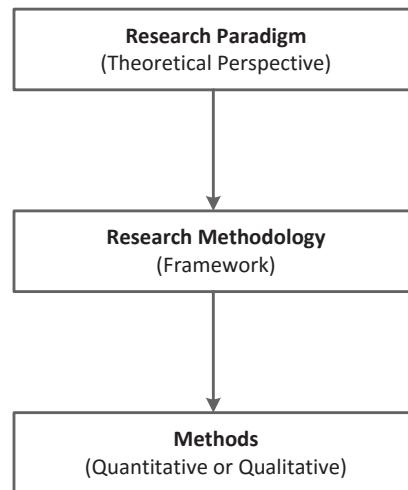
### 3. 1. From Concept to Methodology

The concept of the paradigm is central to the research process in all areas of study. Basically, a paradigm is a world-view; a very general conception of the nature of scientific endeavor [126]. A research paradigm is an integrated cluster of substantive concepts, variables and problems with corresponding methodological approaches and research tools [127]. A research paradigm translates into a set of principles using the research methodology. Each research paradigm has a wide variety of research methodologies associated with it [126], [127].

A research methodology is a systematic way to solve a problem. It is a scientific way of studying how research is to be carried out [128]. A methodology is a framework which demonstrates how the real world can be described, approached, explained, predicted and studied through a scientific approach. In other words, a research methodology is a way of describing and analyzing methods, highlighting their limitations and clarifying their origin, assumptions and consequences. A research methodology is defined as the study of methods through which knowledge is gained; its aim is to provide the work plan along with the research [127], [128].

Research methods are the various procedures, schemes and algorithms used in research. They are essentially planned, scientific and value-neutral. Research methods involve all tools that help researchers to collect samples and data as well as to find a solution to a

problem [128]. Particularly, scientific research methods can be quantitative or qualitative. The relationship between the theoretical perspective and research practice is shown in Figure 3-1.



**Figure 3-1 From the theory to practice: the relation between the research paradigm and research methods – adapted from [127]**

Logistics research has a wide spectrum of methods and tools which are used by researchers during the evolution of logistics as a discipline. Researchers apply many research methodologies to understand, analyze and model different logistics and supply chain systems. Dominant logistics research is based on quantitative methodologies; qualitative methodologies are less often applied [126].

Nevertheless, in order to contribute to the logistics field, more research to view real-world problems from a practical perspective is required. The main reason behind this conclusion is that logistics is a practice-oriented and solution-based discipline. To enhance the body of supply chain and green logistics knowledge, the scientific approach should be built through qualitatively-derived descriptions of a real world system. This conclusion is based on many logistics research contributions published in different research journals such as the Journal of Business Logistics, International Journal of Physical Distribution and Logistics Management and Supply Chain Management [127]. While the majority of this research is based on quantitative methodologies, qualitative methodologies are also explored in this work.



### **3. 2. Qualitative Methodologies: Sustainability in Green Logistics**

Nowadays, green logistics is a crucial concept for a sustainable enterprise. Green logistics interlink economic, environmental and social aspects. However, in many cases it is difficult to establish a balance between the varying requirements due to the multifaceted nature of the logistics discipline. In the light of this challenge, this work explores the notion of sustainability as it is applied to green logistics. Moreover, it studies the interdependencies between the logistics pillars as well as the integrated concept of corporate sustainability. It displays the related economic, environmental as well as social challenges by reviewing the related literature. In addition, the interrelation between sustainability and green logistics in logistics enterprises is explicated. Results of this research are going to provide the scientific basis for this relation. This work reduces the research gap in this field by engaging in an interdisciplinary dialogue; this dialogue helps to improve the quality of the research outcome.

This section focuses on two concepts related to logistics: sustainability and green logistics. First: it reviews the state of the art of sustainable and green supply chains to deal with the challenges that face an international supply chain. Second: it presents an overview of sustainability and green logistics, examining the interlinking between them and the related literature review. Third: it is followed by defining the related challenges of the logistics activities: the economic, environmental and social challenges. Forth: the interrelation between sustainability and green logistics in enterprises is demonstrated.

#### **3. 2. 1. Sustainability and Green Logistics**

Sustainability has been increasingly discussed within recent years as a cross-sectional character which integrates three issues: economy, environment and society. The term ‘sustainability’ is derived from German origin, ‘nachhaltende Nutzung’, and was used in the field of forestry in 1713 by Hans Carl von Carlowitz. This term came to his mind during the building of silver mines under his supervision while he was thinking about how to guarantee a permanent supply of timber. His idea came from not wanting to cut down more trees than that could grow back [129].

In 1972, the concept of sustainable development was officially introduced for the first time based on the concept of eco-development at the United Nations Conference, held in Stockholm. This concept of sustainable development was defined as *‘Man is both creature and moulder of his environment, which gives him physical sustenance and affords him the opportunity for intellectual, moral, social and spiritual growth’* (Declaration of the United Nations Conference, 1972 [128]). According to this definition, governments are the main responsible body for the improvement and protection of the environment for people, now and in the future.

Later, the sustainable development concept has been extended to involve societies with governments to share the prime role in environmental requirements. In order to play this vital role for sustainable development, the economic level of the society should be able to develop and maintain a rising state of development in a sufficient way. Economic targets are the base of stability in markets; the focus moved from ecological to the economical roots. Throughout the logistics activities, more attention is given to related economic issues through examining the production, transportation consumption, waste management and the consequences of actions which are reflected in the state of the future [130].

Afterwards, the focus moved again towards environmental issues. The concept of sustainable development became a benchmark for green logistics - a multifaceted discipline. This new focus comprises economic, environmental and social elements [39]. It focuses on actions that minimize harmful effects on the environment and introduces the tools and behaviours that contribute to improve society and its economic level.

Green concepts integrate environmental thinking into logistics activities in order to develop the society [131]. In 1991, the first green design literature considered the need for a green design to reduce the impact of product waste. According to Fortes (2007), the key themes which came out in the literature over the last twenty years are the concepts of green design, green operations, reverse logistics, waste management and green manufacturing [125]. For many years, logistics activities have only considered economic objectives which mostly include the maximization of the profit or minimization of the total cost. Currently, planning these activities require balance between economic,

environmental and social priorities. Implementing green logistics leads to sustainable enterprises.

### **3. 2. 2. Economic, Environmental and Social Challenges**

With the progressively important rule of globalization, to maintain a competitive enterprise, the offered logistics services have to be unique. Although the barriers have been decreased globally, the pressure to meet the international standards increased the total associated logistics cost. The logistical enterprises are struggling to achieve a balance between the economic, environmental and social benefits in order to compete within this dynamic environment. Dyllick and Hockerts (2002) have framed the three dimensions of sustainability as: the business case (economic); the natural case (environmental); and the societal case (social) [132]. These three issues are described as follows:

- Economic Issues

The economic goal is double-sided. On the one side, it is to maximize the value of creation of logistics services by enterprises. This value is related to the financial performance measures such as revenue, assets and customers' service levels. On the other side, it reduces the related logistics costs by utilizing the available resources [133]. Within global competitive markets, these goals are achievable not only through service quantities, but rather by the quality of services offered by enterprises [130], [134]. In the future, the measure for successful enterprises will be sustainability and therefore this will replace the previously mentioned benchmark.

It is essential that logistics enterprises encourage the development of innovative and efficient logistics services to reach economic sustainability. Economic dimension is considered as a fundamental prerequisite in order to survive in today's highly competitive environmental global market [135]. Moreover, economic challenges are not isolated from the environmental and social challenges. A society with an unstable economic situation will not be able to focus on environmental or social issues. Without a guarantee to income related benefits, conflicts within the society will break out in order to fulfill people's main financial requirements [130].

- Environmental Issues

Environmental goals target to balance between the utilization of natural resources and the requirements of human beings [134]. The environmental integrity principle ensures that the human activities do not erode the earth's land, air and water resources. Human activities can have a significant negative impact on the natural environment such as ozone depletion, accumulation of greenhouse gases (GHG) emissions and waste generation [130]. Environmental benefits include the reduction of waste, fossil fuel consumption, air and water emissions as well as raising the efficiency of energy usage [133].

Generally, transportation is the major activity of most logistics services [26]. As far as more countries continue to industrialize rapidly, the associated carbon emissions are greatly increased. Thus, there is a growing need for climate friendly solutions, especially in the area of logistics transport. Nowadays, significant reductions of carbon emissions as well as costs during transport are achievable by optimizing the design of a logistic network, using the right modes of transportation and efficiently managing the load capacities and routes.

Furthermore, the reduction in total travelled distance by itself provides environmental benefits, not only due to the reduction in fuel consumption and the consequent pollutants, but also because it will trim unpredictable fuel prices and long lead times. Minimizing the distance travelled, is a key step in network optimization because it reduces both emissions and total supply chain costs [101]. Due to the lack of information about the best practices of the green supply chain, optimization tools to achieve a sustainable balance between economic and environmental objectives are still needed by researchers [102].

- Social Issues

Social goals are achievable by increasing people's awareness about their environmental responsibility as well as rules toward their society and culture. Sustainability is a universal goal which implies a concern for social equity between generations [130]. These goals are willing to reduce the negative impacts toward society within all the actors: individuals, enterprises, industries and governments [26].

Although the concept of sustainable development is highly dependent on society, for two decades this human dimension has been neglected in comparison with economic and environmental dimensions [136]. Social sustainability is defined as: *‘Development that meets the needs of the present without compromising the ability of future generations to meet their own needs’* [137].

Social aspects affect the economic development of any society in several ways. These aspects are: the integration of society in decision making process; generating equal opportunities of development for all members of society; and taking into accounts the limitations and requirements of the environment in their decisions [134]. The social equity principle ensures that all society’ members have equal access to resources and opportunities. It is a must that the needs of society are met in the present and future [137].

The World Bank defines sustainability more broadly, including the environmental, social and economic dimensions of sustainability (World Bank 1996). Environmental sustainability conserves natural resources, minimizes pollutants and mitigates impacts on ecosystems such as climate change. Social sustainability includes considerations of health and safety, accessibility and the distribution of benefits and costs among groups of society. Economic sustainability focuses on economic growth, cost effectiveness and financial viability. Few studies consider all these aspects of sustainability but it is important to note that the concept is far broader than just CO<sub>2</sub> emissions [138].

### **3. 2. 3. The Interrelation between Sustainability and Green Logistics in Logistics Enterprises**

Although the term of sustainability was introduced before green logistics, green issues are considered as an evolutionary version of the sustainability concept. Currently, green aspects receive more attention. The traditional focus of many logistics enterprises is the economic issues in comparison to the environmental and social issues. While there is still a long way to go in this regard, there are many positive signs to indicate that environmental responsibility is increasingly accompanying economic development. In fact, it is hard to split between these two terms; green logistics leads to a sustainable supply chain.

Even though the primary initiative to implement green logistics was initially due to legislation, many enterprises nowadays are implementing green aspects to their logistics because it is the right thing to do for the environment. Numerous motivators drive companies to become green: cost reductions for customers, suppliers and partners; an increase in the competitiveness of the enterprise; its revenue and market share; as well as an improved customer relationship and service. Green logistics practices are only about ‘win-win’ relationships in terms of environmental and economic performance [125].

The core of sustainable development is the cooperation and collaboration between the society, environment and economy. The integration between economic, environment and social actions taken by the present society should be considered in terms of their consequences for future generations [134].

Green logistics encourages environmental awareness by driving all of the users’ logistics systems into considering how their actions have an affect on the environment [125]. The main objective of green logistics is to coordinate all activities in the most efficient way in terms of maintaining a balance between the economic, environmental and social priorities. Enterprises should maximize the net benefits of economic development by minimizing the logistics related cost and saving the environment at the same time. Currently, cost is not only related to materials but also involves the additional costs of logistics activities such as climate change, air pollution and waste [134]. In order to incorporate the environmental concerns in the SCM and to respond to higher consumer demands, the environmental aspects should be involved at each step of the chain [139]. Therefore, emerging and developing integrated models for logistics activities within the wider context of sustainable development are necessary [140].

In sum, the implementation of green logistics is an approach that makes enterprises sustainable. The sustainability concept in logistics delivers long term profitability.

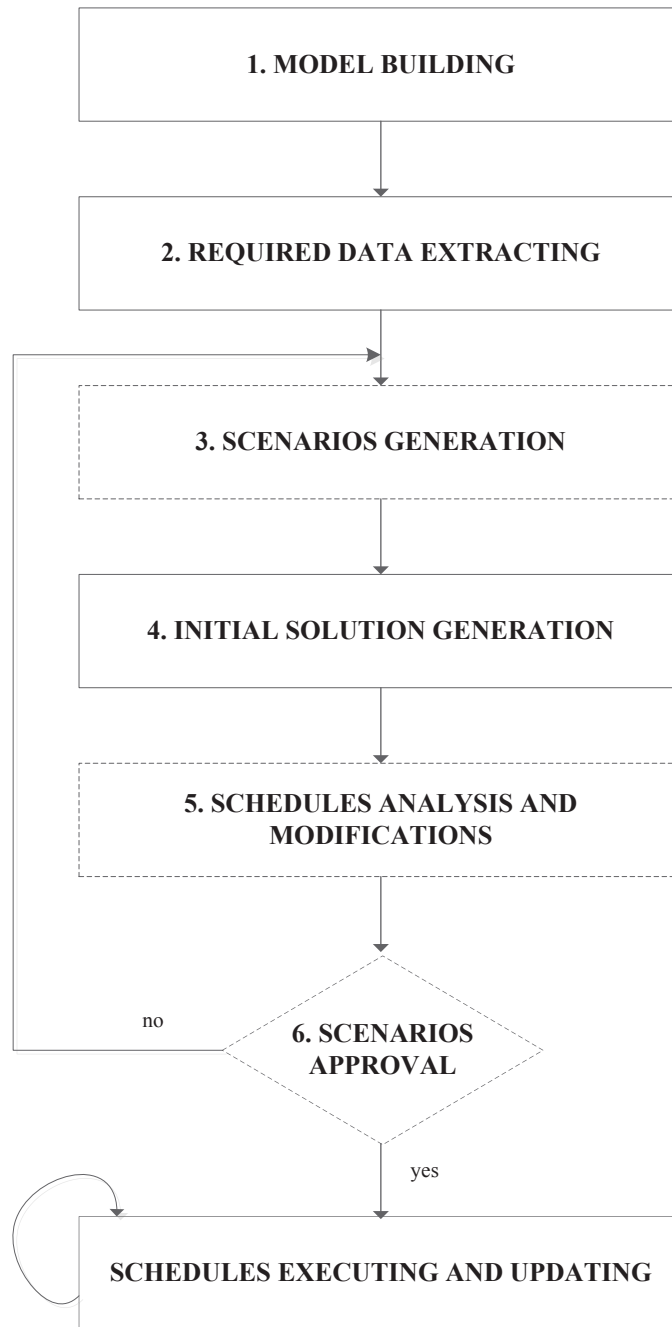
Obstacles which prevent the implementation of green aspects within logistics enterprises are mainly related to the economy, environment and society. These barriers can affect companies from internal or external sources. Internal barriers to initiate green issues may refer to: high investment or implication costs; a lack of financial or human resources; and a lack of knowledge or in-house skills. External barriers involve: a limited access to

technology that reduces environmental impact; a lack of interest or support of customer or transport/logistics suppliers/partners; a lack of a government support system; as well as due to market competition and uncertainty.

Furthermore, societies as a whole need to play a vital role towards green logistics beside the role of enterprises. The lack of awareness of customers is a barrier that governments and enterprises need to pay greater attention to on the whole. With regard to logistics, it is necessary to encourage more people to use public transport such as buses or trains and to avoid, for example, the use of private cars. This action reduces the harmful effect of transport in terms of GHG emissions and other adverse environmental impacts. Therefore, it is essential to improve the infrastructure, poor schedules, a lack of comfort and finally reduce high prices for public transports.

### **3.3. Quantitative Methodologies**

According to Stadtler [141], there are six steps in realizing a framework (methodology). This procedure is shown graphically in Figure 3-2. The first step is to build a model which captures the properties of the production process and its corresponding flows of materials. The second step is to extract all the required data in order to generate feasible production plans at minimum costs. Afterward, the decision-maker at the plant uses this data as well as further knowledge or expectations about the current and future situation on the shop floor to generate a set of assumptions. These inputs are called scenarios. Then, an initial solution is generated for each given scenario. The fifth step is to analyze the production schedule and interactive modifications of the developed model based on the experience and knowledge of the decision-maker and the feasibility of the production plans. The sixth and last step in this procedure is to approve the generated solution. This approval is based on the decision-maker evaluation for all available alternatives. In reality, these steps should be followed by execution and updating.



**Figure 3-2 General procedure for production scheduling – adapted from [141]**

### **3. 3. 1. Model Building**

Generally speaking, models should be built to deal effectively and efficiently with the process, product or system in these industries and their issues. Various ways are available to model a system depending on the system characteristics, purpose of modelling, functional specifications, available information, etc. Commonly, these industries use

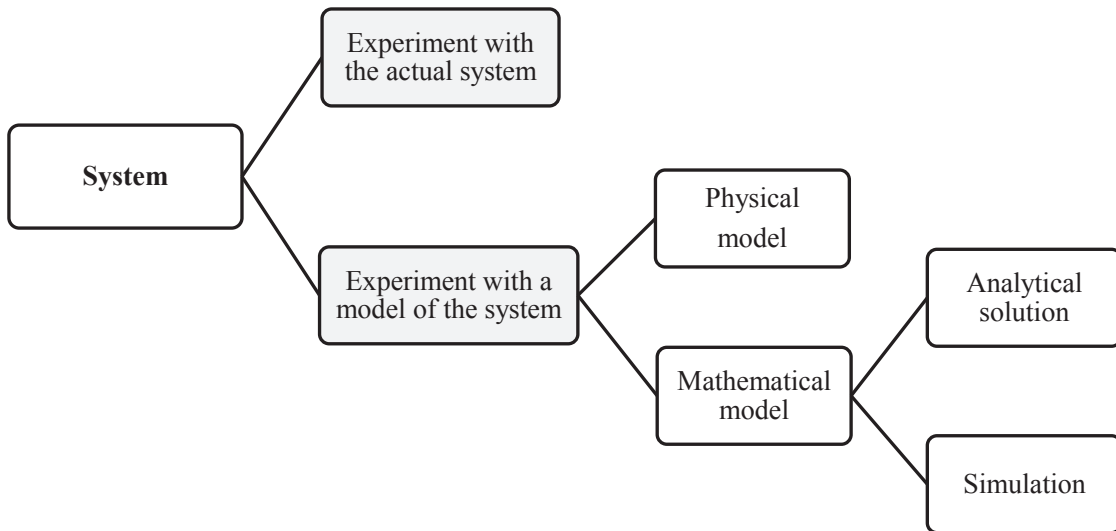


complex production technologies which interact with distributed, intelligent and autonomous entities. Each of these entities has its own dynamics, goals, desires and plans. These entities are managed in a systematic way through supply chains [142].

Since the supply chain management is subject to the scientific values of management; the same scientific rules can be applied. The essence of management science is the model-building approach. Management science is characterized using mathematical models in providing guidelines to managers for making effective decisions within the state of the current information or in seeking further information if current knowledge is insufficient to reach a proper decision. Models are simplified representations of the real world. For models to be useful in supporting management decisions, a balance between being simple and realistic should be considered by the decision maker. They should be simple to understand and easy to use. At the same time, they have to provide a complete and realistic representation of the decision environment [143]. A main classification of system modeling and analysis is shown in Figure 3-3.

In the analytical model, the problem is represented completely in mathematical terms, normally by means of a criterion or objective, which seek to be maximized or minimized, subject to a set of mathematical constraints that portray the conditions of the decisions. The model computes an optimal solution, in other words, one that satisfies all the constraints and gives the best possible value of the objective function [143].

Generally, an optimization model is a mathematical prototype of a problem which is intended to be optimally solved according to one or more objectives and some constraints, if any. This type of mathematical model is an abstract model referred to as, mathematical programming. Mathematical programming is the core of any organizing framework packages, such as ERP and APS [141]. The use of mathematical programming gives rise to integration and optimization processes throughout the supply network. Several types of mathematical programming with optimization purposes exist. These classes include linear programming, mixed integer programming, constraint programming, nonlinear programming, mixed integer nonlinear programming, stochastic programming and robust optimization [143].



**Figure 3-3 System modeling and analysis**

Analytical models are normally the least expensive and easiest models to develop. However, they introduce the highest degree of simplification in the model representation. As a rule of thumb, it is better to be as much to the right as possible in the model spectrum, provided that the resulting degree of realism is appropriate to characterize the decision under study [143].

Traditionally, supply chain functions such as planning and scheduling have been widely modeled through optimization models. This is because the modelling paradigm based solely on the conceptual model specifications is not sufficient [142]. Although there is growing emphasis towards environmental issues in recent research, studies in operations research has been almost absent from the efforts optimizing operational decisions [61]. Therefore, modelling environmentally friendly networks is becoming ever more urgent.

Addressing the environmental objectives while modelling supply chain models can achieve both economic and environmental savings. This consideration not only reduces costs but also ensures environmental benefits. An efficient use of resources is not only cost attractive but also tends to create less greenhouse gas emissions. In other words, operations research contributes to the betterment of the environment because it helps the decision maker to identify the trade-offs between the environmental aspects and costs [36].

Most of the work undertaken by management scientists has been oriented toward the development and implementation of analytical models. As a result of this effort, many tools, techniques and methodologies have been proposed to address specific kinds of problems. Selecting mathematical programming to optimize this framework has many reasons. First, there is still work to be done in the design of environmentally friendly logistics systems where production planning decisions and the transport distribution system are considered together as part of design. Additionally, operations research has a successful application in the field of supply chain planning. The field reached a certain level of maturity as it has been studied for many decades. It is not only an academic but also a practical application.

### **3.3.2. Required Data Extracting**

Within the green logistics network structure, the three most dominant basic features to identify in modelling are the number of products and the number of time periods and decision variable models (deterministic/stochastic model). Out of all the research conducted from 1999-2013 on green logistics network design, 86% of the designs were for single period problems of which 70% were single product models. For these single period models, 67% of the models were formulated as deterministic models. There is a need of research which concentrates on multiple products and multiple time period environments in both deterministic and stochastic environments [13]. The degree of uncertainty associated with the returns of the product as well as the quality of the returns forces the researchers/practitioners to develop deterministic/stochastic models [13].

From reviewing these pieces of literature, many data should be collected in order to formulate a production-distribution model for the batch process industry. Some of these data are production related and others are distribution related. Examples of these data are listed here:

- Planning horizon divided into shorter equal-sized planning periods (time)
- Number of products to be produced
- The plant production capacity
- The plant total storage capacity

- Unit-load (Products are all packaged in a common unit-load pack; example: standard tray)
- Number of locations to be served
- The available number of routes/vehicles
- Trucks' capacities (Maximum capacity of the delivery vehicle)
- Distance (or time) from different locations
- Customers' demands
- The quantities to be produced from each product
- The quantities to be delivered from each product to every location
- The amount of inventory to be stored in the plant from each product
- The accumulated quantities to be delivered up to each location
- The routing sequence of customers in a planning period
- The production cost per product
- The inventory holding cost per product
- The fixed and variable transportation costs (Cost per unit distance associated with traveling from location to location)
- CO<sub>2</sub> emissions

As earlier reviewed in part 2.4.2., there are two ways to calculate CO<sub>2</sub> emissions: fuel-based or distance-based methodology [74]. While the fuel-based method is more reliable, the distance-based method is simpler to use due to the type of data required by each method. Using the distance-based method requires knowing the distance travelled and fuel consumption by vehicles. In addition to this data, the fuel-based method requires knowing the heating values which are very hard to get. Therefore, the common method to estimate CO<sub>2</sub> emissions is the distance-based method. In this approach, distances travelled by vehicle, vehicle type and fuel type are collected. Vehicle type and fuel type are converted to the emissions factors (there are many formulas such as [34], [75], [76]). The vehicle estimated CO<sub>2</sub> emissions are calculated by multiplying distance travelled by the emission factor.

### 3.3.3. Scenarios Generation: Case Study Approaches and Methodologies

A case study is a general approach in which a story is recounted about how something exists within a real world context. This approach captures real life situations that present individuals with a dilemma or uncertain outcome. The case study is created by examining an instance. In each case, a description of a scenario is narrated in the context of the events, people and factors that influence it. The main objective of formulating a case study is to understand the phenomena. Thus, it involves many methodologies such as interviews and direct observation [144].

The case method is the art and science of creating case studies. This method is a well-known approach for learning based on the discussion of various situations faced by decision makers. Therefore, it is a powerful tool for knowledge acquisition. The case method as a science is mainly classified into four main approaches. Each approach has different methods which emerge at different points in time and address different research needs. The classification of these approaches/methods is shown in Figure 3-4 [144].

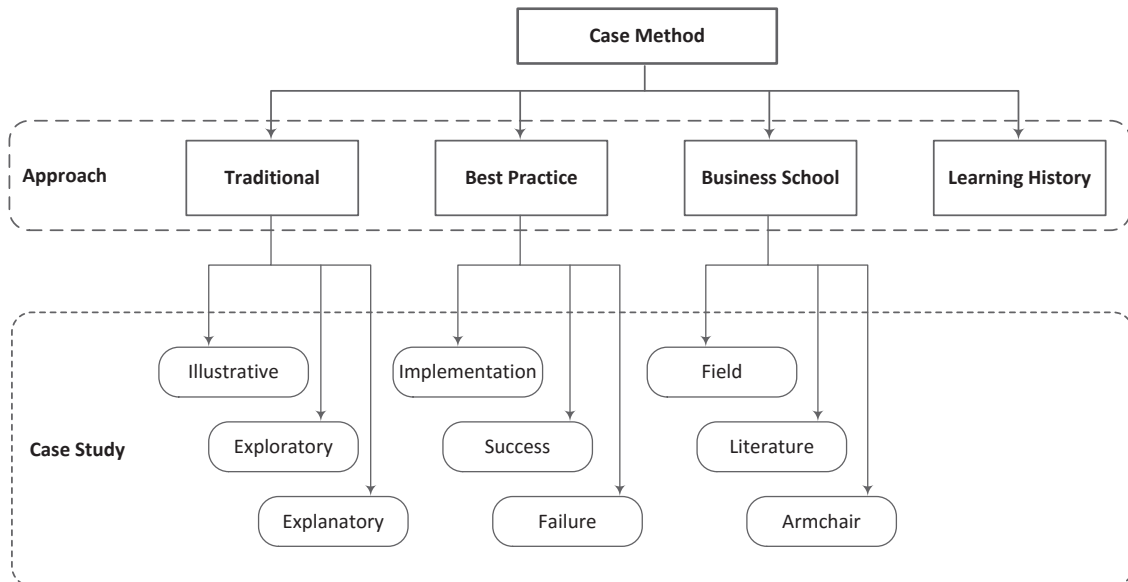


Figure 3-4 Case study approaches and methodologies [144]

The four dominating approaches in the case method are the: traditional, best practice, business school and learning history approach. In the next section, a brief explanation of each approach and their variants is listed.

### **1) Traditional Approach**

The Traditional Approach is the most common and well known case method. In this approach, empirical data is gathered systematically in order to understand a real world situation. Emphasis is placed on ensuring that the research evidence is accurate and unbiased. As a result, much of the case study report is spent describing and justifying the specific methodological decisions made and elaborating on detailed findings. It involves accurate observation and a rigorous collection of evidence. Variants of this approach include:

- a) Illustrative Case Study: is a descriptive account of the main characteristics of a real world example to clarify an idea or reinforce an argument.
- b) Exploratory Case Study: Attempts to understand what happened within a case by looking beyond descriptive features and studying the surrounding context.
- c) Explanatory Case Study: Attempts to explain why certain behaviors occurred by determining causes and effects.

Case studies involve the intense examination of a small number of entities by the researcher. To gather data for the case study, researchers utilize different tools such as: questioners, interviews and systematic observations.

### **2) Best Practice Approach**

This Best Practice Approach method emphasizes analyzing the worthwhile and replicable practices likely to improve the way an organization operates i.e. analyzing factors likely to contribute to success or failure. The primary aim is to identify techniques that can be replicated elsewhere. Variants of this method include:

- a) Implementation Case Study: Focuses on the change management aspects of putting a practice into effect within the workplace. Here the focus is placed on each major stage of the process, not necessarily the long-term outcome.

- b) Success Case Study: Looks at those practices that have proven successful in terms of outcomes. It involves isolating success factors and likely causes of failure. It is the suggestion methodologies where similar practices can be used in other areas of Public Administration.
- c) Failure Case Study: Looks at situation where things went wrong with the intention of generating ideas about the practices that could have been implemented to prevent problems from happening or make recommendations for recovery. In addition, it's about identifying lessons learned from different situations.

### **3) Business School Approach**

The Business School Approach emphasizes analyzing decisions, the actions of managers and their consequences through using real world examples to better prepare students for on the job challenges. Variants include:

- a) Field case study: Involves the gathering of original research by gathering data within the context being studied. Usually involves direct observation and interviews.
- b) Literature case study: Developed by looking exclusively at already existing/published materials.
- c) Armchair case study: Explains a management idea by presenting a hypothetical scenario.

### **4) Learning History Approach**

This method involves collectively reflecting on experience in order to draw constructive lessons. It analyzes actions, events and episodes from multiple points of view in order to gain insights.

### **5) The Applied Approach**

As shown from these different approaches and methods, the implementation case study approach is the most suitable best practice approach for developing a framework. This decision is based on the availability of the real-life data from two international companies in the batch process industries field. Additionally, using this approach allows the developed model to be tested in real-life scenarios in natural settings. The implementation

case study highlights the value of the practical events as well as the circumstances affecting an issue.

### 3.3.4. Initial Solution Generation

Many articles proposed or discussed solution procedures to the integrated production-distribution planning problem in different ways. The solution procedures can be generally classified into exact and approximate algorithms as shown in Figure 3-5. Each has its own advantages and limitations. Approximate algorithms can handle huge problem instances in reasonable computing times [115]. While approximate algorithms provide efficient solutions, optimum solutions are guaranteed by exact algorithms. Therefore, using exact solutions is preferable wherever it is possible. Optimization packages have undergone huge development in the last decade. The problems that were likely solved using heuristic procedures have become more solvable till optimality using exact algorithms [146].

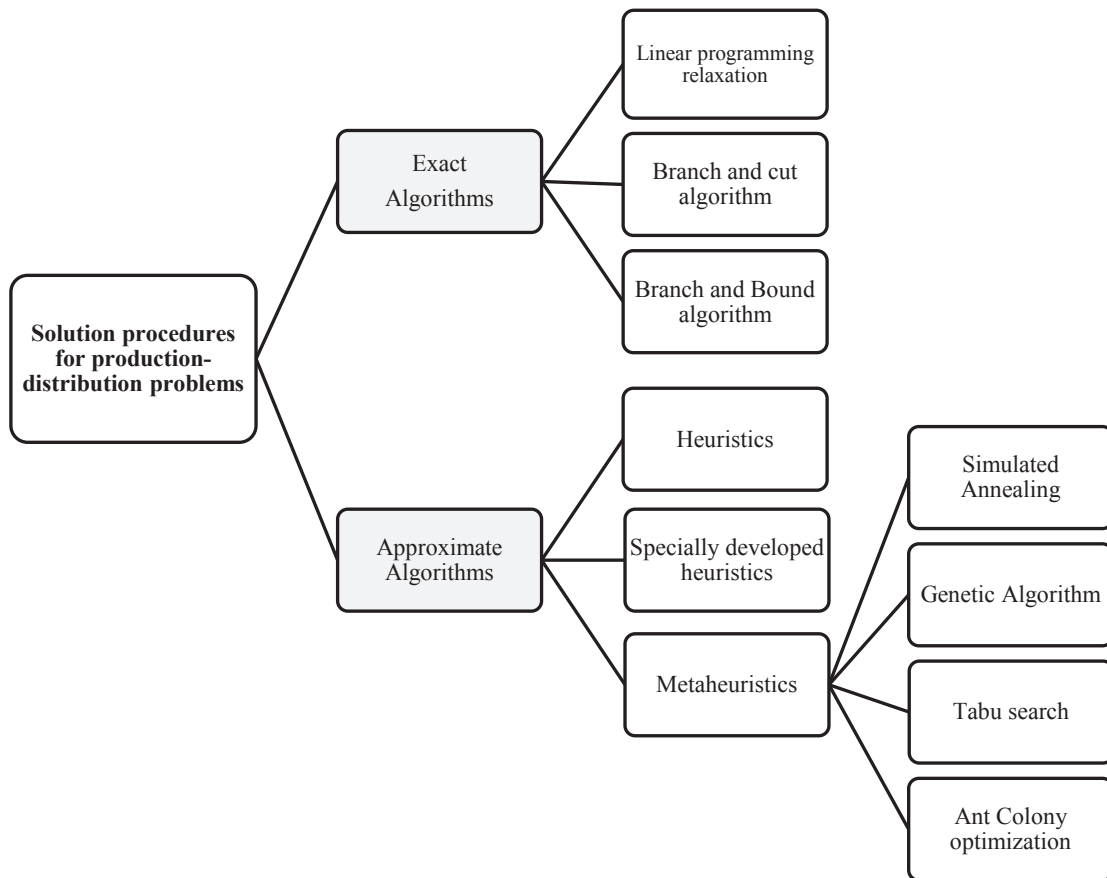


Figure 3-5 Solution procedures for production planning and distribution models



Integrated production-distribution problem is assigned to the P problem (polynomial time) class if an algorithm exists; this solves the problem in polynomial time. Thereafter, a problem is assigned to the NP problem (nondeterministic polynomial time) class if it is not possible to solve it within polynomial time. The class of P problems is a subset of the class of NP problems; there also exists other problems that are not NP [147].

In some models, analytical investigation is only possible to solve small instances in reasonable computing time due to the system's complexity. Thus, simulative approaches should be used to investigate combined production and transport scenarios for a real time scale [146]. Event-based simulations can be used for: modelling production-distribution plans; evaluating the outcomes of the proposed optimization models; visualizing the constructed production-distribution plans adaptable to different scenarios [148]; and estimating the performance of existing systems under some projected set of operating conditions [149].

Simulation is a very useful tool when it is hard to optimize the developed system. In spite of these advantages, simulation results are approximate compared to analytical models which produce an exact result. The development and analysis of simulation models are often expensive and time consuming. Moreover, the validation of the simulation model is critical to the credibility of the obtained results [149].

Simulation models neither generate alternatives nor produce an optimum answer to the decision under study. These types of models are inductive and empirical in nature; they are useful only to assess the performance of alternatives identified previously by the decision-maker. Many simulation models take the form of computer programs, where logical arithmetic operations are performed in a prearranged sequence. Therefore, it is not necessary to define the problem exclusively in analytical terms [143].

Due to the nature of the batch process industry, the problem size of the system is not huge. Therefore, it can be handled via exact algorithms in reasonable times, especially with the recent huge development in hardware and optimization software packages. In addition, the developed model only has integer variables in the first stage, thus, the closed form solution is applicable. Last but not least, there is a growing need to develop a systematic decision-aid tool such as exact mathematical models and solution algorithms for the

GSCM [45]. To conclude, due to previous advantages, exact algorithms will be used to solve the proposed model till optimality using an optimization package. In the following sections, the development of the two-stage stochastic programming model is explained in detail.

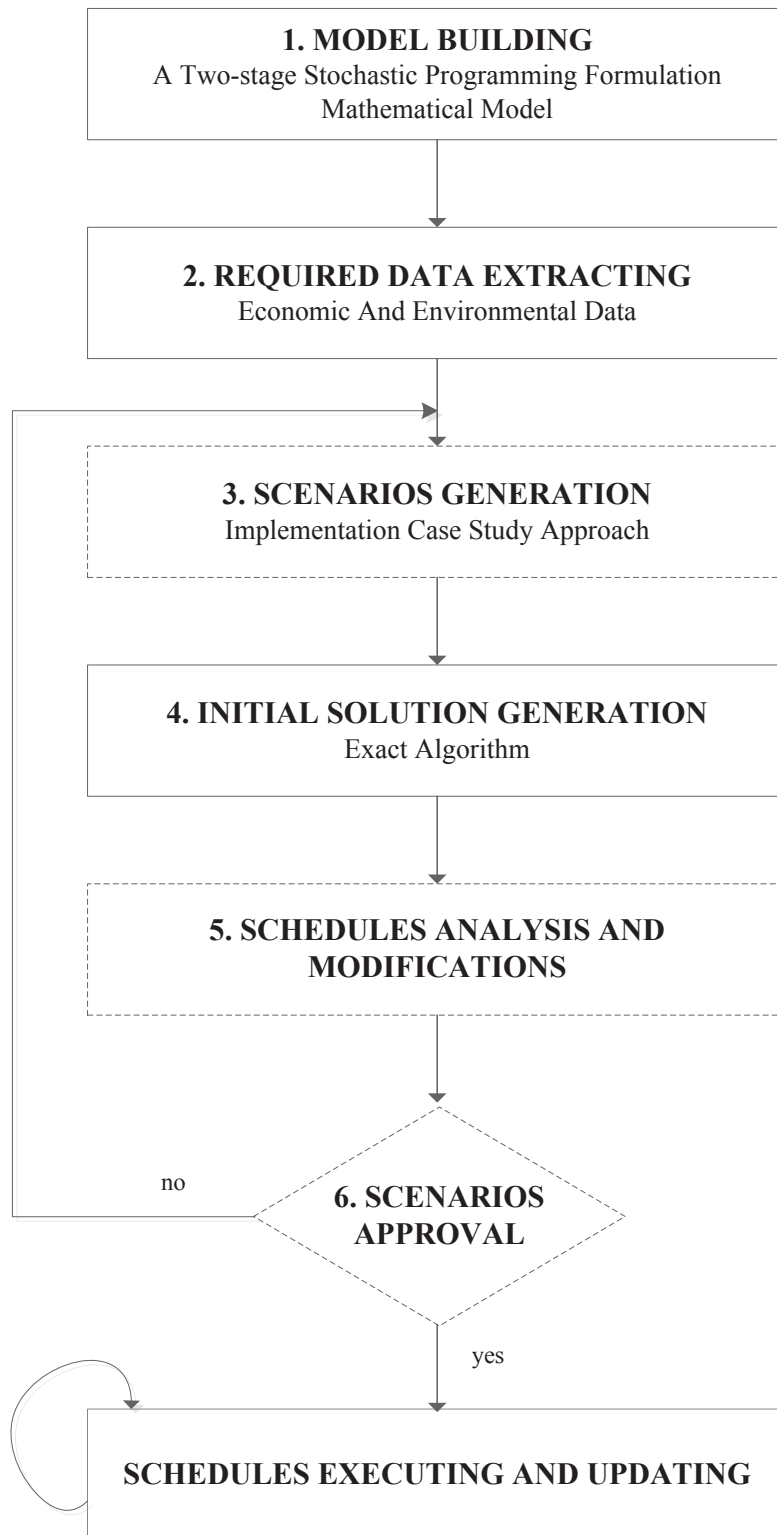
### **3.3.5. Schedules Analysis and Modifications**

A well-defined benchmarking process and the execution of experiments are required. Therefore, numerical modelling is adapted to represent the many supply chain paradigms. To benchmark a model, specific steps should be followed. First: defining the study's objective (to maximize or minimize) is important. Second: the identification of what is to be benchmarked. Third: the evaluation if objects of study are compared. Forth: the performance measures have been determined and specified. Fifth: a description of scenarios (well-structured experiments) and their simulation should be provided. Last: conclusions should be withdrawn from the results [142].

### **3.3.6. Scenarios Approval**

After evaluating all the available alternatives, the decision maker will choose the most promising production schedule relating to a scenario [142]. In this research, the approval of the different tested scenarios will be discussed in detail in chapter 5.

After describing the general procedure for the production scheduling, a diagram of customizing this procedure in the current research is shown in Figure 3-6. In this research the framework will be formulated mathematically based on both the economic and environmental data as well as the capacity constraints which are the inputs of the strategic phase. The feasibility of the developed mathematically model will be checked as previously mentioned. Afterward the applicability of the proposed model will be tested via two different real case studies in batch process industries.



**Figure 3-6 System modeling and analysis**

### **3. 4. Review of the Key Reference Models**

Operations research uses mathematical methods in order to optimize real-world problems. A problem is formulated as a set of mathematical expressions with objective function(s) and constraints. The objective function, such as cost minimization, measures a system's performance whereas the constraints enforce realistic conditions, such as service level, to generate feasible solutions [8].

Operations research has been quite successful in the transportation area. Optimization within transportation is not just a topic studied in academia rather but within all modes of transportation, including: the airline, railway, trucking and shipping industries. Additionally, techniques are used to optimize the interplay between these modes of transportation [150]. Physical distribution is one of the key functions in logistics systems, involving the flow of products from manufacturing plants or distribution centers through the transportation network to consumers. It is a very costly function, especially for the distribution industries. The Operational Research literature has addressed this problem as the vehicle routing problem (VRP). The VRP is a generic name referring to a class of combinatorial optimization problems in which customers are to be served by a number of vehicles. The vehicles leave the depot, serve customers in the network and return to the depot after completion of their routes. Each customer is described by a certain demand.

In sections 3.4.1. and 3.4.2., two key reference models are presented. These models are the core of the proposed model: The Capacitated Vehicle Routing Problem (CVRP) and the two-stage stochastic programming modeling. For each model, the problem description and formulation will be discussed.

#### **3. 4. 1. Review of Capacitated Vehicle Routing Problem (CVRP)**

By the end of the first half of the 20<sup>th</sup> century, the Vehicle Routing Problem (VRP) was first introduced by Dantzig and Ramser [151]. They define the mathematical programming formulation and algorithmic approach to solve a real-world delivery problem [99]. The problem concerning dispatching gasoline delivery trucks between a terminal and large numbers of service stations was studied. When the numbers of the service stations become larger, options of routes increase dramatically. Their proposed

algorithm approach was based on integer linear formulation to obtain a near optimal solution. Since the capacity of each truck is known, this problem was defined later as the CVRP. In 1981, the updated formulation of the CVRP is presented by Fisher and Jaikumar. This CVRP model is indicated as follows [46]:

**Constants**

- $K$       The number of vehicles
  
- $N$       The number of all customer nodes. All customers are indexed from 1 to  $n$  and the central depot is denoted as index 0
  
- $b_k$      The capacity of vehicle  $k$
  
- $a_i$      The weight or volume of the shipment to customer  $i$
  
- $c_{ij}$     The cost of direct travel from customer  $i$  to customer  $j$

**Decision variables**

- $y_{ik}$     equals 1 if the order from customer  $i$  is delivered by vehicle  $k$ .  
Otherwise,  $y_{ik}$  equals 0
  
- $x_{ijk}$    equals 1 if vehicle  $k$  travels directly from customer  $i$  to customer  $j$ .  
Otherwise,  $x_{ijk}$  equals 0

**Model formulation**

$$\mathbf{min} \quad z = \sum_{ijk} c_{ij} x_{ijk} \tag{i}$$

s.t.

$$\sum_i a_i y_{ik} \leq b_k \quad k = 1, \dots, K \quad (\text{ii})$$

$$\sum_k y_{ik} = \begin{cases} K, & i = 0 \\ 1, & i = 1, \dots, n \end{cases} \quad (\text{iii})$$

$$y_{ik} \in \{0, 1\} \quad \begin{array}{l} i = 0, \dots, n; \\ k = 1, \dots, K \end{array} \quad (\text{iv})$$

$$\sum_i x_{ijk} = y_{jk} \quad \begin{array}{l} j = 0, \dots, n; \\ k = 1, \dots, K \end{array} \quad (\text{v})$$

$$\sum_j x_{ijk} = y_{ik} \quad \begin{array}{l} i = 0, \dots, n; \\ k = 1, \dots, K \end{array} \quad (\text{vi})$$

$$\sum_{ij \in S \times S} x_{ijk} \leq |S| - 1 \quad \begin{array}{l} S \subseteq \{1, \dots, n\}; \\ 2 \leq |S| \leq n - 1; \\ k = 1, \dots, K \end{array} \quad (\text{vii})$$

$$x_{ijk} \in \{0, 1\} \quad \begin{array}{l} i = 0, \dots, n; \quad j = 0, \dots, n; \\ k = 1, \dots, K \end{array} \quad (\text{viii})$$

The objective function (i) aims at minimizing the total cost of transportation. Constraints from (ii) to (iv) are the constraints of a generalized assignment problem. Constraint set (ii) ensures that the load assigned to a vehicle does not exceed the vehicle capacity. In constraint (iii), each vehicle starts and ends at the depot. Constraint (iv) guarantees that each customer is visited by some vehicle. Constraint (v) – (viii) define a traveling salesman problem over the customers that have been assigned to a given vehicle  $k$ .

### 3. 4. 2. Review of the Two-Stage Stochastic Programming Models

Uncertainty is one of the most challenging problems to face the practical analysis of the design of the supply chain network. The most widely applied stochastic programming models are the two-stage linear and mixed integer linear algorithms [11]. To describe uncertainty in the two-stage stochastic programming, the scenario-based approach is widely used. This approach is applicable when the uncertainty is illustrated by a set of discrete scenarios. These scenarios forecast how the uncertainty might take place in the future. Each scenario is associated with a probability level which presents the expectation of the occurrence of a particular scenario [32].

The decision variables of a two-stage stochastic programming model under uncertainty are classified into two levels. The first stage variables have to be decided before the actual realization of the uncertain parameters [18]. Once the random events have presented themselves, further design improvements can be made by selecting the values of the second stage recourse variables. Whereas the first stage variables values are scenario-independent, the recourse decisions are scenario-dependent [11]. The objective is to indicate the first stage variables in a way which minimizes the sum of the first stage costs and the expected value of the random second stage costs.

In this section, a review is presented of the formulation of the general two-stage stochastic models [152], [154]. The developed model is formulated as follows:

$$\mathbf{min} \quad z = c^T x + E_{\xi}[\min q(\omega) \cdot y(\omega)] \quad (\text{I})$$

s.t.

$$Ax = b \quad (\text{II})$$

$$T(\omega)x + Wy(\omega) = h(\omega) \quad (\text{III})$$

$$x \geq 0, y(\omega) \geq 0 \quad (\text{IV})$$

Where the first stage decisions are represented by the  $n_1 \times 1$  vector  $x$ . Corresponding to  $x$  are the first stage vectors and matrices  $c$ ,  $b$ , and  $A$ , of sizes  $n_1 \times 1$ ,  $m_1 \times 1$ , and  $m_1 \times n_1$ , respectively. In the second stage, a random event  $\omega \in \Omega$  may occur. For a given realization  $\omega$ , the second stage problem data  $q(\omega)$ ,  $h(\omega)$ , and  $T(\omega)$  become known, where  $q(\omega)$  is  $n_2 \times 1$ ,  $h(\omega)$  is  $m_2 \times 1$ , and  $T(\omega)$  is  $m_2 \times n_2$ . Each component of  $q$ ,  $h$ , and  $T$  is thus a possibly random variable.

Let  $T_i(\omega)$  be the  $i^{\text{th}}$  row of  $T(\omega)$ . Piecing together the stochastic components of the second stage data, a vector  $\xi^T(\omega) = (q(\omega)^T, h(\omega)^T, T_{1\cdot}(\omega), \dots, T_{m_2\cdot}(\omega))$  is obtained, with sums up to  $N = n_2 + m_2 + (m_2 \times n_2)$  components. A single random event  $\omega$  influences several random variables, here, all components of  $\xi$ . Let also  $\Gamma \subset \mathbb{R}^n$  be the support of  $\xi$ , that is, the smallest compact subset in  $\mathbb{R}^n$  such that  $P(\Gamma) = 1$ . The second stage problem data  $q$ ,  $h$ , and  $T$  become known when the random event  $\omega$  is realized. So, the second stage decision  $y(\omega)$  or  $T((\omega, x))$  must be taken.

The objective function of the above formulation contains a deterministic term  $c^T x$  and the expectation of the second stage objective  $q(\omega)^T y(\omega)$  taken over all realizations of the random event  $\omega$ . This second stage term is the most difficult one because, for each  $\omega$ , the value  $y(\omega)$  is the solution of a linear program. To stress this fact, one sometimes uses the notion of a deterministic equivalent program. For a given realization  $\omega$ , let:

$$Q(x, \xi(\omega)) = \min_y \{q(\omega)^T y \mid Wy = h(\omega) - T(\omega)x, y \geq 0\} \quad (\text{V})$$

be the second stage (recourse) value function. Then, define the expected recourse value function as:

$$Q(x) = E_\xi Q(x, \xi(\omega)) \quad (\text{VI})$$

and the deterministic equivalent program is formulated as follows:

$$\mathbf{min} \quad z = c^T x + Q(x) \quad (\text{VII})$$



s.t.

$$Ax = b \quad (\text{VIII})$$

$$x \geq 0, y(\omega) \geq 0 \quad (\text{IX})$$

This representation of a stochastic program explains that the major difference from a deterministic formulation is in the second stage value function. If the second stage value function is given, then a stochastic program is just an ordinary linear program. Extensions to the above formulation can be easily made.

### **3. 5. The Proposed Framework Modelling Requirements and Issues**

Focusing on these challenges, a design of a green logistics oriented framework which integrates production and distribution decisions will be covered. In this section, the green logistics oriented framework modelling requirements and issues are investigated.

By reviewing the related research in this field, the four elements required to build-up the framework are efficiency, flexibility, robustness and sustainability. This framework addresses the economic and environmental aspects in order to manage the dynamics in supply chain operations.

#### **3. 5. 1. Efficiency**

Characteristics addressed in the batch process industry include production, inventory and distribution phases. Therefore, developing a model for production plans and distribution schedules which captures all these characteristics together will be achieved via mathematical programming. This approach is one of the most convenient tools in modelling production planning and scheduling [107].

#### **3. 5. 2. Flexibility**

The increase of structural and dynamic complexity of production and logistics systems is caused by diverse changes. This competitive environment imposes new requirements which should be considered by companies. Examples of these requirements are shorter

product life cycles, larger number of product variants and higher product complexity. These demands cannot be fulfilled with conventional controlling methods. Conventional production systems are characterized by central planning which do not allow fast and flexible adaptation to changing environmental influences. Establishing cooperating logistics processes is believed to be an appropriate method to meet these requirements [152].

### **3. 5. 3. Robustness**

To manage the increasing dynamics inside and outside a production system, an approach that is decentralized and at the same time controls green logistics is required. This control should consider the interrelation between the production and distribution processes. The integrated framework should be able to handle the dynamic environment.

Constructing an automated decision support system helps the decision-maker in determining the optimal master production schedules and the optimal distribution sequences in the batch process environment. The proposed framework provides a systematic approach for production plans and transportation solutions. This approach enables managers to answer the "what-if" questions related to the tactical and operational decisions [107].

### **3. 5. 4. Sustainability**

Economic performance has been the traditional focus for many supply chains. Sustainability in the supply chain is increasingly seen essential to deliver long term profitability by helping to maintain the quality of the environment assets for production, thereby supporting the long-term productivity [155]. Sustainability described is in detail on section 2.1.4.

Taking into consideration the production and distribution of green logistics in the batch process industry, a number of issues should be considered and need to be addressed when modelling an integrated framework:

- The Level of Integration

ICM with green prospective receives a great level of attention nowadays. Integrated chain management aims to multiply the reduction of environmental impacts. It has much in common with other environmental management concepts such as life cycle management and green or sustainable supply chain management [139]. Achieving a level of integration between production and distribution decisions will yield: shorter product life cycles; faster product development cycle; higher overall quality; as well as a globalization and customization of product offerings [156].

Due to the complexity of the supply chain, it is usually not appropriate to build a model that encompasses the decisions of all functions. For this reason, there is an increased interest on optimization models that integrate supply chain decisions [40]. The level of integration which is able to configure all the features of the green logistics system is one of the most important questions that should be answered during modelling.

Higher levels of integration between decisions is generally lead to better performance [22]. A lack of integration indicates processes working at cross-purposes leading to lower levels of organizational performance [54].

- Performance Measures

Due to the complexity of logistics systems, choosing the appropriate supply chain performance measures are challenging [157]. The performance measures have implications for all managerial levels – strategic, tactical and operational. These measures have tangible and intangible characteristics. Many issues must be addressed such as which to use, when to measure and how to measure them [158].

The performance measure has also been divided into various categories of costs/revenue to understand the common parameters considered and those that should be considered in the green logistics network design [13]. During the time period (1999-2013), limited number of studies considered the environmental cost (11%) [13]. It is also important to model environmental issues as objectives and not as constraints because it can generate more information regarding cost and implications of environmental impact [8].

Quantitative models presented in the literature are classified according to either the number of the objectives or the objective type. Models can be developed as single or

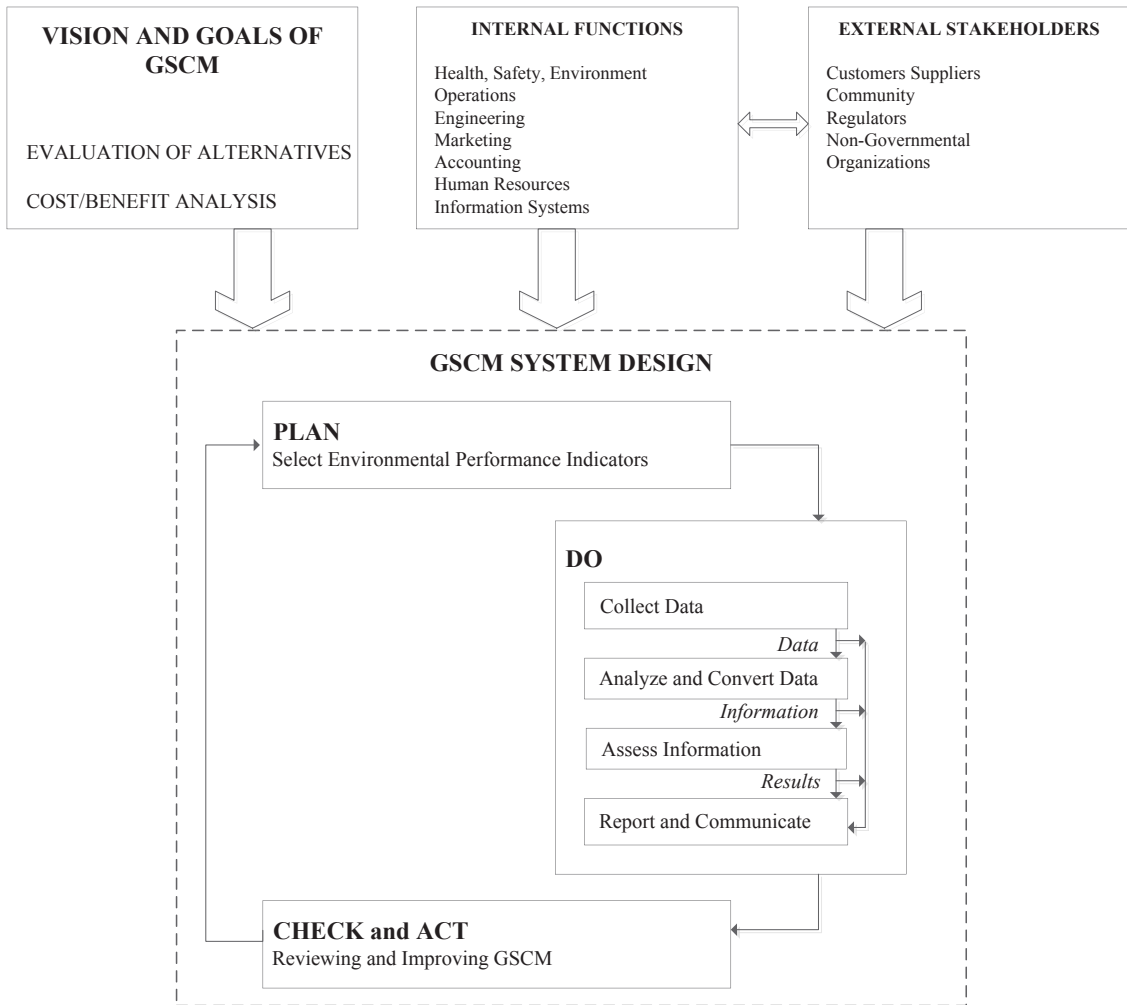
multi-objective with respect to the number of the objectives. Based on the objective type, models can be formulated as economic or non-economic objectives. The development of a single objective performance measure is dominant because of its simplicity. This measure has usually an economic focus of either cost minimization or profit/revenue maximization [31].

Since real life problems involve frequently multi-disciplinary action, the optimization of multiple or even incompatible objectives becomes a necessity [157]. The performance in terms of the economical (such as related system cost) and environmental effects (such as distances travelled, which represents the amount of carbon emissions) should be measured.

The dynamic supply chain environment requires a production-distribution planning system to enable a quick and arranged collaboration between the production and distribution units. The variety and level of performance measures depends greatly on the goal of the organization and the structure of logistics networks. More research is needed in order to determine the economic and environmental performance measures which in the batch process environment [158].

The types of environmentally based performance measures used by an organization depend largely on evolutionary stage of the organization in environmental management. Thus, the amount of regulated emissions or disposal of hazardous waste would be the core performance metrics. Organizations seeking to be more proactive may focus not only on performance measures for compliance issues but may also provide information related to the greenness of products as well as processes and metrics for the green supplier evaluation.

Green supply chain performance measures may be determined through supplier certification processes or surveys completed for current practices among organizations in the negotiation of future contracts. For example, ISO 14031 focuses on the evaluation of the environmental performance over time. The core document focuses on planning, applying, describing, reviewing and improving the environmental performance evaluation. This concept is shown in Figure 3-7 [158].



**Figure 3-7 Design of ISO 14031 performance measurement system [158]**

The importance of the integration production-distribution decisions is forced by its direct effect on the overall performance of the system. This performance is measured in terms of quality of services presented to the customer and costs handled by the organization.

## **CHAPTER 4    DESIGN OF THE GREEN LOGISTICS ORIENTED FRAMEWORK FOR INTEGRATED SCHEDULING OF PRODUCTION AND DISTRIBUTION NETWORKS**

In this chapter two main area are described. First, an introduction is presented concerning all the related inputs for the model and the description of the production environment. A two-stage stochastic programming model is then formulated in order to handle all the key features of the planning decisions for the batch process which are discussed in the previous chapter. The main drive of introducing the stochastic programming is to handle the uncertainties of the distribution decisions and mainly the dynamics in delivering velocities and consequently, their related emissions. Detailed description of the sets, parameters, decision variables and constraints that regulate the developed model are also presented. Second, the design of the network structure model and its development are identified.

### **4. 1. Problem Definition**

Production and distribution planning are two traditional problems that factories have to deal with. Production planning is concerned with the determination of production, inventory and resources requirements over known production capacities. This capacity is limited to the available production resources which involve both human and time resources. Throughout the entire network, the production costs, transportation, as well as inventory holding cost are assumed to be known and deterministic.

In the planning problem considered in this research, there are  $P$  products,  $T$  time periods and  $L$  locations. To fulfil the demand of customers in a single plant, there are several products which are produced and grouped into batches.

At the operational level, the planning problem is multi-period  $T$  with a given short planning horizon. Typically, the planning horizon is a month, with weekly or bi-weekly

periods. The production cost  $PC_p$  includes all the elements which contribute to the cost of producing one unit (labor, material, setups, etc).

Carrying inventory of any product from one period to the next is allowed at the single plant. Safety stocks and inventory capacities are also assumed to be known and deterministic. Backlogging and outsourcing are not allowed. Batch splitting during the production or distribution is not permitted.

A production schedule indicates scheduling decisions as well. For each batch type, the start and completion times within the planning interval is calculated. Hence, a production schedule also specifies the sequence of processing. In scheduling, dispatching rules are applied to prioritize all the jobs that are waiting for processing. In this model, the combination of the earliest due date and shortest processing time is constrained the production schedule. In the literature as well as real life, many rules have been developed and studied for several decades. Samples of these dispatching rules involve service in random order rule, earliest due date rule, shortest processing time rule, longest processing time, etc. [141].

The distribution problem determines vehicles' tours and schedules. It generates solutions which minimize transportation costs economically and environmentally. Furthermore, it ensures that the developed production schedules are used for determining the vehicle tours that satisfy customer orders.

The distribution problem is modelled on a full graph  $G = (V, L)$ , where  $V = \{0, 1, 2, \dots, n\}$  as the set of vertices, and  $L = \{(l, k) : l, k \in V, l \neq k\}$  as the set of arcs. The first node in the set  $V$ , denote as  $V_o$ , represents the depot/plant where  $V_o = \{0\}$ . The remaining  $n$  nodes represent customer locations.

In the presented model, the plant is the single depot out of which products (batches) are to be distributed to several known customer locations. Each customer has a certain demand. The transportation cost from the depot to these locations can vary. Thus, a unit transportation cost  $DC_{lk}$  is a function of the travelled distance for delivering the customer orders. This formulation consists of finding minimum total cost of vehicles.

Delivery vehicles are homogeneous in size and type with a known capacity. The number of used vehicles varies from one planning period to another according to the resulting distribution plan. All vehicles start from and return to the production site (depot). Each customer location should be visited by one vehicle in each time period with its full required batches delivered. Thus, no split delivery is allowed. The transportation distances to and from the depot and the customer locations are known. The load of each vehicle must not exceed its capacity (*CAP*). The generated schedule for the existing order is static. Therefore, it is not affected by the incoming orders.

Routes sequencing decision variables are based on integer linear programming formulations in order to eliminate the vehicles sub-tours. The decision variable  $Z_{tlk}$  is equal to 1 if the route of location  $l$  to location  $k$ ,  $\{(l, k): l, k \in L, l \neq k\}$  will be travelled in time period  $t \in T$  to satisfy customers demand, else it is zero.

The model also includes environmental aspects represented in the emitted GHG quantities. These emissions are dependent on vehicle velocities. Those velocities are chosen between the minimum and maximum permissible velocity of each chosen route. However, due to the uncertainty in travel times, these latter minimum and maximum velocities are random. Using a model with realistic dynamic assessment will lead to an estimation of the effective emissions [73].

To reduce the total environmental impact, logistics managers will have to become more sophisticated in their understanding of how they can reduce the environmental impact of their transportation operations, without negatively affecting the cost or effectiveness of these operations.

Velocities are assumed to follow a known joint probability distribution. Let  $\Omega$  denote the vector of the uncertain minimum and maximum velocities on each route (between any two nodes in the network) in each period. This vector can be mathematically formulated as follows:

$$\Omega = (MinV, MaxV)$$



where;

$MinV$  corresponds to the minimum velocity,

$MaxV$  corresponds to the maximum velocity, and

$\omega$  is a given realization of the uncertain parameters.

The two-stage stochastic programming model is developed because the model deals with two levels of decisions. Both stages present the tactical and operational decisions. The uncertainties are mostly found in the operational stage because most operational parameters are not fully known when the tactical decisions have to be made.

The model is formulated as follows: In the first stage, all production, inventory and distribution decisions (i.e., choose the routes for demand delivery to customers) are generated. These decisions are made in order to ensure that the customer demands are satisfied without exceeding any of the capacities. Additionally, these decisions are made to minimize the total costs of the production, inventory, transportation as well as the expected costs of the second stage problem. Depending on these decisions, the production schedule is set and the required vehicles are rented for demand deliveries.

In the second stage, after the uncertainty is revealed, the delivering velocity of each route is chosen (between the permissible minimum and maximum values). These values depend on the condition of the road, traffic and travel times on each time period for each route. The chosen velocity might result in emissions values higher or lower than the permissible emission limits. These limits are interpreted as an ethical or governmental boundary [32]. Usually, the maximum permissible emission ( $MaxE$ ) is indicated by the government and the lowest permissible value ( $MinE$ ) is the lowest expected value for each vehicle type.

Thus, in addition to the costs paid for emissions, for the former case, the company have to pay an extra penalty to the government if they are exceeding the value of the maximum allowed carbon emission. This penalty is assumed to be linearly proportional to the amount of overage emissions. While for the latter case, characterized by very low velocities, there would not be any extra emissions produced but there would be delays in customer delivery. This occurs in cases of delays due to rush hour, failure in the routes,

etc. These delays are penalized assuming that they are linearly proportional to the amount of underage emissions. All these emission related costs and penalties in the objective function of the second stage problem are minimized.

In our model, for any feasible solution of the first stage problem, we assume that a feasible solution for the second stage problem can always be constructed. Consequently, the model has a relatively complete recourse [152].

It is necessary to incur a set of cost elements in terms of the batches production cost, holding cost, delivering cost and environmental cost. In the design of the introduced model, based on the level of planning, the model is developed for a given short planning horizon divided into shorter equal-sized planning periods. The number of products per batch is known and determined in advance. The forecasted demand from each product is well known beforehand for each period. All required materials are assumed to be available when needed. The process route for each product is also provided.

After a review of the two-stage stochastic models is given, the formulation of the described integrated framework is presented in detail in the following section. An integrated model is developed for the SCND problems under uncertainty. The stochastic programming approach is applied to deal with the distribution velocity uncertainty and their corresponding emissions. GHG emissions are incorporated into the model as an indicator of a green supply chain.

## **4. 2. Model Development**

The mathematical model is multi-product and dynamic (i.e., it has multiple periods) which should be delivered to different locations. In the following sections the sets, parameters, variables, and formulation of the model are presented.

The model notations indicate the following:

#### 4. 2. 1. Sets

$L$	Set of locations
$P$	Set of products
$T$	Set of time periods

#### 4. 2. 2. Parameters

$B_l$	Environmental (emissions trading) factor at location $l \in L$ (€/emissions unit)
$CAP$	Vehicle available capacity (batch)
$DC_{lk}$	Cost per unit distance for quantities on route between locations $l \in L$ and $k \in L: l \neq k$ (€/unit distance)
$D_{lk}$	Distance for the route between locations $l \in L$ and $k \in L: k \neq l$ (unit distance)
$DD_p$	Due date of product $p \in P$ (minute)
$EM_{lk}$	Emissions constant for the route between locations $l \in L$ and $k \in L: l \neq k$ (emissions unit/unit velocity)
$F_{lk}$	Additional cost per each above permissible emission unit on route between locations $l \in L$ and $k \in L: l \neq k$ (€/overage emissions unit)

$G_{lk}$	Additional cost per each under permissible emission unit on route between locations $l \in L$ and $k \in L: l \neq k$ (€/underage emissions unit)
$GB_p$	Processing time for batch $p \in P$ (minute)
$H$	Beginning inventory on-hand (batch)
$HC_p$	Holding cost per unit per period of product $p \in P$ kept in inventory (€/batch/period)
$IC_{tp}$	Available inventory capacity for product $p \in P$ in period $t \in T$ (batch)
$IRC$	Total available inventory resource capacity at the plant (total number of resources)
$IR_p$	Inventory resource utilization for producing one unit of production $p \in P$ (number of resources used/unit of product $p$ )
$MaxE$	Maximum permissible emission (emissions unit)
$MinE$	Minimum permissible emission (emissions unit)
$MaxV_{tlk}(\omega)$	Maximum velocity on route between locations $l \in L$ and $k \in L: l \neq k$ in time period $t \in T$ , for scenario $\omega \in \Omega$ (unit velocity)
$MinV_{tlk}(\omega)$	Minimum velocity on route between locations $l \in L$ and $k \in L: l \neq k$ in time period $t \in T$ , for scenario $\omega \in \Omega$ (unit velocity)

$LC_p$	Unit lateness cost per unit time (€/batch)
$PC_p$	Unit production cost for product $p \in P$ (€/batch)
$PC_{tp}$	Available production capacity at the plant for product $p \in P$ in time period $t \in T$ (batch)
$PRC$	Total available production resource capacity at the plant (total number of resources)
$PR_p$	Production resource utilization for producing one unit of production $p \in P$ (number of resources used/unit of product $p$ )
$Q_{tlp}$	Required demand from product $p \in P$ at location $l \in L$ for time period $t \in T$ (batch)
$S_{tp}$	Required safety stock for product $p \in P$ in time period $t \in T$ (batch)
$us$	Emissions factor for GHG resulting from mobile sources

#### 4.2.3. Decision Variables

$C_p$	Completion time of product $p \in P$ (minutes)
$E_p$	Earliness of product $p \in P$ (minutes)
$W_p$	Lateness of product $p \in P$ (minutes)
$ST_p$	Start time of product $p \in P$ (minute)

$Y_{pr}$	$\begin{cases} 1 \text{ if the product } p \in P \text{ precedes product } r \in P \text{ in sequence} \\ 0 \text{ otherwise} \end{cases}$
$X_{tp}$	Quantity of product $p \in P$ produced in time period $t$ (batch)
$Z_{ilk}$	$\begin{cases} 1 \text{ if the route of location } l \in L \text{ to location } k \in K, l \neq k, \\ \text{will be used in time period } t \in T \\ 0 \text{ otherwise} \end{cases}$
$H_{tlp}$	Quantity of ending inventory of product $p \in P$ kept at location $l \in L$ for time period $t \in T$ (batch)
$A_{tlp}$	Quantity of product $p \in P$ delivered to location $l \in L$ in time period $t \in T$ (batch)
$V_{ilk}(\omega)$	Vehicle velocity in route between locations $l \in L$ and $k \in L: l \neq k$ in time period $t \in T$ , for scenario $\omega \in \Omega$ (unit velocity)
$E_{ilk}(\omega)$	Total carbon emissions value in route between locations $l \in L$ and $k \in L: l \neq k$ , in time period $t \in T$ , for scenario $\omega \in \Omega$ (emissions unit)
$OE_{tlk}(\omega)$	Total produced carbon emissions over the permissible limits in route between locations $l \in L$ and $k \in L$ in time period $t \in T$ , for scenario $\omega \in \Omega$ (emissions unit)
$UE_{tlk}(\omega)$	Total produced carbon emissions under the permissible limits in route between locations $l \in L$ and $k \in L$ in time period $t \in T$ , for scenario $\omega \in \Omega$ (emissions unit)

#### 4. 2. 4. Objective Function and Constraints

Given the previous problem definition, model dynamics and notation, the resulting formulation is as follows:

$$\begin{aligned} \min \quad & \sum_{t \in T} \sum_{p \in P} PC_p \cdot X_{tp} + \sum_{p \in P} \sum_{t \in T} HC_p \cdot H_{tp} + \sum_{p \in P} LC_p \cdot W_p \\ & + \sum_{t \in T} \sum_{p \in P} DC_{lk} \cdot D_{lk} \cdot Z_{tlk} + E_{\omega}[Q(X, H, Z, \omega)] \end{aligned} \quad (1)$$

*Subject to*

$$X_{tp} \leq PC_{tp} \quad \forall p \in P, \forall t \in T \quad (2)$$

$$\sum_{p \in P} PR_p X_{tp} \leq PRC \quad \forall t \in T \quad (3)$$

$$H_{tp} \leq IC_{tp} \quad \forall t \in T, \forall p \in P \quad (4)$$

$$\sum_{p \in P} IR \cdot H_{tp} \leq IRC \quad \forall t \in T \quad (5)$$

$$X_{1p} = H_{1lp} - H + S_{1p} + \sum_{l \in L} A_{1lp} \quad \forall p \in P \quad (6)$$

$$X_{tp} = H_{tlp} - H_{(t-1)lp} + S_{tp} + \sum_{l \in L} A_{tlp} \quad \forall p \in P, \forall t \in T \setminus \{1\} \quad (7)$$

$$C_p \geq \sum_{p \in P} X_{tp} \cdot GB_p \quad \forall t \in T, \forall p \in P \quad (8)$$

$$C_p + ST_p + E_p - W_p \leq DD_p \quad \forall t \in T, \forall p \in P \quad (9)$$

$$ST_r \geq ST_p + (X_{tp} \cdot GB_p) - M(1 - Y_{pr}) \quad \forall \{p \neq r\} \in P, \forall t \in T \quad (10)$$

$$ST_p \geq ST_r + (X_{tr} \cdot GB_r) - (M \cdot Y_{pr}) \quad \forall \{p \neq r\} \in P, \forall t \in T \quad (11)$$

$$Y_{pr} + Y_{rp} = 1 \quad \forall \{p \neq r\} \in P \quad (12)$$

$$Y_{pr} = 0 \quad \forall \{p = r\} \in P \quad (13)$$

$$\sum_{l \in L} Z_{tlk} = 1 \quad \forall k \in L \setminus \{1, l\}, t \in T \quad (14)$$

$$\sum_{k \in L} Z_{tlk} = 1 \quad \forall l \in L \setminus \{1, k\}, \forall t \in T \quad (15)$$

$$\sum_{p \in P} Q_{tlp} \leq \sum_{p \in P} A_{tlp} \leq CAP \quad \forall l \in L, t \in T \quad (16)$$

$$\begin{aligned} \sum_{p \in P} A_{tkp} &\geq \sum_{p \in P} A_{tlp} + \sum_{p \in P} Q_{tkp} - CAP \\ &\quad + CAP \cdot (Z_{tkl} + Z_{tlk}) - \left[ \sum_{p \in P} Q_{tkp} + \sum_{p \in P} Q_{tlp} \right] \cdot Z_{tkl} \end{aligned} \quad \forall t \in T, \forall k \in L \setminus \{1\}, \forall l \in L \setminus \{1, k\} \quad (17)$$

$$\sum_{p \in P} A_{tkp} \leq CAP - \left( CAP - \sum_{p \in P} Q_{tkp} \right) \cdot Z_{t1k} \quad \forall t \in T, \forall k \in L \quad (18)$$



$$\sum_{p \in P} A_{tlp} - \sum_{p \in P} Q_{tlp} - \sum_{p \in P} \sum_{i \in L \setminus \{1\}} Q_{tip} \cdot Z_{til} \geq 0 \quad \forall t \in T, \forall l \in L \quad (19)$$

$$\sum_{k \in L \setminus \{1\}} Z_{t1k} - 0.99 \geq \sum_{l \in L \setminus \{1\}} \frac{Q_{tlp}}{CAP} \quad \forall t \in T, \forall p \in P \quad (20)$$

$$Z_{tlk}, \quad Y_{pr} \in \{0,1\} \quad \forall l \in L \quad (21)$$

$$X_{tp}, H_{tlp}, A_{tlp}, C_p \geq 0 \quad \forall l \in L, \forall t \in T, \forall p \in P \quad (22)$$

Where  $Q(X, H, Z, \omega)$  is the optimal value of the following second stage problem.

$$\begin{aligned} \text{Min } Q(X, H, Z, \omega) \\ = \sum_{l \in L} \sum_{k \in L \setminus \{l\}} \sum_{t \in T} [(EM_{lk} \cdot B_{lk}) \cdot V_{tlk}(\omega) + F_{lk} \cdot OE_{tlk}(\omega) \\ + G_{lk} \cdot UE_{tlk}(\omega)] \end{aligned} \quad (23)$$

**Subject to**

$$\begin{aligned} \text{Min} V_{tlk}(\omega) \cdot Z_{tlk} &\leq V_{tlk}(\omega) \\ &\leq \text{Max} V_{tlk}(\omega) \cdot Z_{tlk} \end{aligned} \quad \forall t \in T, \forall l \in L, \forall k \in L \setminus \{l\}, \forall \omega \in \Omega \quad (24)$$

$$\sum_{l \in L} EM_{lk} \cdot V_{tlk}(\omega) = E_{tlk}(\omega) \quad \forall t \in T, \forall l \in L, \forall k \in L \setminus \{l\}, \forall \omega \in \Omega \quad (25)$$

$$OE_{tlk}(\omega) \geq E_{tlk}(\omega) - \text{Max} E \cdot Z_{tlk} \quad \forall t \in T, \forall l \in L, \forall k \in L \setminus \{l\}, \forall \omega \in \Omega \quad (26)$$

$$UE_{tlk}(\omega) \geq \text{Min} E \cdot Z_{tlk} - E_{tlk}(\omega) \quad \forall t \in T, \forall l \in L, \forall k \in L \setminus \{l\}, \forall \omega \in \Omega \quad (27)$$

$$OE_{tlk}(\omega), UE_{tlk}(\omega), V_{tlk}(\omega) \geq 0 \quad \forall t \in T, \forall l \in L, \forall k \in L \setminus \{l\}, \forall \omega \in \Omega \quad (28)$$

The objective function (1) minimizes the total costs of production, scheduling, distribution and inventory for all productions across the whole planning horizon, in addition to the expectation of the second stage (recourse value) problem.

The total production costs involve the manufacturing cost throughout all the production stages and idle cost of utilized production capacities. The total scheduling costs involve the penalty costs associated to lateness of each batch. Minimizing the product lateness costs ensures the on-time delivery of batches. The total distribution costs are composed of the variable cost associated with the traveled distance between the locations and fixed cost of the vehicles. The environmental cost term is calculated by assigning values related to the travelled routes. The costs related to the inventory holding charge are also considered in this model.

Constraints (2) and (3) set the production capacity restrictions. Constraint set (2) models the capacity for each individual product, while constraint (3) models the joint capacity across products, as indicated by the available capacity for manufacturing resources. Constraint set (2) restricts the total produced number of batches in each time period with the total plant capacity. Constraint set (3) sets a limit to the total allowable storage from all batches to be stored at each time period.

Similar capacities are modelled for inventory quantities in constraints (4) and (5), respectively. Constraints sets (4) and (5) are used to balance the total amounts produced from the products at any time period to satisfy the required demand. For each product, these sets of constraints ensure that the required demand at a time period is equal to the amounts produced through the production stages, in addition to the inventory quantities left from the previous period subtracted from the currently required amount and the safety stock amount. Constraint set (4) deals with the demand of the first period, indicating that it can be only fulfilled from the initial inventory already existing at the beginning of the planning horizon. The balance for the rest of periods is presented by constraint set (5).

Constraints (6) and (7) are the lot sizing constraints used to balance the total amounts produced with the quantities kept in the inventory, safety stocks and demand satisfaction. For each product in each period, these balance constraints ensure that the produced quantities added to the ending inventory in the previous period is equal to the total demand delivered to all customers for that product, in addition to the safety stock and ending inventory in this period for that product. The only difference between constraints (6) and (7) is that constraint (7) deals with all periods except the first period. Constraint (6) models the first period, whereas the ending inventory of the previous period is nothing but the initial inventory (which is a parameter/input).

Constraint set (8) presents the completion time of each product. The completion time of any product should be more than its total product processing times. In order to define the completion time, the earliness and lateness of each product are calculated with respect to the defined due date. The relationship between the completion time, earliness and lateness are defined by constraint set (9).

Constraint sets (10), (11) and (12) guarantee that no products can be processed simultaneously. The start time of any product must be later the completion time of any other product that preceding it. This condition is ensured by constraint set (12) which introduces the binary constraints for the binary variables. In constraint set (10), if the product  $r$  succeeds the product  $p$  in sequence, then the start time for product  $r$  should be greater than or equal to the start time for product  $p$ .

The difference between the two start times is related to the setup and production time for the product  $p$ . In this case, the value of the binary decision variable  $y_{pr}$  equals one. Otherwise, the product  $r$  precedes the product  $p$  in sequence and the start times are ensured by constraint set (11). Constraint set (12) ensures that product  $p$  can only precede or succeed product  $r$  in sequence and not both; if a product has been chosen in one stage of the sequence; it cannot appear again in any other stages. A product should be processed by only one stage at a time.

The sequence of these products is based on the earliest due date dispatching rule. For each instance, on the same machine with processing times and deadlines, there is a schedule

meeting all deadlines. The production processes are scheduled as early as they are required.

Constraint set (13) controls the start time for the same product. It is not logical to switch from a product type to the same product type. Consequently, switching is only possible between different product types.

Constraints (14) and (15) ensure that each location (except the depot) is visited exactly once in each time period. Constraint (14) deals with the inbound vehicles to each location. This constraint set implies that for each location excluding the depot, there can be only a single outgoing arc to any other node belonging to other locations. Constraint (15) deals with the outbound vehicles from each location. There can only be a single entering arc to a location from any other node belonging to other locations, excluding the depot. Both equate each of the total inbound and the total outbound vehicles to one.

Constraint (16) controls the relationship between the production and distribution quantities. It sets the total quantities to be delivered at each location be greater than or equal to the demand. The generated value will be set equal to the demand since the objective is to minimize the transportation costs and lessen the capacity of the vehicle used in the delivery.

Constraints (17), (18) and (19) are the route sequencing constraints. Connectivity between the locations on a route will be satisfied by these constraints. These sets of constraints avoid sub-tours for any location except the depot (location 0). For each set of locations, including the plant, the total load for each vehicle should not be more than the capacity of the vehicle.

To check the correctness of the formulation of constraints (17), some cases are tested. These cases examine all the possibilities which could be happen in reality. The constraint (17) is:

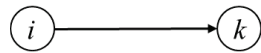
$$\sum_{p \in P} A_{tkp} \geq \sum_{p \in P} A_{tlp} + \sum_{p \in P} Q_{tkp} - CAP + CAP \cdot (Z_{tkl} + Z_{tlk}) - \left[ \sum_{p \in P} Q_{tkp} + \sum_{p \in P} Q_{tlp} \right] \cdot Z_{tkl}$$

$$\forall t \in T, \forall k \in L \setminus \{1\}, \forall l \in L \setminus \{1, k\}$$

**Case I: if  $i, k$  located at the same route:**

(1)  $i$  precedes  $k$ :

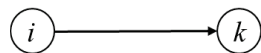
a.  $i$  is the first stop after the depot:



$$\begin{aligned} \sum Q_i &= 5 & \sum Q_k &= 10 \\ A_i &= 5 & A_k &= 15 \end{aligned}$$

$$15 \geq 5 + 10 - 25 + 25 \cdot (0+1) - [10+5] \cdot 0 \quad \gg \quad 15 \geq 5 + 10$$

b.  $i$  isn't the first stop after the depot:



$$\begin{aligned} \sum Q_i &= 5 & \sum Q_k &= 10 \\ A_i &= 10 & A_k &= 20 \end{aligned}$$

$$20 \geq 10 + 10 - 25 + 25 \cdot (0+1) - [10+5] \cdot 0 \quad \gg \quad 20 \geq 10 + 10$$

(2)  $k$  precedes  $i$ :

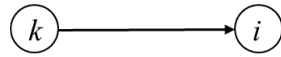
a.  $k$  is the first stop after the depot:



$$\begin{aligned} \sum Q_k &= 10 & \sum Q_i &= 5 \\ A_k &= 20 & A_i &= 15 \end{aligned}$$

$$10 \geq 15 + 10 - 25 + 25 \cdot (1+0) - [10+5] \cdot 1 \quad \gg \quad 10 \geq 15 + 10 - [10+5] \quad \gg \quad 10 \geq 10$$

b.  $k$  isn't the first stop after the depot:

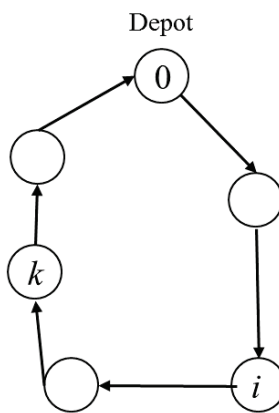


$$\sum Q_k = 10 \quad \sum Q_i = 5$$

$$A_k = 20 \quad A_i = 25$$

$$20 \geq 25 + 10 - 25 + 25 \cdot (1+0) - [10+5] \cdot 1 \quad \gg \quad 20 \geq 25 + 10 - [10+5] \quad \gg \quad 20 \geq 20$$

**Case II: if  $i, k$  not located at the same route:**



$$\sum Q_k = 10 \quad \sum Q_i = 5$$

$$A_k = 20 \quad A_i = 15$$

$$20 \geq 15 + 10 - 25 + 25 \cdot (0+0) - [10+5] \cdot 0 \quad \gg \quad 20 \geq 15 + 10 - 25 \quad \gg \quad 20 \geq 0$$

The sequence of each route is given by constraints (18) and (19), where constraint (18) models locations that are visited as a first stop (right after the depot) in any tour, while constraint (19) models all other locations in all tours. Constraint (20) secures enough vehicles to serve the assigned locations, i.e., enough vehicles are sent out of the depot. The minimum number of vehicles required is rounded to the nearest integer number.

Constraint (21) sets the binary restrictions for the first stage binary variables and constraints (22) are the non-negativity constraints for all first stage continuous variables.

The second stage objective function (23) minimizes the total costs associated with emissions, penalties for overage emissions (paid to the governments) and that for underage emissions (associated with delivery delays for customers). The idea behind this definition of penalties is to obtain meaningful combinations of companies and customers concerns. From the perspective of the distributor companies, the goal is to deliver the batches to different customers as efficiently as possible (concerning economic cost and overage emissions which paid to the governments). From the customers' point of view, the main concern is to reliably receive the deliveries on-time. Therefore, the second stage objective function has emissions limits and stochastic travel velocities, leading to stochastic arrival times. The latter are used to calculate the delivery delay costs, calculated from the underage emissions. Velocities vary throughout the day due to the events such as accidents or congestion during the rush hours [124].

Constraint (24) ensures that the chosen velocity at each route in each time period at each scenario is between the realized minimum and maximum velocities on that route. This occurs if that route is chosen in the first stage.

Constraint (25) calculates the total emissions level of each chosen route. Emission factors for vehicles are based on the vehicle type, fuel usage, vehicle velocity and vehicle or control technology. These values are known and can be directly used in this form:  $EM_1 = (u_{CO_2} + 0.021 u_{CH_4} + 0.31 u_{N_2O})$  [75]. These emissions mainly depend on three factors: transport demand, energy consumption and GHG emission factor. Transport demand is measured in kilometers travelled. Energy consumption depends on vehicle design and load, traffic conditions and driving behavior. Lastly, the GHG emission factor depends on the final energy carrier and inclusion of upstream GHG emissions.

As mentioned before, emission standards set specific limits to the amounts of pollutants that can be released into the environment. The EU has its own set of emissions standards that all new vehicles must meet [63]. As real emissions are almost impossible to measure for a complete traffic network, several models are available to estimate these traffic emissions [73].

Constraints (26) and (27) calculate the overage or underage emissions, respectively, based on the comparison between the actual emissions that would result due to the chosen

velocity and the standard emissions limits. The overage emissions value is calculated by constraint (26). This value is either zero (if there is no overage, i.e., if the resulted emissions  $E_{tlk}(\omega)$  turns out to be less than or equal to the maximum emissions  $MaxE$ ), or equal to the difference between the two values if there is an overage (i.e.  $E_{tlk}(\omega) > MaxE$ ). The overage emissions in the objective function are penalized, thus it will be set to zero if no overage is needed. Similarly, the underage emissions are calculated via constraint (27).

Constraints (28) are the non-negativity constraints for the second stage variables.

In the next chapter, the model is applied to two real world case studies in the batch processes industry. The importance of integrating the different aspects (production, distribution and green logistics represented by emissions values) in one model is shown.



## **CHAPTER 5      IMPLEMENTATION, EXPERIMENTAL RESULTS, CASE STUDIES AND ANALYSIS**

In this chapter, the solution procedure and results of several tests conducted to assess the performance of the proposed model and investigate the sensitivity of the solutions regarding the parameter settings are presented. This solution procedure involves using the LINGO<sup>®</sup> optimization package which applies exact algorithms to solve the two-stage stochastic programming model. Afterwards, the proposed model is tested and verified by solving a number of different problem instances. The implementation of this model in two industrial case studies is presented and discussed. These companies are the world's leading organizations of batch processed products. Finally, the quality of the results obtained from the implementation of the proposed solution procedure is evaluated.

### **5.1. Model Verification**

To verify the mathematical model, a series of stages and problem instances are made. The testing models are solved using the LINGO<sup>®</sup> optimization package. LINGO<sup>®</sup> is a commercial package which is produced by LINDO<sup>™</sup> [159]. This optimization package has the following features:

- Variety of problems: it allows formulating linear, nonlinear and integer problems quickly in a highly readable form.
- Easy expression of large models: one of the most powerful features of LINGO<sup>®</sup> is its ability to model large systems. The key concepts which provide this power are the possibility of grouping similar objects into sets. Once the objects in a model are grouped into sets, one can make single statements which apply to all members of the set via set looping functions. LINGO<sup>®</sup> version 10.0 has no limit on the number of variables or constraints in models that it can solve.
- Powerful solvers: LINGO<sup>®</sup> possesses a comprehensive set of fast, built-in solvers for linear and nonlinear models. The used algorithm for solving the proposed mixed integer linear programming model is the branch and bound algorithm, where the problem in each branch is solved via the simplex algorithm.
- Modelling interactivity: models can be built and solved within LINGO<sup>®</sup>, or one can call LINGO<sup>®</sup> directly from other applications. For developing models

interactively, LINGO<sup>®</sup> provides a complete modelling environment to build, solve and analyse models. For building turn-key solutions, it allows convenient data options as it enables building models that import data directly from databases and spreadsheets. Similarly, it can export solution results right into a database or a spreadsheet making it easier to generate reports.

- Debugging infeasible models: LINGO<sup>®</sup> 10.0 has the ability to debug infeasible models and indicate the sources of infeasibility, i.e. the constraints, if removed or relaxed, will resolve the infeasibility.
- Adjusting the required sensitivity: LINGO<sup>®</sup> has a powerful feature of determining the required sensitivity. For very large models which will not be solved till optimality in a reasonable time, a sensitivity limit, which is a percent of the objective bound, can be set in advance. This gives the advantage of getting a solution deviating from the optimum with at most the pre-specified sensitivity.

The proposed model is solved using the LINGO<sup>®</sup> optimization package. LINGO<sup>®</sup> is used for solving problem with different instances ranges successfully. It proved to get optimal solutions within a short period of time.

## **5. 2. Model Testing**

Model verification checks whether the model has been coded correctly and consistently. It deals with the way models are formalised using equations and algorithms [142]. To verify the presented model, appropriate benchmark instances are required. Valid and useful conclusions can only be drawn from a benchmarking study [142].

For testing our model, fixed input data are given. These hypothetical data are used in four small instances. To prove that the model yields right results as expected, these hypothetical data is prepared. Thus, the output can be expected before solving the model.

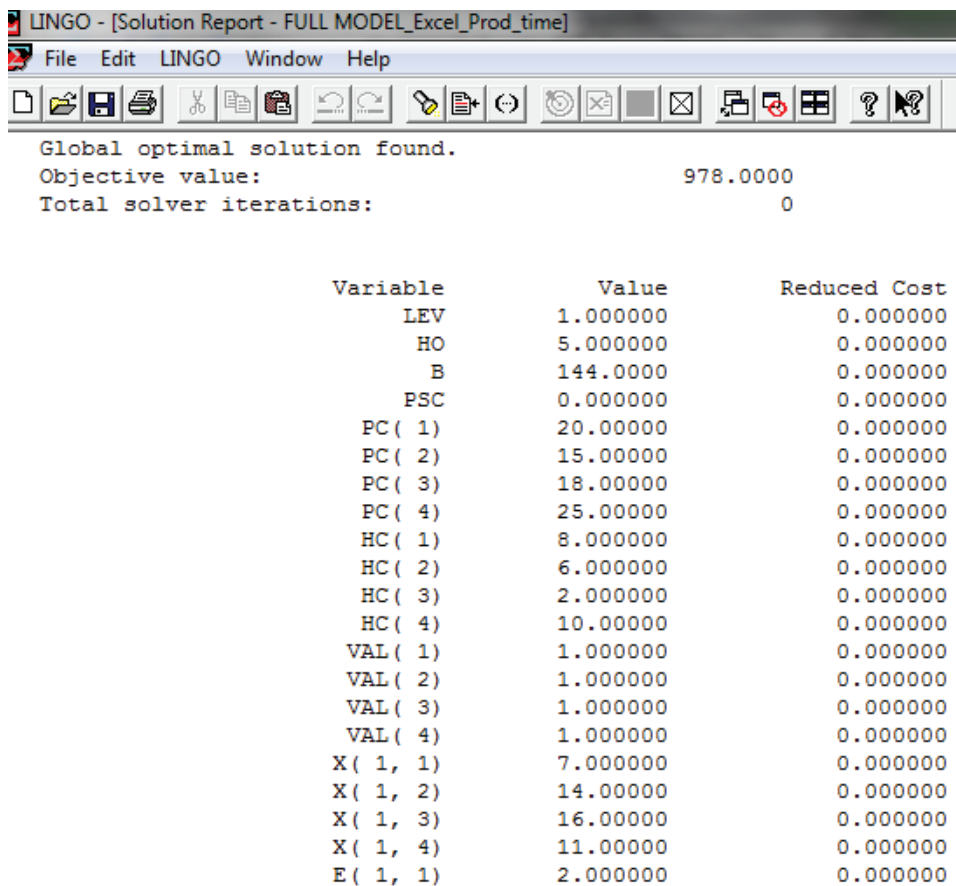
All computations are run using the LINGO<sup>®</sup> 10.0 optimization package on a machine with CORE<sup>™</sup> i5 2.6 GHz processor and 4 GB RAM under Windows 7 Enterprise. The code for each of the presented test models is attached in Appendix "A". A completely practical application is presented in the case study which is described at the end of this chapter.

### 5. 2. 1. Test Models 1: Test Models for Production Decisions

In these instances, it is intended to mainly test the correctness of the production decisions – involving the production quantities and inventory accumulation resulting from the model. Therefore, the hypothetical data in each of the scenarios tends to force the model to yield different production decisions. This test model involves using four product types ( $P=4$ ) and a single time period ( $T=1$ ).

The customer service level is set to one in order to ensure that the entire demand is satisfied. The required quantities from the batch can be satisfied using the available time at the production period. Therefore, it is expected that the model should yield a feasible solution using this data. Beginning inventory on-hand is 5 batches for all product types. The total available production resource capacity at the plant is 48 batches. Table 5-1 summarizes all LINGO® inputs for this case. Figure 5-1 presents a part of the solution report resulting from running the model.

**Figure 5-1 Solution report for the first test problem with planning decisions**



Variable	Value	Reduced Cost
LEV	1.000000	0.000000
HO	5.000000	0.000000
B	144.0000	0.000000
PSC	0.000000	0.000000
PC ( 1)	20.00000	0.000000
PC ( 2)	15.00000	0.000000
PC ( 3)	18.00000	0.000000
PC ( 4)	25.00000	0.000000
HC ( 1)	8.000000	0.000000
HC ( 2)	6.000000	0.000000
HC ( 3)	2.000000	0.000000
HC ( 4)	10.00000	0.000000
VAL ( 1)	1.000000	0.000000
VAL ( 2)	1.000000	0.000000
VAL ( 3)	1.000000	0.000000
VAL ( 4)	1.000000	0.000000
X ( 1, 1)	7.000000	0.000000
X ( 1, 2)	14.00000	0.000000
X ( 1, 3)	16.00000	0.000000
X ( 1, 4)	11.00000	0.000000
E ( 1, 1)	2.000000	0.000000

**Table 5-1 Customers' demand quantities and safety stocks and their costs for the first test models**

	$P_1$	$P_2$	$P_3$	$P_4$
$Q_p$ (batch/period)	10	15	20	15
$S_p$ (batch/period)	2	4	1	1
$PC_p$ (€/batch/period)	20	15	18	25
$HC_p$ (€/batch/period)	8	6	2	10

The outcomes from this model show that the optimal produced quantities are required from each batch to satisfy customers' demands as well as the required amounts of inventory as safety stocks in a single time period are totally fulfilled (Table 5-2). The inventory quantities are generated from the balance constraints. The amount of average inventory at any period from a certain product is the summation of the average of the amount of inventory from that product present in the previous period and the amount of that product hold as a stock through the same period. The value of the objective function is € 978.

**Table 5-2 The production decisions first test model outcomes for a single time period**

	$P_1$	$P_2$	$P_3$	$P_4$
$X_{tp}$ (batch/period)	7	14	16	11
$H_{tp}$ (batch/period)	0	0	0	0

By analysing product type 1 (for example), the produced quantities in that time period are only 7 batches, although that the total required quantities are 12 batches; 10 batches by customers and 2 batches as a safety stock. This can be justified by two reasons: firstly, the availability of 5 batches as the beginning inventory on-hand; secondly, the cost of holding a batch is cheaper than producing it.

To emphasize all the production decisions, the results from the first test model have been considered as a benchmark model. In this instance, the same inputs from the previous model have been used except the time period. For multiple periods, the demand from all product types is repeated, thus the outcomes can be expected and compared. The produced quantities must be the same as the single time period instance for the first time period. For all the rest of time periods, the produced quantities increased by the amount of the required safety stock quantities and shall be copied for all the planning periods. The model runs with three time period ( $T=3$ ). Table 5-3 shows these outcomes. In this instance, the value of the objective function is € 3,584.

**Table 5-3 The production decisions first test model outcomes for multiple time periods**

	$T_1$				$T_2$				$T_3$			
	$P_1$	$P_2$	$P_3$	$P_4$	$P_1$	$P_2$	$P_3$	$P_4$	$P_1$	$P_2$	$P_3$	$P_4$
$X_{tp}$ (batch/period)	7	14	16	11	12	19	21	16	12	19	21	16
$H_{tlp}$ (batch/period)	0	0	0	0	0	0	0	0	0	0	0	0

After verifying the correctness of all the production decisions, in the next stage, some examples of the test models for the distribution decisions are clarified.

### 5.2.2. Test Models 2: Test Models for the Integrated Production and Scheduling Decisions

The generated decisions from the production and scheduling operations are tested in these instances. The main addition in the model is the due dates of each product type. This issue is mainly intended to test the sequencing of the products with respect to their due dates. In this instance, four product types ( $P=4$ ) are scheduled within a single time period ( $T=1$ ).

The due dates are chosen in order to generate a predefined schedule. These dates are shown in Table 5-4. Products follow the earliest due date criteria for sequencing. Thus, the expected sequence of this test is  $P_3 - P_2 - P_1 - P_4$  which is the same sequence of the products' due dates.

**Table 5-4 Products' due dates and processing times (in minutes) and the required quantities for the second test models**

	$P_1$	$P_2$	$P_3$	$P_4$
$DD_p$ (minutes)	4,000	2,000	1,500	5,000
$GB_p$ (minutes)	2	1	2	3
$Q_p$ (batch/period)	10	5	5	15

To emphasize the scheduling decisions, the relation between the completion time and processing time as well as earliness and lateness will be examined. For the sequence, the model generates successfully the required sequence as shown in table 5-5. This sequence is matched with the given due date.

**Table 5-5 Products' sequencing decision variable values  $Y_{pr}$  for the second test models**

	$P_1$	$P_2$	$P_3$	$P_4$
$P_1$	0	0	0	1
$P_2$	1	0	0	1
$P_3$	1	1	0	1
$P_4$	0	0	0	0

By analyzing the result, the correctness of the model will be noticed. As intended, the generated schedule follows the products due dates. The third product  $P_3$  should be produced in the first place. Mathematically, all the values of the sequencing binary variables are equal to zero except the value of switching between  $P_3$  itself. The last products to be produced in this group  $P_4$ , therefore, all the binary decisions equal zero.

During production, all the time-related decision variables are generated as well. As shown in Table 5-6, these values are completion times, starting processing time, lateness and earliness. For the third  $P_3$  batches, the total required processing time is 10 minutes; each

requires 2 minutes of processing time for the total time of 5 batches. Therefore, this total required time for the third batch as well as its sequence is its completion time. Then, there is still 1490 minutes left before its due date (at 1500 minutes).

**Table 5-6 Products' completion time, starting time, earliness and lateness for the second test models**

	$P_1$	$P_2$	$P_3$	$P_4$
$C_p$	20	5	10	45
$ST_p$	3,980	1,995	1,490	4,955
$E_p$	0	0	1490	955
$W_p$	0	0	0	0

### 5. 2. 3. Test Models 3: Test Models for Distribution Decisions

These instances are intended to mainly test the correctness of the distribution decisions, mainly routing decisions, resulting from the model. In these test instances, fleet vehicles responsible for the delivery of a single product type ( $P=1$ ) to six locations ( $L=2$ ) in a single time period ( $T=1$ ) are examined.

For these test models, the demand quantities at each location are deterministic as shown in Table 5-7. The vehicle capacities as well as the distances from location 1 to location k are given. The distance matrix is shown in Table 5-8. Because all the vehicles should end their trip at the depot, it is assumed that the distance travelled back from any location to the depot equals zero. In the first test model, a unit distance cost is considered to emphasise the ability of the model to select the minimum total travelled distance.

**Table 5-7 Required demand at each location (in batches) for the third test models**

	$L_1$ (depot)	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$
$Q_t$	0	6	3	15	4	5	2

**Table 5-8 Distance matrix (in unit distance) for the third test models**

	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$
$L_1$	0	99	216	106	50	205	21
$L_2$	0	0	116	100	600	122	155
$L_3$	0	116	0	175	20	190	25
$L_4$	0	100	175	0	700	15	120
$L_5$	0	600	20	700	0	40	158
$L_6$	0	122	190	15	40	0	40
$L_7$	0	155	25	120	158	40	0

The outputs of the instance are the optimum routing sequence for the accumulated quantities to be delivered and the number of the required vehicles. Table 5-9 summarizes these outputs which ensure the minimum total travelled distances.

The summarized results in Table 5-9 are based on the vehicles' routing decision variable values  $Z_{lk}$  generated from the model. Table 5-10 shows these values which indicate that three routes are required to distribute all of the customers' needed quantities and consequently three vehicles if the vehicle capacity is 15 batches. The total travelled distance is 311 unit distances according to the objective function value; this is the minimum distance which can be travelled.



**Table 5-9 Optimum routing sequence for the third test models**

	Route	$Q_t$	U
1	$L_1 - L_2 - L_1$	6	6
2	$L_1 - L_4 - L_1$	15	15
3	$L_1 - L_7 - L_3 - L_5 - L_6 - L_1$	2	2
		3	5
		4	9
		5	14

**Table 5-10 Vehicles' routing decision variable values  $Z_{lk}$  for the third test models**

	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$
$L_1$	0	1	0	1	0	0	1
$L_2$	1	0	0	0	0	0	0
$L_3$	0	0	0	0	1	0	0
$L_4$	1	0	0	0	0	0	0
$L_5$	0	0	0	0	0	1	0
$L_6$	1	0	0	0	0	0	0
$L_7$	0	0	1	0	0	0	0

After verifying the correctness of the model in the selection of the optimum routes based solely on the distances, the travel cost effect has been taken into consideration. The outcomes from this test model are compared with the previous one which is assumed a unity distance cost matrix. To use the first test model as a benchmark solution, the

modification is made on one of the optimum routes and the difference is calculated. If the distance cost between the third and the fifth location by ten times is modified, the cost of the third route will be raised to 286 instead of 106 unit distance cost. The sequence of the third route itself changed to be  $L_1 - L_7 - L_6 - L_5 - L_3 - L_1$  instead of  $L_1 - L_7 - L_3 - L_5 - L_6 - L_1$ . The optimum sequence beside another two generated routes ( $L_1 - L_2 - L_1$  and  $L_1 - L_4 - L_1$ ) which are the same for both test models raised the value of the objective function to 326 instead of 311 unit distance cost. That means a savings of 165 unit distance cost is achieved, verifying the correctness of the proposed model till now. The comparison between the benchmark model outcomes and the third test model outcomes is presented in Table 5-11.

**Table 5-11 The cost based VRP with the optimum route (a) for unity travel cost and (b) with travel cost consideration for the third test models**

	Case (a)	Case (b)
Sequence	1 - 7 - 3 - 5 - 6 - 1	1 - 7 - 6 - 5 - 3 - 1
cost value (unit distance cost)	106	121
Objective function value (unit distance cost)	311	326

#### **5. 2. 4. Test Models 4: The Integrated Production, Scheduling and Distribution Decisions**

In this scenario, the integration of the production and distribution decisions are tested. The input data for production is the required demand from product  $p$  at location  $l$  for time period  $t$  ( $Q_{ltp}$ ) in batches, the production cost per unit produced ( $PC$ ) in unit cost per batch and the holding cost per unit per period of product ( $HC$ ) in unit cost per batch. These inputs are shown in Table 5-12. The beginning inventory on-hand is 7 batches from all product types. The input data for distribution are the capacity of all the transporting vehicles which is 60 batches, the distance matrix in unit distance (Table 5-13) and distance cost in unit cost per unit distance (Table 5-14).

**Table 5-12 Required demand at each location at each time period (in batches) for the fourth test models**

	$T_1$							$T_2$									
Location	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$	PC	HC	DD
$P_1$	0	3	2	3	5	6	4	0	5	2	3	9	6	4	20	8	100
$P_2$	0	1	10	5	2	3	5	0	4	1	5	2	3	5	15	11	80
$P_3$	0	0	4	4	10	5	2	0	5	6	4	8	15	2	18	7	200
Sum	0	34	32	24	34	28	22	0	28	42	24	38	48	22			

**Table 5-13 Distance matrix in unit distance for the fourth test models**

	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$
$L_1$	0	99	216	106	50	205	21
$L_2$	0	0	116	100	600	122	155
$L_3$	0	116	0	175	20	190	25
$L_4$	0	100	175	0	700	15	120
$L_5$	0	600	20	700	0	40	158
$L_6$	0	122	190	15	40	0	40
$L_7$	0	155	25	120	158	40	0

**Table 5-14 Distance cost in unit cost/unit distance for the fourth test models**

	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$
$L_1$	10000	9	4	6	1	9	2
$L_2$	9	10000	9	2	3	9	9
$L_3$	4	9	10000	5	8	2	1
$L_4$	6	2	5	10000	6	9	4
$L_5$	1	3	8	6	10000	4	4
$L_6$	9	9	2	9	4	10000	4
$L_7$	2	9	1	4	4	4	10000

The total cost of this scenario measured by unit cost is 10,622. The model results regarding the production and distribution decisions are presented from Table 5-15 to Table 5-17. In Table 5-15 the production quantities are summarize the total produced quantities from each product type at each time period ( $X_{tp}$ ); the total inventory quantities from each product type at each time period stored at the depot ( $E_{tlp}$ ); and the amount of each product type to be delivered to each location at each time period ( $A_{tlp}$ ).

If we trace for example the total demand for product  $P_1$  in the first time period which is 18 batches, it is within the available production capacity for each period – 50 batches. The amount to be delivered from  $P_1$  from the depot to all locations at the first time period is 23 batches. In addition, there are 2 batches required as a safety stock. Thus, the total required amount from product  $P_1$  is 25 batches; 18 of them will be produced and 7 of them are already available as beginning inventory on-hand.

Moreover, the scheduling decisions are also generated correctly. The production sequence follows the due dates scheduling criteria. These decisions are shown in Table 5-16 which means the sequence  $P_2 - P_1 - P_3$ . The corresponding due dates are 80 – 100 – 200 time unit.

**Table 5-15 The production decisions fourth test models' outcomes**

Product	$X_{tp}$ (batch/period)	$E_{t p}$ (batch/period)	Amount to be delivered ( $A_{t p}$ ) (Batch/location/period)								
			$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$	Sum	
$T_1$	$P_1$	18	2	0	3	2	3	5	6	4	23
	$P_2$	24	5	0	1	10	5	2	3	5	26
	$P_3$	27	9	0	0	4	4	10	5	2	25
	<i>Sum</i>	69	16	0	4	16	12	17	14	11	74
$T_2$	$P_1$	30	1	0	5	2	3	9	6	4	29
	$P_2$	21	1	0	4	1	5	2	3	5	20
	$P_3$	41	1	0	5	6	4	8	15	2	40
	<i>Sum</i>	92	3	0	14	9	12	19	24	11	89

**Table 5-16 Products' sequencing decision variable values  $Y_{pr}$  for the full test model**

	$P_1$	$P_2$	$P_3$
$P_1$	0	0	0
$P_2$	1	0	0
$P_3$	1	1	0

In Table 5-17, the distribution routes for each time period are emphasized based on the value of the binary decision variable  $Z_{ilk}$ . It shows the number of the required routes to fulfil the customers' demands and the sequence of each vehicle at each route with the transported quantities.

**Table 5-17 The optimum routes resulted from the fourth tested instance**

	Route	Location	$U_{it}$	Sum
$T_1$	$L_1 - L_2 - L_4 - L_1$	2	17	29
		4	12	
	$L_1 - L_3 - L_1$	3	16	16
	$L_1 - L_5 - L_1$	5	17	17
	$L_1 - L_6 - L_1$	6	14	14
	$L_1 - L_7 - L_1$	7	11	11
$T_2$	$L_1 - L_2 - L_1$	2	14	14
	$L_1 - L_3 - L_7 - L_1$	3	21	32
		7	11	
	$L_1 - L_4 - L_1$	4	12	12
	$L_1 - L_5 - L_1$	5	19	19
	$L_1 - L_6 - L_1$	6	24	24

As shown in Table 5-17 for both time periods 5 routes are required to fulfil all the customers' demands. These routes satisfy these demands while considering the vehicle maximum capacity. The accumulation of delivery at each route is found to be correct with the corresponding demand to be served.

From the previous analysis and solution tracing, it is concluded that the integrated production and distribution planning decisions are verified as the model tends to distribute the required customers' demands batches correctly.

### **5.3. Computational Results: Implementation of the Model in Two Case Studies**

In order to examine these instances in reality, two real world case studies that describe how the verified model within a real world are implemented. Numerical experiments using the proposed methodology for solving these case studies are described. Each case study from a batch process industry recounts real life situations which present individuals with uncertain outcomes. In the first place, the characteristics of the test problems and some implementation details are described. Then, the analysis of the results given by the proposed method is demonstrated. Finally, the quality of the stochastic programming solution in comparison to those obtained using a deterministic approach and the advantages of the integration concept are shown.

The first case study was conducted in one of the world's leading companies in the field of foods and beverages processing industry. This company began its activity 90 years ago. Now, the company employs more than 1,500 employees. Currently, the core business of this company includes processing and distribution of their products which are ordered in batches within their portfolio across 62 countries around the world.

The company is a single huge plant with seven departments. Their facilities produce a wide range of dairy and frozen products packaged under more than 40 brand names. These products include long life processed milk, flavored milk, long life juices, natural pure ghee, natural butter, processes cheese, cheddar cheese and different frozen food types.

In 2005, the company was determined to be one step ahead on social responsibility and environmental-friendly management issues. It started by using new materials during the production processes, importing eco-efficiency methods and increasing employee involvement. Recently, the management has focused on developing solutions which consider the environmental impact of their distribution activities particularly in the field of reducing emission related issues.

The second case study was conducted in a multinational consumer goods company and manufacturer of product ranges including personal care, household cleaning, laundry detergents, prescription drugs and disposable nappies. It was founded 180 years ago. In

2014, it recorded \$83.1 billion in sales as profit from more than 80 brands across more than 70 countries all over the world. In 2013, the number of employees was 121,000 within the company. Since 1999, the company has provided products of superior quality and value that improve the lives of the world's consumers. They use the power of innovation to improve lives, the environment and shareholder value.

Their sustainability objective is to create industry-leading value with consumer-preferred brands and products while conserving resources, protecting the environment and improving the social conditions for those who need it most. Therefore, they continue to make progress by optimizing the distribution routes and involving economic, environmental and social sustainability objectives during the planning and distribution processes. By 2010, the company has reduced their energy usage by about 7% and the total CO<sub>2</sub> emissions by about 14% per unit of production. Additionally, they reduce truck transportation by 20% per unit of production.

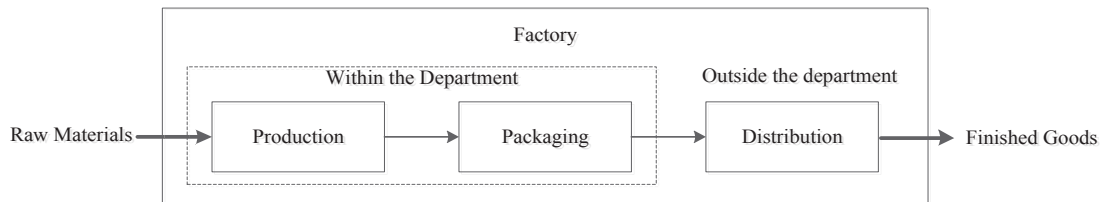
In the next sections, the presented mathematical model is implemented. Outcomes such as the optimal delivery routes sequencing, the corresponding numbers of required delivering trucks and the optimum delivering speeds are generated in order to achieve these environmental targets. All related data for this case study and LINGO<sup>®</sup> codes are attached in Appendix "B". This data belongs to one concrete month (for the first case study from the 5<sup>th</sup> till the 30<sup>th</sup> of November 2012 and for the second study from the 1<sup>st</sup> till the 29<sup>th</sup> of July 2013). Due to confidentiality commitments, this data does not include the exact values of the company but represent them to scale.

### **5. 3. 1. First Case Study Description and Input Data**

In the present research, the developed model is implemented in the liquid department. The selection of this department is based on its good reputation with about 30 percent of the market share. Within that department, three types of liquids are produced: long life processed milk, flavored milk and long life juices. Each of these liquids is packaged under different brand names with different volumes. The department designed capacity is 13.8 Tons per hour. The maximum actual production capacity efficiency is 80 percent of the designed capacity.



Figure 5-2 presents a simple diagram for the three main supply chain tasks of the liquid department. The first task comprises the batch processing of the raw materials into liquid products (either milk or juice), which are packaged in the second phase and then distributed. Merging the packaging and the production tasks is frequently observed in food supply chains.



**Figure 5-2 The main supply chain tasks of the liquid department**

The company planning problem comprises decisions on the scheduling of production orders on multiple time periods and the distribution of customer orders using the company's fleet of vehicles. These decisions should be based on economic and environmental considerations. There is a single production facility and a set of customer locations dispersed geographically. Each location has a known demand in each time period that must be satisfied, therefore, shortages and order splitting are not permitted.

Due to constraints of resource availability, a limited number of items can be produced and stored in each time period at a unit cost. The production and holding costs differ from one product to another depending on their ingredients, sizes and shape. Seven different groups of products are produced in batch forms to be distributed. Production demand, beginning inventory and safety stock quantities for all locations in each time period (in batches) of the case study are shown in Table 5-18.

**Table 5-18 Production demand, beginning inventory and safety stock quantities for all locations in each time period (in batches) of the case study**

<i>Depot</i>	<i>L<sub>1</sub></i>		<i>L<sub>2</sub></i>		<i>L<sub>3</sub></i>		<i>L<sub>4</sub></i>		<i>L<sub>5</sub></i>		<i>L<sub>6</sub></i>		<i>L<sub>7</sub></i>		<i>H</i>	<i>S<sub>tp</sub></i>		
	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>				
<i>P<sub>1</sub></i>	0	0	500	333	180	270	0	0	506	506	23	10	4	3	7	27	12	2
<i>P<sub>2</sub></i>	0	0	0	0	0	0	3	6	0	0	35	15	0	0	3	1	15	5
<i>P<sub>3</sub></i>	0	0	175	117	0	0	0	0	13	13	35	15	0	0	3	13	2	9
<i>P<sub>4</sub></i>	0	0	213	142	0	0	3	6	73	73	35	15	3	4	27	7	3	1
<i>P<sub>5</sub></i>	0	0	400	267	0	0	0	0	83	83	29	13	4	3	7	27	5	1
<i>P<sub>6</sub></i>	0	0	375	250	0	0	0	0	0	0	0	0	0	0	27	7	3	1
<i>P<sub>7</sub></i>	0	0	438	292	0	0	3	6	0	0	0	0	3	4	0	0	4	1

Each of these products should be scheduled at the production lines. Due dates of these products are shown in Table 5-19. These internal deadlines are set by the company to meet the health and safety constraints. In some conditions, particularly during the summer, the time that the mix of raw material ingredients is being processed cannot exceed a waiting time known in advance. Normally, the production planning time period is divided into a time bucket. Therefore, the master production schedule (MPS) is generated every month, while the operations schedule (OS) is generated weekly. All the batches are assumed to be ready to be transported at the end of the planned time period.

**Table 5-19 Processing times, due dates, processing and holding costs for the required production quantities**

	$P_1$	$P_2$	$P_3$	$P_4$	$P_5$	$P_6$	$P_7$
$DD_p$ (hours)	100	1,500	120	200	2,500	280	3,000
$GB_p$ (hours)	10	20	50	15	25	5	35
$PC_p$ (€/batch/period)	20	28	20	20	15	18	25
$HC_p$ (€/batch/period)	8	11	8	8	6	7	10

All products are packaged in a standard load pack before distribution. The unit load stacked at each pallet is 7 Kg. Therefore, the amount of each product carried in a pallet varies from one product type to another. This amount differs depending on the batch type, dimensions and size.

The current distribution strategy is to ship all the requirements of the target customer using homogeneous trucks and single delivery shipment. Each truck is a twenty-foot equivalent unit. The numbers of pallets that can fit on a truck are 11.

The distribution network of the company consists of seven delivery locations served directly from the depot. This plant is considered as the facility's depot. Figure 5-3 shows the relative position between the depot and customers' locations illustrated into a real scale. Distance related input data are shown in Table 5-20 and Table 5-21. For each potential route, the different possible combinations of the minimum and maximum random velocities and their corresponding probabilities are provided.

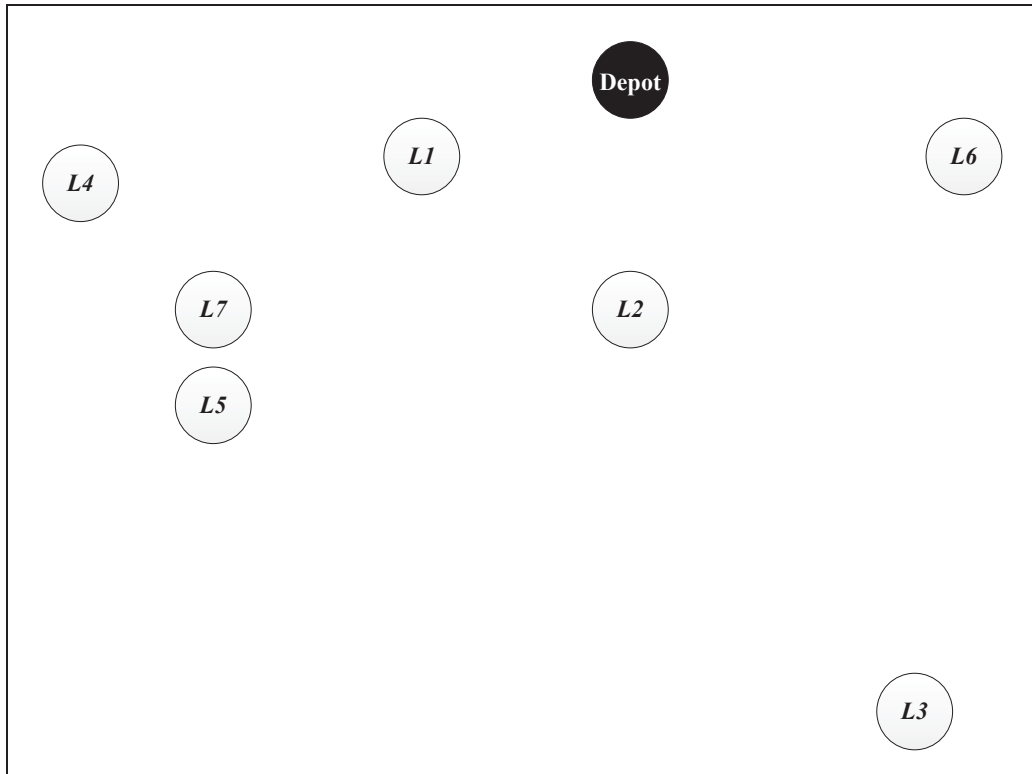


Figure 5-3 The geographical field of the case study in scale

Table 5-20 Distance matrix (in km) of the case study

	0	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$
0	0	35	156	599	428	96	246	375
$L_1$	35	0	202	678	293	281	381	252
$L_2$	156	202	0	476	446	346	298	345
$L_3$	599	678	476	0	876	714	508	742
$L_4$	428	293	446	876	0	180	508	742
$L_5$	96	281	346	714	180	0	627	48
$L_6$	246	381	298	508	508	627	0	613
$L_7$	375	252	345	742	742	48	613	0

Although there is not a standard exact way to measure the values of fuel consumption and GHG emissions for a mobile source, many formulas could be applied to easily calculate their approximate values [34]. The same method described in chapter 3 is used. For medium and heavy duty trucks (emit 4 times more than passenger cars on average [80]), these values are 1.726 kg CO<sub>2</sub> per vehicle-mile, 0.021g CH<sub>4</sub> per vehicle-mile and 0.017 g N<sub>2</sub>O per vehicle-mile at the average velocity (50 mph) [75]. As mentioned previously, these values demonstrate that CO<sub>2</sub> represents more than 99 percent by mass of all the gaseous components of exhaust [62].

**Table 5-21 Distance cost (in unit cost/km) of the case study**

	0	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$
0	10000	9	4	60	14	9	24	39
$L_1$	9	10000	9	2	32	9	29	44
$L_2$	4	9	10000	52	38	20	51	29
$L_3$	60	2	52	10000	64	9	44	4
$L_4$	14	32	38	64	10000	4	24	2
$L_5$	9	9	20	9	4	10000	24	1
$L_6$	24	29	51	44	24	24	10000	49
$L_7$	39	44	29	4	2	1	49	10000

Distance-based emissions values have been calculated for each route at the average vehicle's velocity as shown in Table 5-22, approximated to the nearest integer. If the velocity does not match the average velocity, the amount of the total emissions should be modified based on the relation between the actual speed and the generated emissions [160]. Emissions standards are requirements which set specific limits to the amount of pollutants that can be released into the environment. The EU has its own set of emissions standards that all new vehicles must meet.

**Table 5-22 Estimation of the emissions values for each route (kg CO<sub>2</sub>/km) of the case study**

	0	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$
$EM_{ik}$	10	12	10	12	10	11	12	10
UE (€/ kg CO <sub>2</sub> /km)	6	7	8	8	9	6	7	8
EM (€/ kg CO <sub>2</sub> /km)	9	7	8	8	8	7	6	8
OE (€/ kg CO <sub>2</sub> /km)	6	7	8	8	9	6	7	8

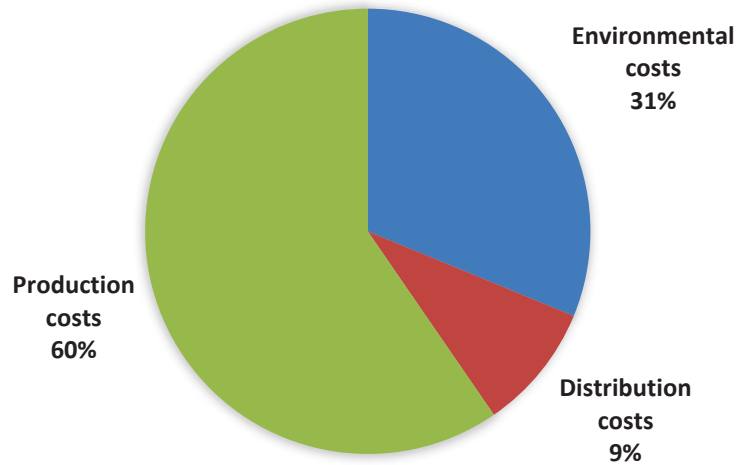
In the studies situation, the company delivers its products daily to all customers. In order to accomplish this target in an environmentally friendly way, both the production and distribution plans need to be generated in an integrated manner. Additionally, the elimination of the stored inventory quantities will save a considerable amount of resources and hence reduce the related costs dramatically. Lastly, the optimal delivering speeds and their related emissions values are generated to reduce the company's environmental impact. This is taking into consideration that the cost, time and delivering speed are all high necessity in order to balance the economic and environmental issues while planning.

### **5. 3. 2. First Case Study Results and Discussions**

The proposed model is solved using the standard sequential linear programming via the LINGO<sup>®</sup> 10.0 optimization package. As the model class is an integer linear programming (ILP), the global optimum solution is raised using branch and bound algorithm (i.e. the solver type is branch and bound). Different instances of this case study with 20 scenarios for speed uncertainty get solved in 8 seconds using default LINGO<sup>®</sup> options.

The model is linear in both the first and second stages. It includes 10,695 variables; 170 of them are integer decision variables. The relation between these variables is constrained by 13,452 linear constraints. The total numbers of iterations till optimality are 64,516. The resulting optimal objective function value is € 778,015.40, indicating the full achievement of all model constraints. The model for the current situation of the above

described case study has been solved till optimality. The contribution of each cost element to the total cost is shown in Figure 5-4.



**Figure 5-4 Cost distribution to the total cost for the first case study**

For the production and inventory decisions, the total demand for both planning periods is satisfied. The optimal quantities to be produced are shown in Table 5-23.

**Table 5-23 Optimal quantities to be produced for the case study**

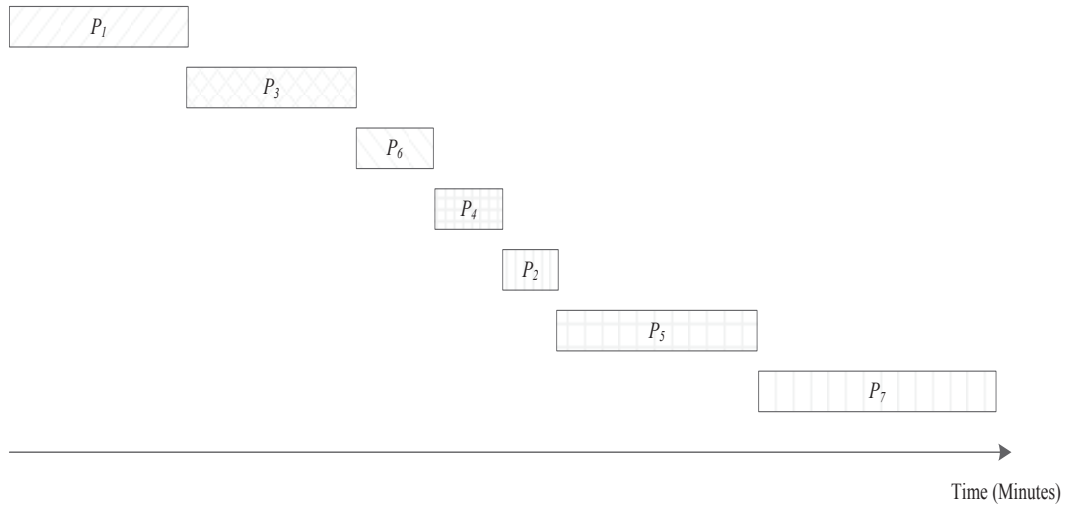
	$P_1$	$P_2$	$P_3$	$P_4$	$P_5$	$P_6$	$P_7$
$T_1$	1,182	16	195	315	488	931	405
$T_2$	1,151	17	167	248	488	568	303
	$E_1$	$E_2$	$E_3$	$E_4$	$E_5$	$E_6$	$E_7$
$T_1$	2	5	9	1	5	1	1
$T_2$	2	5	9	1	5	1	1
	$N_1$	$N_2$	$N_3$	$N_4$	$N_5$	$N_6$	$N_7$
$T_1$	20	25	20	20	20	20	20
$T_2$	0	5	0	0	0	0	0

The schedule that should be followed to produce these batches is yielded via the scheduling decisions. The optimal sequences of batches are described in the following product sequence;  $P_1 - P_3 - P_4 - P_6 - P_2 - P_5 - P_7$ . This sequence is determined as a result of the binary decision variable  $Y_{pr}$ . Table 5-24 shows these values. It is obvious that there is no switching between the same types of batches. These results are graphically presented at a Gantt chart in Figure 5-5. All the schedule related measure such as the starting time, the total required processing time as well as the earliness or lateness comparing to batches' due dates are the outcomes which are generated from the mathematical model. These measures are shown in Table 5-25.



**Table 5-24 Batches' sequencing decision variable value  $Y_{pr}$  for the case study**

	$P_1$	$P_2$	$P_3$	$P_4$	$P_5$	$P_6$	$P_7$
$P_1$	0	1	1	1	1	1	1
$P_2$	0	0	0	0	1	0	1
$P_3$	0	1	0	1	1	1	1
$P_4$	0	1	0	0	1	1	1
$P_5$	0	0	0	0	0	0	1
$P_6$	0	1	0	0	1	0	1
$P_7$	0	0	0	0	0	0	0



**Figure 5-5 The Gantt chart for the first case study batches**

**Table 5-25 Batches' scheduling related decisions for the first case study**

	<i>Starting time</i> $S_P$	<i>Due Date</i> $DD_P$	<i>Total processing time</i> $C_P$	<i>Lateness</i> $L_P$
$P_1$	0	100	11,820	11,720
$P_2$	26,380	1500	340	25,220
$P_3$	11,820	120	9,750	21,450
$P_4$	21,570	200	4,725	26,095
$P_5$	28,735	2500	12,200	38,435
$P_6$	26,295	280	4,655	30,670
$P_7$	40,935	3000	14,175	52,110

These batches should be transported to customers' locations. In Table 5-26 the delivered quantity of each batch to each location in each time period and their total quantities are shown. Both values are automatically generated within the solution.

For the distribution decisions, distribution plans are generated. These plans are presented in the form of the optimal delivery routes. These routes should be driven to distribute the production quantities to the different locations according to the customers' needs. The values of the binary decision variable  $Z_{ilk}$  yielded these distribution routes. Two tours are needed in the first time period ( $T_1$ ); Depot –  $L_2$  –  $L_1$  – Depot and Depot –  $L_6$  –  $L_3$  –  $L_7$  –  $L_5$  –  $L_4$  – Depot while three tours are needed in the second time period ( $T_2$ ). These routes are: Depot –  $L_2$  – Depot, Depot –  $L_5$  –  $L_7$  –  $L_3$  –  $L_1$  – Depot, and Depot –  $L_6$  –  $L_4$  – Depot. The number of routes represents the number of delivery trucks required at each time period. The optimum routes of vehicles at each time period of the case study are shown in Table 5-27 and illustrated in Figure 5-6.

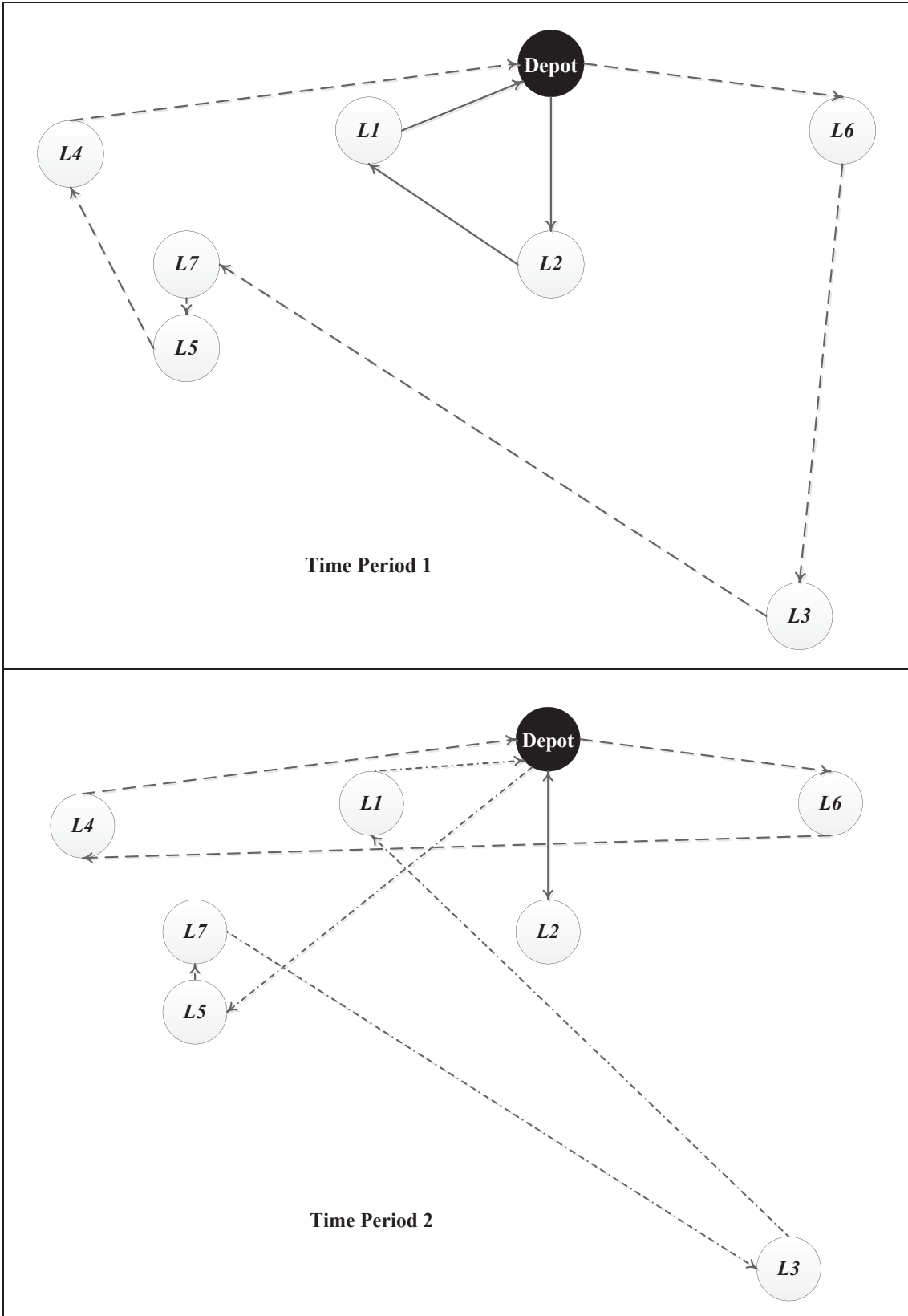


Figure 5-6 The optimum routes of vehicles at each time period of the case study

**Table 5-26 Batches' delivered quantities for the first case study to all locations at each time period in their total values**

		$A_1$	$A_2$	$A_3$	$A_4$	$A_5$	$A_6$	$A_7$	$U_{TL}$
<i>Depot</i>	$T_1$	0	0	0	0	0	0	0	0
	$T_2$	0	0	0	0	0	0	0	0
$L_1$	$T_1$	500	0	175	213	400	555	438	2,281
	$T_2$	333	0	117	142	357	328	292	1,569
$L_2$	$T_1$	180	0	0	0	0	0	0	180
	$T_2$	270	0	0	0	0	0	0	270
$L_3$	$T_1$	0	3	0	3	0	14	3	23
	$T_2$	0	6	0	6	0	150	6	168
$L_4$	$T_1$	506	0	13	73	83	254	0	929
	$T_2$	506	0	13	73	83	14	0	689
$L_5$	$T_1$	23	35	35	35	29	97	0	254
	$T_2$	10	15	15	15	13	0	0	68
$L_6$	$T_1$	4	0	0	3	4	0	3	14
	$T_2$	3	0	0	4	3	0	4	14
$L_7$	$T_1$	7	3	3	27	7	50	0	97
	$T_2$	27	1	13	7	27	75	0	150

**Table 5-27 Vehicles' routing decision variable values  $Z_{ilk}$  for the case study**

	$T_1$								$T_2$							
	<i>Depot</i>	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$	<i>Depot</i>	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$
<i>Depot</i>	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1	1
$L_1$	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
$L_2$	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
$L_3$	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
$L_4$	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
$L_5$	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
$L_6$	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
$L_7$	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0

In Table 5-28 the utilization of the resulting distribution plan is calculated. It can be noticed that the total quantities to be delivered at each time period of each route does not exceed the total available vehicle capacity. Using this capacity, the vehicle utilization in percentage reflects how full each delivery vehicle is.

The results of the second stage are also optimized. The optimum velocity and its related emission quantities are performed via LINGO®. Full results are shown in Appendix "B". These values are generated corresponding to return trips to the depot. A sample of the optimum delivering velocities within the first time period ( $T_1$ ) is summarized in Table 5-29. At that time period, two routes are followed to distribute batches. The first destinations of the first and second routes are respectively  $L_2$  and  $L_6$ .

**Table 5-28 Vehicles' routing decision variable values  $Z_{ilk}$  for the case study**

<i>Time Period</i>	<i>Route</i>	<i>Total Quantities to be delivered</i>	<i>Vehicle Utilization %</i>
<i>T1</i>	<i>Depot – L<sub>2</sub> – L<sub>1</sub> – Depot</i>	<i>2,461</i>	<i>98.44</i>
	<i>Depot – L<sub>6</sub> – L<sub>3</sub> – L<sub>7</sub> – L<sub>5</sub> – L<sub>4</sub> – Depot</i>	<i>1,317</i>	<i>52.68</i>
<i>T2</i>	<i>Depot – L<sub>2</sub> – Depot</i>	<i>270</i>	<i>10.8</i>
	<i>Depot – L<sub>5</sub> – L<sub>7</sub> – L<sub>3</sub> – L<sub>1</sub> – Depot</i>	<i>1,955</i>	<i>78.2</i>
	<i>Depot – L<sub>6</sub> – L<sub>4</sub> – Depot</i>	<i>703</i>	<i>28.12</i>

Two observations are made from this sample. Firstly, values are yielded only when the route is selected – when the vehicles' routing decision variable value  $Z_{ilk}$  equal one. Secondly, the maximum velocity value on each selected road is yielded for all scenarios ( $\omega$ ). These outcomes are expected because the overage and underage emissions costs are almost equal, thus the neutrality of the model is ensured. As a result of the discussion with the company, 20 scenarios of datasets which present the reality are afforded. Nonetheless, the related emissions values are estimated from the literature due to the absence of their real values. These values calculated based on the equations listed in the GHG Protocol [75]. On-road truck product transport emissions (ton-miles) are described in details in the fourth chapter, Section 4.1 Equation 6, page 9.

**Table 5-29 Sample of vehicles' corresponding velocity decision variable values  $V_{11k}(\omega)$  in km/hr for the routes *Depot – L<sub>2</sub>* and *Depot – L<sub>6</sub>***

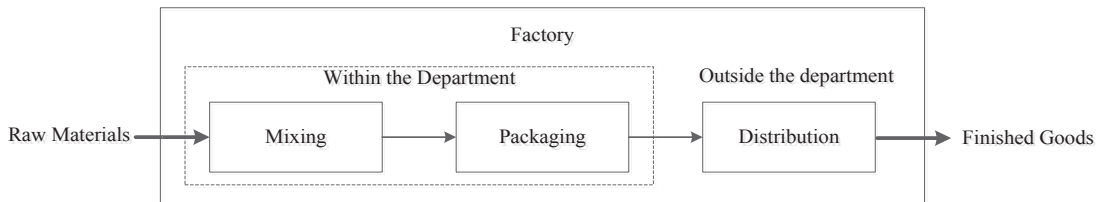
$(\omega)$	<i>Depot</i>	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$
1	0	0	83	0	0	0	83	0
2	0	0	83	0	0	0	83	0
3	0	0	86	0	0	0	86	0
4	0	0	82	0	0	0	82	0
5	0	0	89	0	0	0	89	0
6	0	0	96	0	0	0	96	0
7	0	0	96	0	0	0	96	0
8	0	0	94	0	0	0	94	0
9	0	0	83	0	0	0	83	0
10	0	0	92	0	0	0	92	0
11	0	0	94	0	0	0	94	0
12	0	0	87	0	0	0	87	0
13	0	0	96	0	0	0	96	0
14	0	0	84	0	0	0	84	0
15	0	0	85	0	0	0	85	0
16	0	0	80	0	0	0	80	0
17	0	0	94	0	0	0	94	0
18	0	0	94	0	0	0	94	0
19	0	0	89	0	0	0	89	0
20	0	0	91	0	0	0	91	0

In the next section, the same methodology of implementing the developed model in another case study is used. As previously mentioned, the second case study is performed at a multinational batch process industry company. More details about the second case study are described in detail in section 5.3.3.

### 5.3.3. Second Case Study Description and Input Data

This case study is carried out over one of the consumer goods and health care department; particularly in terms of the beauty, hair and personal care liquids section. The developed model was implemented in the shampoo department which brought the company about 8% of its income [161]. The selection of this department is based on its experience with applying the environmental approach during the production and distribution processes. Products not only contain eco-friendly products such as natural ingredients, but also use biodegradable packaging and refillable packages.

Figure 5-7 presents a simple diagram for the three main supply chain tasks of the shampoo department. As noticed at the first case study, the first task comprises the batch processing of raw materials into liquid form. Afterwards, these products are packaged in the second phase and then distributed.



**Figure 5-7 The main supply chain tasks of shampoo batches**

Within the studied data, the product customers are distributed in 6 different locations. Customers' demands should be satisfied through the production and holding inventory quantities. Additionally, the required safety stock quantities should be considered during the planning. All of these quantities in batches are shown in Table 5-30 for all locations in each time period. The geographic locations of these customers and the manufacturing facility are shown in Figure 5-8 and the distances between these locations are shown in



Table 5-31. All vehicles have the same capacity and should start and end their routes in the depot (the manufacturing facility).

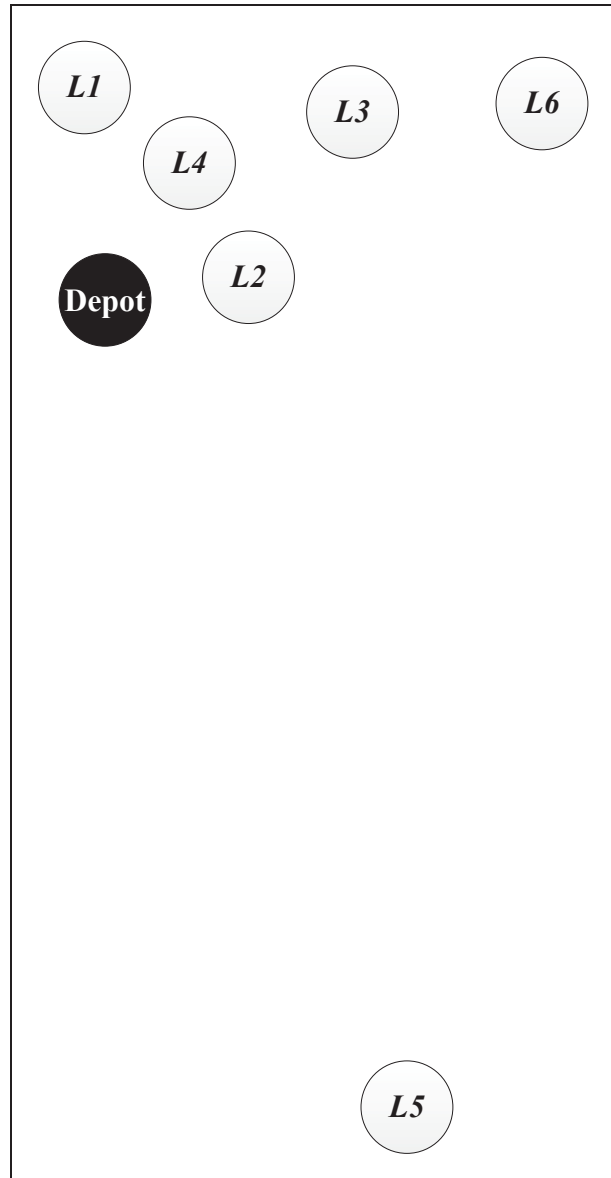


Figure 5-8 The geographical field of the second case study in scale

**Table 5-30 Production demands for all locations in each time period (in batches) of the case study**

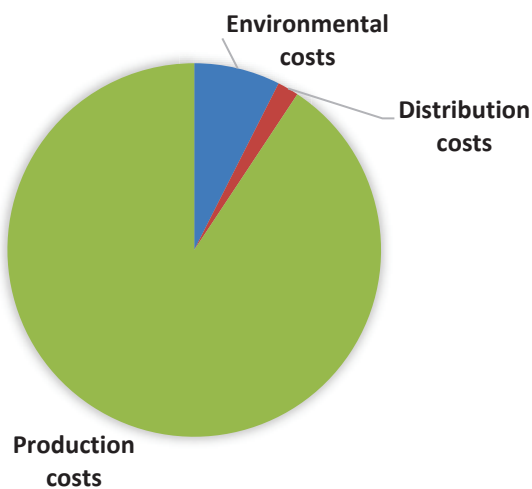
	<i>Depot</i>			<i>L<sub>1</sub></i>			<i>L<sub>2</sub></i>			<i>L<sub>3</sub></i>			<i>L<sub>4</sub></i>			<i>L<sub>5</sub></i>			<i>L<sub>6</sub></i>		
	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>3</sub></i>	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>3</sub></i>	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>3</sub></i>	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>3</sub></i>	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>3</sub></i>	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>3</sub></i>	<i>T<sub>1</sub></i>	<i>T<sub>2</sub></i>	<i>T<sub>3</sub></i>
<i>P<sub>1</sub></i>	0	0	0	171	71	43	171	71	43	513	214	128	85	36	21	427	178	107	342	142	85
<i>P<sub>2</sub></i>	0	0	0	584	243	146	584	243	146	1753	730	438	292	122	73	1461	609	365	1169	487	292
<i>P<sub>3</sub></i>	0	0	0	553	230	138	553	230	138	1659	691	415	277	115	69	1383	576	346	1106	461	277
<i>P<sub>4</sub></i>	0	0	0	653	272	163	653	272	163	1958	816	490	326	136	82	1632	680	408	1305	544	326
<i>P<sub>5</sub></i>	0	0	0	156	65	39	156	65	39	468	195	117	78	32	19	390	162	97	312	130	78
<i>P<sub>6</sub></i>	0	0	0	479	199	120	479	199	120	1436	598	359	239	100	60	1197	499	299	957	399	239
<i>P<sub>7</sub></i>	0	0	0	443	185	111	443	185	111	1329	554	332	222	92	55	1108	462	277	886	369	222
<i>P<sub>8</sub></i>	0	0	0	329	137	82	329	137	82	986	411	247	164	68	41	822	342	205	658	274	164
<i>P<sub>9</sub></i>	0	0	0	300	125	75	300	125	75	901	375	225	150	63	38	751	313	188	601	250	150
<i>P<sub>10</sub></i>	0	0	0	322	134	80	322	134	80	965	402	241	161	67	40	804	335	201	643	268	161

**Table 5-31 Distance matrix (in km) of the second case study**

	0	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$
0	0	170	40	220	120	860	350
$L_1$	170	0	190	350	190	1,040	510
$L_2$	40	190	0	195	100	850	330
$L_3$	220	350	195	0	195	1,020	205
$L_4$	120	190	100	195	0	960	390
$L_5$	860	1,040	850	1,020	960	0	1,150
$L_6$	350	510	330	205	390	1,150	0

### 5.3.4. Second Case Study Results and Discussions

In this case study, the mathematical model introduced in the previous section is solved to optimality. The input data generates 15,952 constraints which control the relation between 12,523 variables. The value of the optimum objective function is € 5,759,829. It is the total cost of the production, scheduling and distribution cost elements. The share of each cost element to the total cost is illustrated in Figure 5-9.



**Figure 5-9 Cost distribution to the total cost for the second case study**

As it is represented in the first case study, the related production, sequencing and routing decisions are generated. Some of these decisions are shown in Table 5-32 and Table 5-33. Full outcomes are available at Appendix "B". In Table 5-32, the optimum quantities of each batch at each time period are generated. In addition to these produced quantities, the available quantities at the depot, which are held as inventory, are the source used to satisfy the customers' demands. These quantities will be transported to different six locations as shown in Table 5-33.

**Table 5-32 Production quantities from each batch at each time period  $X_p$  at the second case study**

	$P_1$	$P_2$	$P_3$	$P_4$	$P_5$	$P_6$	$P_7$	$P_8$	$P_9$	$P_{10}$
$T_1$	1,378	3,219	3,042	3,133	322	1,179	1086	782	702	767
$T_2$	1,378	3,219	3,042	3,828	1,094	3,059	2,826	2,580	1,921	2,053
$T_3$	0	3,219	3,042	3,828	1,094	3,654	3,386	2,026	2,298	2,453

**Table 5-33 Batches' total delivered quantities  $U_H$  at the second case study to all locations at each time period**

	<i>Depot</i>	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$
$T_1$	0	0	0	3,990	1,661	9,970	9,970
$T_2$	0	9,970	11,968	4,986	2,992	1,994	8,310
$T_3$	0	9,975	4,156	2,493	7,979	3,324	1,994

The production will be processed in the following order:  $P_1 - P_3 - P_4 - P_6 - P_2 - P_5 - P_7 - P_8 - P_9 - P_{10}$ . This is the optimum sequence of producing these ten batches. All the other related scheduling decisions such as the starting time of each batch, the total processing time and the earliness or lateness referred to due dates are generated as well. Values of these outcomes are shown in Appendix "B".

When these batches are processed, these quantities are delivered via various routes. At each time period, the sequence of delivery for these batches is indicated in Table 5-34.

**Table 5-34 Number of the distribution routes at each time period and their optimum sequence at the second case study**

Time Period	Number of generated routes	Routes
$T_1$	4	Depot – $L_2$ – $L_1$ – $L_5$ – Depot Depot – $L_3$ – Depot Depot – $L_4$ – Depot Depot – $L_6$ – Depot
$T_2, T_3$	6	Depot – $L_1$ – Depot Depot – $L_2$ – Depot Depot – $L_3$ – Depot Depot – $L_4$ – Depot Depot – $L_5$ – Depot Depot – $L_6$ – Depot

The results of both case studies show that the developed model generates the optimal production and distribution schedules and their related decisions for the batch process industry. It is completely verified and successfully implemented on real industrial situations that prove its capability as a decision support system that can address both the production planning and distribution decisions. To sum up, the formulated framework helps planners to standardize the main planning activities in the batch process industry.

## **5. 4. Analysis of the Results**

After obtaining the optimal solution and explaining and analyzing it, the analysis of the outcomes is performed. The goal of this analysis is to show the importance of modelling the presented framework in this way. This target has been achieved via three steps. First: the different scenarios are tested to emphasize the benefits of integrating the economic and environmental aspects. Second: the usefulness of the stochastic modelling approach instead of a deterministic one is studied. Finally: the sensitivity analysis of the most influential model parameters is conducted in order to check the sensitivity of the model parameters around the optimal values.

### **5. 4. 1. Interrelation between Production and Distribution Decisions and Transport Emission**

This analysis is carried out in order to show the benefits of including the economic and environmental aspects simultaneously in an integrated approach. This analysis is done by conducting different variants of the developed model. Each variant is solved to get its outcome value. Afterwards, the cost of the missing elements is calculated offline for each variant. The equivalent objective function (EOF) value is the summation of the variant outcome value to the missing element offline value. Then, the EOF value is compared to the optimal solution discussed earlier which is then generated from the developed model. The importance of this analysis is to assess the savings obtained in terms of the total cost, composed of the three main cost elements: production, distribution and the environmental cost elements. In this section, the change of the terms of the total cost on the overall results is discussed.

- Variant 1 – Considering only the economical side of the supply chain

In this variant, the impact of governmental regulations on the total supply chain costs is quantified. The governmental regulations were the main obligated of the environmental aspects [138]. These aspects are presented in terms of the emissions costs and penalties. Thus, the environmental aspects are excluded from the developed model. The new model is run only with the economic cost elements that include the production and distribution

costs. Afterwards, the environmental aspects cost is added as an offline value to calculate the equivalent objective function.

When the solution of this variant is compared with the optimal solution, the EOF value considerably increased by almost 8 percent in the first case study ( $Z_{EOF1} = €846,324.2$ ) and by almost 1 percent in the second case study ( $Z_{EOF1} = €5,810,326.4$ ). This percentage can be saved by integrating the economic and environmental issues.

The importance of this variant lies in today's governmental regulations which force the enterprises to consider environmental aspects within their supply chains [162]. Considering that green aspects nowadays is no longer an option, it is necessary to compete within the global market.

- Variant 2 – Considering the environmental side of the supply chain with only one of the economic cost elements: neglecting the production-distribution integration

Many researchers have ignored the integration between supply chain decisions. To prove the importance of the integration between production and distribution, two variants are presented. In these variants, either production or distribution costs along with the green aspects are considered. The EOF values of these two variants are compared to the optimal solution. The outcomes of these variants are:

*a) Only consider production costs along with the green aspects:*

In the solution of this case, the total cost has increased from € 778,015.4 to € 921,979.6 in the first case study and from €5,759,829 to €5,763,530 which is the value of the equivalent objective function (EOF) when it is compared to the optimal solution. As a percentage, the proposed model in the first case saves around 16 percent and the second case saves around 1 percent of the total cost. This saving is calculated compared to using a model which only adds the green aspects to the production issues and does not explicitly include the distribution issues.

*b) Only consider distribution costs along with the green aspects:*

In this variant, the same concept of the *variant 2.a.* is applied. However, in this case the distribution element along with green aspects is focused. Respectively, almost a 25 and 43 percent saving, in the first and second case study, is granted if the developed model is used rather than this variant. The obtained solutions in the first and second case study are:

$$Z_{\text{EOF2b}} = \text{€ } 1,041,144.7 \text{ (first case study)}$$

$$Z_{\text{EOF2b}} = \text{€ } 10,131,154.3 \text{ (second case study)}$$

A comparison between the optimal solution and the output of three variants is shown in Table 5-35. In addition, the percentage differences relative to the optimal values are highlighted. These values illustrate that significant reductions in costs can be achieved by the developed integrated model. The efficient use of the proposed model is proven via its results; as it yielded the solution with the last possible total costs. In addition, it is uncomplicated to solve any specific scenario proposed to the model and find the optimal solution in that scenario.



**Table 5-35 Summary of the results of the three considered variants and for the case study optimal solution**

	Variant	Objective function value €	Offline cost €	EOF value €	% Difference to total cost
1 <sup>st</sup> Case Study	Optimal solution	778,015.4	0	–	–
	1. Only economic decisions	524,917	321,407.2	846,324.2	8.071
	2.a. Only production decisions and green aspects	697,102.6	224,877	921,979.6	15.614
	2.b. Only distribution decisions and green aspects	288,508.6	752,636.1	1,041,144.7	25.273
2 <sup>nd</sup> Case Study	Optimal solution	5,759,829	0	–	–
	1. Only economic decisions	5330,302	480,024.4	5,810,326.4	0.869
	2.a. Only production decisions and green aspects	5,653,155	110,375	5,763,530	0.064
	2.b. Only distribution decisions and green aspects	460,304.3	9,670,850	10,131,154.3	43.147

#### 5.4.2. Quality of the Stochastic Solutions: Stochastic Modelling Approach versus Deterministic Planning

In this section, a comparison between the solutions of the stochastic programming model to that of a deterministic optimization problem is done. Commonly, deterministic models are used in order to simplify the real world problems. In these simpler versions, all random variables values are replaced by their mean (expected) values. A major question which should be answered in this replacement is whether the generated values are nearly optimal solution or entirely inaccurate.

In addition, due to the computational difficulty of solving the stochastic models, the usefulness of the stochastic modelling approach is always questionable. In this section, the suitability of using stochastic programming is illustrated. The value of using a stochastic modelling versus deterministic planning is quantitative.

For stochastic models, when multiple runs of the models are averaged out, it still cannot be concluded that the output will also be the same. But after looking at the definition of the models and how the results are produced, it is possible to get a better understanding of how models will behave under different inputs and different scenarios [142].

To achieve this purpose, two values should be calculated: the expected recourse problem (RP) solution value and the expected result of using the expected value (EEV). The difference between the RP and EEV is defined as the value of the stochastic solution (VSS). These values are emphasized as the following [152]:

- *The expected recourse problem (RP) solution value*

It is the generated value when a model is solved using the real values. All scenarios here are taken into consideration while solving the model; therefore, the model yields an optimal expected value.

- *The expected result of using the expected value (EEV)*

In reality, the mean value is corresponding to one particular scenario. Instead of observing the random returns, these values are replaced by their corresponding expected value (EV)

which is the mean value. If the EV is used to solve the model, the generated result is the expected result of using the expected value (EEV).

- *The value of the stochastic solution (VSS)*

The value of the stochastic solution is the difference between EVV and RP values. It presents the possible gain from solving the stochastic model. The VSS is the concept that precisely measures the quality of a decision. This quantity is the cost of ignoring uncertainty in choosing a decision.

$$VSS = EEV - RP$$

To display these values, datasets of 10, 20, 30, 40 and 50 scenarios are tested. Table 5-36 shows the values of running these numbers of scenarios and their corresponding running time. For each dataset, the expected recourse problem (RP) solution value, the expected result of using the expected value (EEV) and the value of the stochastic solution (VSS) values are calculated. Moreover, the VSS as a percentage of the overall RP solution is reported.

Since all VSS have positive values, dealing with uncertainty really matters. Therefore, optimal solutions are sensitive to the value of the random elements. The difference between the optimal solution (generated from the stochastic modelling) and the expected solution (generated from the deterministic modelling) is between 13 and 4 percentages for datasets of 10, 20, 30, 40 and 50 scenarios. The VSS values verify the significance and benefits of using the stochastic modelling approach.

**Table 5-36 VSS results for 10, 20, 30, 40 and 50 scenarios**

	Number of Scenarios	RP Value €	EEV Value €	VSS Value €	(VSS/RP) %
1 <sup>st</sup> Case study	10	774,733	875,873.8	101,141.3	13.055
	20	778,015	863,558.2	85,542.79	10.995
	30	779,884	851,718.6	71,835.07	9.211
	40	780,113	829,470.3	49,357.72	6.327
	50	780,940	820,705.7	39,765.47	5.092
2 <sup>nd</sup> Case study	10	5,763,244	6,365,157	601,913.2	10.444
	20	5,759,829	6,253,798	493,968.7	8.5761
	30	5,761,690	6,202,179	440,488.7	7.64513
	40	5,755,079	6,060,943	305,864	5.31468
	50	5,759,358	6,023,298	263,940	4.5828

**Table 5-37 Size of the deterministic equivalent of the problem**

	Number of Scenarios	Number of iterations	Number of constraints	Variables	
				Integer	Total
1 <sup>st</sup> Case Study	10	292,462	7,052	170	5,575
	20	64,516	13,452	170	10,695
	30	13,403	19,815	170	15,815
	40	14,239	26,252	170	20,935
	50	14,565	32,652	170	26,055
2 <sup>nd</sup> Case Study	10	259	6,643	219	6,643
	20	243	15,952	219	12,523
	30	10,743	23,302	219	18,403
	40	262	30,652	219	24,283
	50	258	38,002	219	30,163

**5. 4. 3. Sensitivity analysis of the proposed model results**

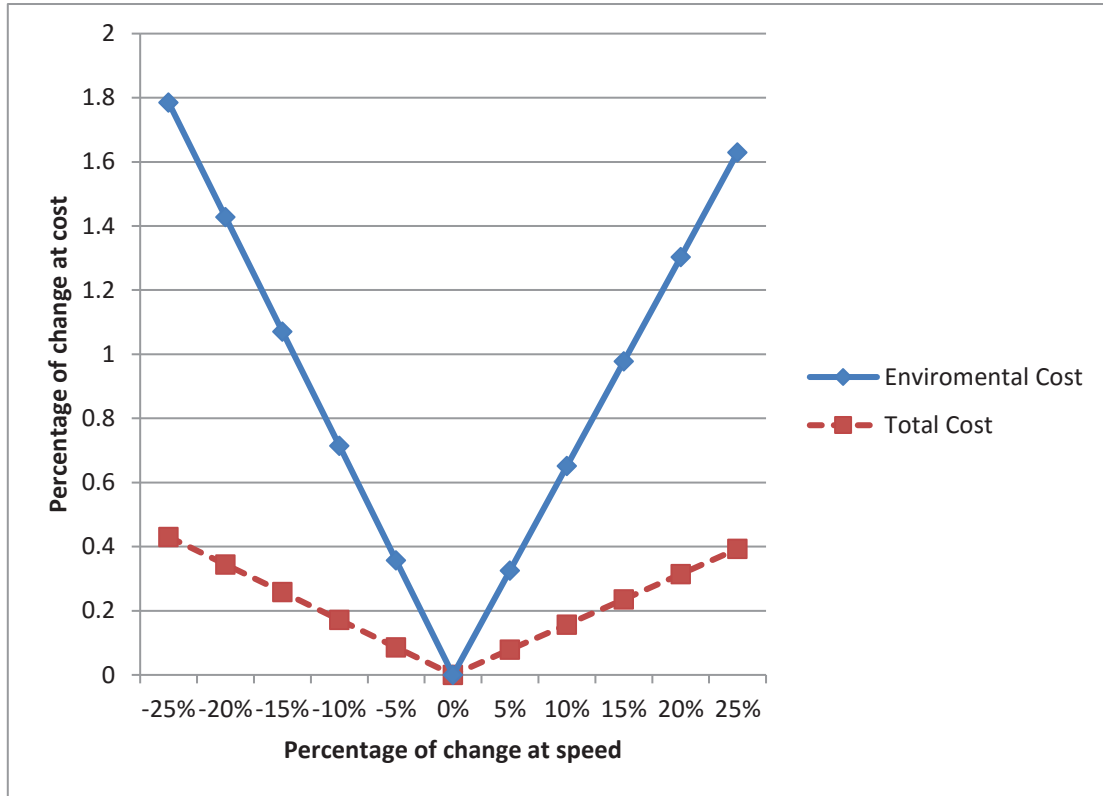
The sensitivity analysis is an analytical examination of input parameters. It is performed in order to check the effect of changing the system major parameters around the optimal solution of the objective function value [163]. This analysis aids in model validation provides guidance for future research [164]. Since the velocity is the major contributor in

the model uncertainty and the core of the stochastic model, the effect of changing the delivering velocity as the most influencing parameter for batches through the optimum routes is examined in this section.

The literature contains various methods of sensitivity analysis utilized for various modeling situations. Differential analysis is the backbone of nearly all other sensitivity analysis techniques. In this method, the optimum solution is termed the 'base case'. In the base case, all parameters are held constant in their optimum values. Afterwards, the ratio of the change in output to the change in input, while all other parameters remain constant, is calculated. This ratio is called a sensitivity coefficient. With the application of the sensitivity analysis, the degree of importance of each parameter in the mathematical model is determined. Parameters can be either strongly related (sensitive) or insignificant to the objective function. Thereby, controlling these parameters is possible with the analysis of their sensitivity [165].

The delivering velocity of the base in the second stage in the developed stochastic model is examined. The generated emissions during distribution depend mainly on the delivering velocity as mentioned earlier. The optimum transporting velocity values are generated in the case study. Skilled drivers significantly affect these velocities and hence control the related generated emissions. When the required batches are delivered faster than the optimum, more emissions are generated which is directly proportional to over emission costs. Figure 5-10 illustrates the effect of changing the delivering velocities in the distribution phases on the total cost.

Table 5-38 describes the details of these changes. The figure shows that the change of the velocity negatively or positively results in the increase of the value of the total cost. However, decreasing the velocity parameter increases the costs at a higher rate more than the effect of increasing this factor. The optimal solution guarantees that the output schedule generated with the least cost value. The conclusion is that the optimum solution is more sensitive for decreasing the delivering velocity time than increasing it. The total cost increases when the velocities decrease due to the increase in the lateness penalty. On the other hand, when the velocities increase, the total cost increases due to the increase of the emission penalty.



**Figure 5-10 Sensitivity analysis of the velocity parameter into the environmental and total costs**

In sum, the results of the model analysis show that the developed model can generate the optimal solution for the batch process industry. This is verified and successfully implemented on two real industrial case studies that prove the model's capability as a decision support system which addresses both the production planning and distribution decisions made under green aspects. Using the previous scenarios, the flexibility of the proposed integrated green model is proven while taking into consideration most of the special features in the batch processes industry.

**Table 5-38 Change of objective cost value in response to change of velocity**

<b>Velocity changing %</b>	<b>The total environmental cost</b>	<b>The objective function total cost</b>	<b>% of the environmental /total cost</b>	<b>Sensitivity coefficient in the environmental cost</b>	<b>Sensitivity coefficient in the total cost</b>
-25%	250,414.2	780,619	32.07	1.35	0.43
-20%	249,745	779,950	32.02	1.08	0.34
-15%	249,075.5	779,281	31.96	0.81	0.25
-10%	248,406	778,611	31.90	0.54	0.17
-5%	247,736.7	777,942	31.84	0.27	0.08
0%	247,067.3	777,272	31.78	0.00	0.00
5%	247,678.3	777,883.3	31.84	0.24	0.07
10%	248,289.3	778,494.3	31.89	0.49	0.15
15%	248,900.3	779,105.3	31.94	0.74	0.23
20%	249,511.2	779,716.2	32.00	0.98	0.31
25%	250,122.2	780,327.2	32.05	1.23	0.39



## **CHAPTER 6      CONCLUSIONS AND DIRECTIONS FOR FUTURE WORK**

In this chapter, the work presented in this research is summarized; the main conclusions in this work are examined; the bridged gap added to the body of the knowledge is described; and the direction for the future work is recommended.

### **6. 1. Summary and Conclusion**

Once the company exists, the main design of its supply chain network is known. To maintain the competitive nature of the company in the dynamic and complex global market, effectively and efficiently managing the planning decisions as well as quickly responding to the customers' requirements are crucial. Nowadays, taking into consideration the environmental aspects is as equally important as taking economic measures into consideration.

As mentioned earlier, customers are willing to buy environmentally friendly products which increase the company's sales, hence improving the economic performance from the company's point of view. As the batch process products are greatly and directly demanded by customers, the frequency of generating the production and distribution plans for these products is very high and extremely important. Generally, in the batch process industry environment, these plans are scheduled by the same management within the company.

In this thesis, a green logistics oriented framework for the integrated scheduling of production and distribution decisions in the batch process industry is developed. As described in the previous chapters, this framework is translated to a three-phase procedure with a core of a two-stage stochastic programming formulation. The two-stage formulation shows the tactical and operational decision levels. These decisions are modeled in an integrated manner because the scheduling of customer demands is strongly influenced by the interrelated stages of production and distribution.

The development of this framework is designed to model the real world situation for the case of the batch process industry under uncertainty. The model covers the main characteristics which are identified in the comprehensive state of the art. The considered environmental aspect is related to carbon emissions as a function of random vehicle velocities.

Delivering velocity is selected to present the greenness of the distribution process for three reasons, first: it is a variable value during the planning phase; therefore, it is not fixed with each generated schedule. Controlling the distribution velocities is as frequent as generating the integrated production and distribution plans, unlike the other green initiatives. Second: it depends on human behavior and road conditions. Last: as previously described in detail, the transportation sector is the second largest emitter of green gases.

The model is tested, verified and applied in two real world cases in the batch process industry. As a result, the problem complexity is reduced considerably and the integrated problem is solved in a reasonable time. The numerical results showed that conducting such integration is significantly beneficial. A considerable saving up to 43 percent of the total costs are realized when all the integrated elements are involved (Table 5-35). These elements include production, distribution and green aspects. Thus, the environmental and economic benefits are achievable via the integration.

Furthermore, results showed that environmental regulations can increase the overall costs by 8 percent as deduced from case study computational analysis. Lastly, the analysis of the results demonstrates the value of using a stochastic model versus deterministic planning. Developing the model in a stochastic programming formulation achieves savings of up to 13 percent for a realistic number of random scenarios (Table 5-36).

By accomplishing this work, contribution to the body of knowledge has been added. The gap in this field has been bridged by this research. The main contributions of this research are fourfold:

- It presents a systematic methodology to handle the uncertainties in green logistics within the batch process industry. A clear framework with a core of an integrated two-stage stochastic programming model for the production-distribution planning of products at the tactical-operational levels under uncertainty is designed. The model includes the green aspect of the permissible carbon emissions as a function of uncertain vehicle velocities which is novel in this research area. This could be considered as a decision support tool for the integrated production, distribution planning and scheduling by helping the decision-maker in the production, inventory as well as delivering decisions.

- It models the stochasticity of the travel velocities which plays a role in the calculations of emissions cost components. The production and distribution costs are the actual costs which companies pay. On the other hand, the intangible lateness costs in terms of emissions are included to provide reliability to the customers. Cost saving are achievable by limiting overage and underage emissions. A comprehensive analysis is performed to examine the behaviour and the particular features of the obtained solutions.

- The model was applied to two real world case studies in the batch processes industry. This is an addition to the literature review in this field. The resulting savings of the integrated production, distribution and green aspects within the framework are shown. Different facilities which are based on the batch process industry type of production are tested separately and have proved the ability of the developed framework to deal with the batch process environment.

- Costs savings from both an economic and environmental standpoint cause long-term profitability and, therefore, sustainability. Thus, the central finding of this study is that the integration of production and distribution processes, tactical and operational decisions as well as economic and environmental objectives in the logistics networks are essential to sustain a worldwide competitive advantage. Building such a framework provides a practical tool which links together being green and being economically successful.

In conclusion, although this research is a practical decision tool in the real life world of the batch process industry, more research on the scheduling of the integrated production and distribution in green aspects under the context of uncertainty is needed. Various cases and parameters should be studied in order to provide more advanced logistics systems.

## **6.2. Future Work**

The presented research work is an initiative towards the establishment of a sustainable production and distribution logistics practice. The research is applied to a real world case study in the batch process industry and addresses its related issues. Based on the case study results concluded by this research, several opportunities have evolved for the future works. The most important concern is the concept of sustainability which promises the long term profitability. Thus, focusing on green logistics as well as integration production and distribution decisions are playing a crucial role in developing, improving and implementing sustainability.

There is a need for additional application of integrated production and distribution models of the logistics market in order to better understand their performance in reality. These models should be designed in a way which considers both the economic and environmental issues. The results of this thesis open many directions for further research. The following prospects are worth further consideration in future research:

- Involving the green aspects in the production stage, rather than just in the distribution stage. Some issues such as optimum number of products per batch and ordering quantities policies and their effects on green logistics decisions are worth investigating.

- Using different ways of calculating emissions and comparing them altogether. It is necessary to examine not only the simplest but also the most reliable methods. Defining a useable way to get real measures will highly improve the accuracy of the results and therefore the decision of the driver during delivery routes.

- Adding other sources of uncertainty within the production and distribution phases. In this dynamic environment, uncertainties are represented by the gap between the planned and actual system status. This gap shows a new challenge for the management of complex and dynamics supply chain processes. Uncertainties related with production and

distribution planning processes are various such as the production and distribution demanded quantities, costs and capacities. In the proposed model these parameters are assumed to be deterministic. In reality, these parameters are influenced by several factors; establishing methodologies to deal with these uncertainties are crucial.

- Connecting the presented work with a Geographic Information System (GIS) to generate a Spatial Decision Support System (SDSS). The resulted output will be displayed in a User Friendly Interface (UFI) which will definitely improve the quality of decision making and scenario generation.

- Investigating more distribution related issues such as using heterogeneous delivery fleets or even determining the optimum fleet mix. In addition, applying the developed framework in a multi depot real case study will be an addition to the research done in this field.

- Enhancing the presented framework upon more precise implementation of green logistics concepts on different logistics networks. Other examples for batch process industry such as fast moving consumer goods and pharmacological industry products should be tested in order to move towards a more feasible applicability of the developed model in the industrial world. Each of these applications has special features which influence the constraints of the planning model.

- Calculating the effect of considering the social criteria such as improving labour conditions and human rights. The social dimension of sustainability is still not met in solely a matter of numbers. Human resource is the most valuable asset of any enterprise; human resource is still the main reason of the success or failure of any logistics activity. Training and education can increase the level of green awareness and knowledge among employees as well as customers.

- Testing different modes of transportation will enhance the applicability of this model. The research in this thesis has focused on delivering batches using vehicles. It would be interesting to extend the study to include other modes of transportation in order to understand if they show similar emission results as well.

- Involving the setup time during the processing of the batches processing will generate more realistic production schedules. The research in this thesis has not gone into detail in regard to the different processing stages of the required batches.

- Splitting batches in delivery phases would be an interesting decision to study. The trade-off between the: vehicles capacities; number of generated routes; frequent shipments between the supply chain partners; and splitting orders is an important decision made during the scheduling of the distribution processes.

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# APPENDIX

## Appendix A: LINGO® Code for the Test Models

### Test Models 1-A: Production Decisions Only

```
SETS:
!T;          TIMEPERIOD/1..1/;
!L;          PRODUCT/1..4/:Q.PC.HC.val;
!(T.L);     PRODUCTION(TIMEPERIOD.PRODUCT):X.E.N;
!(L.LL);    PROPRO(PRODUCT.PRODUCT);
ENDSETS

!Defining Data;
DATA:
Q= 15 20 15 10 ;
val= 1 1 1 1;
LEV=1;
PC= 20 15 18 25;
HC= 8 6 2 10;
E= 1 1 5 2;
Ho=5;
B=100;
VCAP=2500;
ENDDATA

!Objective Function;
MIN=(@SUM(PRODUCTION(T.L):PC(L)*X(T.L)))+@SUM(ACCUM(T.K.L):(HC(L)*N(T.L)));

!Production Constraints;
!Capacity;
@FOR(TIMEPERIOD(T):@SUM(PRODUCT(L):X(T.L))<=B);
!Inventory;
@FOR(PRODUCTION(T.L)|T#EQ#1:H(T.1.L)=(Ho+X(T.L)-E(T.L)-@SUM(LOCATION(K):A(T.K.L))));
@FOR(PRODUCTION(T.L)|T#GT#1:H(T.1.L)=(H(T-1.1.L)+X(T.L)-E(T.L)-@SUM(LOCATION(K):A(T.K.L))));
@FOR(TIMEPERIOD(T):@SUM(PRODUCT(L):H(T.1.L))<=PSC);
@FOR(ACCUMM(T.K)|K#GT#1:U(T.K)<=(@SUM(PRODUCT(L):A(T.K.L))));
@FOR(ACCUM(T.K.L):A(T.K.L)>=(LEV*Q(T.K.L)));
!Av Inv Qty;
@for(ACCUM(T.K.L)|T#GT#1:N(T.L)=(0.5*(H(T-1.K.L)+H(T.K.L))));
@for(ACCUM(T.K.L)|T#EQ#1:N(T.L)=(0.5*(Ho+H(T.K.L))));
END
```

## Test Models 1-B: Production Decisions with Time Periods

```
SETS:
!T;          TIMEPERIOD/1..3/;
!L;          PRODUCT/1..4/:PC,HC,VAL;
!(T,L);     PRODUCTION (TIMEPERIOD,PRODUCT) :X,E,N,H,Q;
!(L,LL);    PROPRO (PRODUCT,PRODUCT) ;
ENDSETS

!Defining Data;
DATA:
Q= 15 20 15 10 15 20 15 10 15 20 15 10;
VAL= 1 1 1 1;
LEV=1;
PC= 20 15 18 25;
HC= 8 6 2 10;
E= 1 1 4 2 1 1 4 2 1 1 4 2 ;
Ho=5;
B=144;
ENDDATA

!Objective Function;
MIN= (@SUM (PRODUCTION (T,L) : PC (L) *X (T,L) )) +@SUM (PRODUCTION (T,L) : (HC (L) *N
(T,L) ));

!Production Constraints;
!Capacity;
@FOR (TIMEPERIOD (T) :@SUM (PRODUCT (L) :X (T,L) ) <=B) ;
!Inventory;
@FOR (PRODUCTION (T,L) | T#EQ#1 :H (T,L) = (Ho+X (T,L) -E (T,L) -
@SUM (PRODUCTION (T,L) :LEV*Q (T,L) )) ) ;
@FOR (PRODUCTION (T,L) | T#GT#1 :H (T,L) = (H (T-1,L) +X (T,L) -E (T,L) -
@SUM (PRODUCTION (T,L) :LEV*Q (T,L) )) ) ;
@FOR (TIMEPERIOD (T) :@SUM (PRODUCT (L) :H (T,L) ) <=PSC) ;
!Av Inv Qty;
@for (PRODUCTION (T,L) | T#GT#1 :N (T,L) = (0.5* (H (T-1,L) +H (T,L) )) ) ;
@for (PRODUCTION (T,L) | T#EQ#1 :N (T,L) = (0.5* (Ho+H (T,L) )) ) ;
END
```

## Test Models 2: The Integrated Production and Scheduling Decisions

```
SETS:
!T;          TIMEPERIOD/1..3/;
!L;          PRODUCT/1..2/:PC.HC.val.Db.Cb.Lb.Eb.Gb.sb.wb;
!(T.L);     PRODUCTION(TIMEPERIOD.PRODUCT):X.E.N.H.Q;
!(L.LL);    PROPRO(PRODUCT.PRODUCT):yb;
ENDSETS

!Defining Data;
DATA:
Q= 15 20 15 20 10 15;
val= 1 1;
LEV=1;
PC= 20 25;
HC= 8 10;
E=1 1 4 1 2 2;
Ho=5;
B=200;
Db=300 500;
Gb=50 20;
wb=1 2;
ENDDATA

!Objective Function;
MIN=(@SUM(PRODUCTION(T.L):PC(L)*X(T.L)))+@SUM(PRODUCTION(T.L):(HC(L)*N
(T.L)))+@SUM(PRODUCT(L):(Lb(L)*wb(L)));

!Production Constraints;
!Capacity;
@FOR(TIMEPERIOD(T):@SUM(PRODUCT(L):X(T.L))<=B);
!Inventory;
@FOR(PRODUCTION(T.L)|T#EQ#1:H(1.L)=Ho+X(T.L)-E(T.L));
@FOR(PRODUCTION(T.L)|T#GT#1:H(1.L)=H(T-1.L)+X(T.L)-E(T.L));
@FOR(TIMEPERIOD(T):@SUM(PRODUCT(L):H(T.L))<=PSC);
!//ADDED//;
!Av Inv Qty;
@for(PRODUCTION(T.L)|T#GT#1:N(T.L)=(0.5*(H(T-1.L)+H(T.L))));
@for(PRODUCTION(T.L)|T#EQ#1:N(T.L)=(0.5*(Ho+H(T.L))));

!Scheduling;
@FOR(PRODUCTION(T.L):Cb(L)>=@sum(PRODUCT(L):X(T.L)*Gb(L)));
@FOR(PRODUCTION(T.L):Cb(L)+sb(L)+Eb(L)-Lb(L)<=Db(L));
@FOR(TIMEPERIOD(T):@for(PROPRO(L.LL)|L#LT#LL:sb(LL)>=(sb(L)+(@sum(PROD
UCT(L):X(T.L)*Gb(L)))-
@if(Db(L)#LE#Db(LL).0.M)*yb(LL.L);@bin(yb(L.LL))));
@FOR(TIMEPERIOD(T):@for(PROPRO(L.LL)|L#LT#LL:sb(L)>=(sb(LL)+(@sum(PROD
UCT(L):X(T.L)*Gb(LL)))-
@if(Db(LL)#LE#Db(L).0.M)*yb(L.LL);@bin(yb(LL.LL))));
@for(PROPRO(L.LL)|L#NE#LL:yb(L.LL)+yb(LL.L)=1);
@for(PROPRO(L.LL)|L#EQ#LL:yb(L.LL)=0);

!Binary;
@FOR(PROPRO:@BIN(yb));

END
```

## Test Models 3-A: Distribution Decisions Only

```
SETS:
!K;          LOCATION/1..7/: Q, U;
!K.K;       ROUTE( LOCATION, LOCATION): DIST, Z;
ENDSETS

!Defining Data;
DATA:
Q = 0 6 3 15 4 5 2;
DIST =
          0   99   216  106  50   205  21
          0   0    116  100  600  122  155
          0  116   0    175  20   190  25
          0  100  175   0    700  15  120
          0  600  20   700   0    40  158
          0  122  190  15   40   0   40
          0  155  25   120  158  40   0;

VCAP = 15;
ENDDATA

!Objective Function;
MIN = @SUM( ROUTE: DIST * Z);

!Distribution Constraints;
!For all except depot;
@FOR( LOCATION( K) | K #GT# 1:
!a vehicle doesn't travel inside itself;
    Z( K, K) = 0;
!a vehicle must enter;
@SUM( LOCATION( I) | I #NE# K #AND# ( I #EQ# 1 #OR#
Q( I) + Q( K) #LE# VCAP): Z( I, K)) = 1;
!a vehicle must leave;
@SUM( LOCATION( J) | J #NE# K #AND# ( J #EQ# 1 #OR#
Q( J) + Q( K) #LE# VCAP): Z( K, J)) = 1;
!capacity;
@BND( Q( K), U( K), VCAP);
!Sequencing;
@FOR( LOCATION( I) | I #NE# K #AND# I #NE# 1:
    U( K) >= U( I) + Q( K) - VCAP + VCAP *
    ( Z( K, I) + Z( I, K)) - ( Q( K) + Q( I))
    * Z( K, I);
);
!if K is 1st stop;
    U( K) <= VCAP - ( VCAP - Q( K)) * Z( 1, K);
    U( K) >= Q( K) + @SUM(LOCATION( I) |
    I #GT# 1: Q( I) * Z( I, K));
);
!Binary;
@FOR( ROUTE: @BIN( Z));
!Enough ;
@SUM(LOCATION( J) | J#GT#1:Z( 1, J))=<
@FLOOR(@SUM(LOCATION( I) | I#GT#1:Q( I)/VCAP))+0.999);
END
```

## Test Models 3-B: Distribution Decisions with Cost

```

SETS:
!K;          LOCATION/1..7/: Q. U;
!K;K;       ROUTE(LOCATION. LOCATION): DIST. Z. D;
ENDSETS

!Defining Data;
DATA:
Q = 0 6 3 15 4 5 2;
DIST =
      0   99   216  106  50   205  21
      0   0   116  100  600  122  155
      0  116   0   175  20   190  25
      0  100  175   0   700  15  120
      0  600  20   700   0   40  158
      0  122  190  15   40   0   40
      0  155  25  120  158  40   0;

D=
      1   1   1   1   1   1   1
      1   1   1   1   1   1   1
      1   1   1   1  10   1   1
      1   1   1   1   1   1   1
      1   1   1   1   1   1   1
      1   1   1   1   1   1   1
      1   1   1   1   1   1   1;

VCAP = 15;
ENDDATA

!Objective Function;
MIN = @SUM( ROUTE: DIST * Z *D);

!Distribution Constraints;
!For all except depot;
@FOR( LOCATION( K) | K #GT# 1:
!a vehicle doesn't travel inside itself;
      Z( K. K) = 0;
!a vehicel must enter;
@SUM( LOCATION( I) | I #NE# K #AND# ( I #EQ# 1 #OR#
Q( I) + Q( K) #LE# VCAP): Z( I. K)) = 1;
!a vehicel must leave;
@SUM( LOCATION( J) | J #NE# K #AND# ( J #EQ# 1 #OR#
Q( J) + Q( K) #LE# VCAP): Z( K. J)) = 1;
!capacity;
@BND( Q( K). U( K). VCAP);
!if K is 1st stop;
@FOR( LOCATION( I) | I #NE# K #AND# I #NE# 1:
      U( K) >= U( I) + Q( K) - VCAP + VCAP *
      ( Z( K. I) + Z( I. K)) - ( Q( K) + Q( I))
      * Z( K. I);
);
      U( K) <= VCAP - ( VCAP - Q( K)) * Z( 1. K);

```



```
U ( K) >= Q ( K) + @SUM (LOCATION ( I ) |
I #GT# 1 : Q ( I ) * Z ( I . K ) ) ;
);
!Binary;
@FOR ( ROUTE : @BIN ( Z ) ) ;
!Enough Capacity ;
@SUM (LOCATION ( J ) | J #GT# 1 : Z ( 1 . J ) = <
@FLOOR ( @SUM (LOCATION ( I ) | I #GT# 1 : Q ( I ) / VCAP ) + 0 . 999 ) ) ;
END
```

## Test Models 4: The Integrated Production, Scheduling and Distribution Decisions

SETS:

```

!K;          LOCATION/1..7/;
!T;          TIMEPERIOD/1..2/;
!L;          PRODUCT/1..3/:PC.HC.val.Db.Cb.Lb.Eb.Gb.sb.wb;
!(T.L);     PRODUCTION(TIMEPERIOD.PRODUCT):X.E.N;
!(K.K);     CXC(LOCATION.LOCATION):DIST.D;
!(T.K.K);   ROUTE(TIMEPERIOD.CXC):Z;
!(T.K);     ACCUMM(TIMEPERIOD.LOCATION):U;
!(T.K.L);   ACCUM(TIMEPERIOD.LOCATION.PRODUCT):H.A.Q;
!(L.LL);    PROPRO(PRODUCT.PRODUCT):yb;

```

ENDSETS

!Defining Data;

DATA:

Q=

	0	0	0	3	1	0	2
	10	4	3	5	4	5	2
	10	6	3	5	4	5	2
	0	0	0	5	4	5	2
	1	6	3	5	4	9	2
	8	6	3	15	4	5	2;

DIST=

	0	99	216	106	50	205	21
	0	0	116	100	600	122	155
	0	116	0	175	20	190	25
	0	100	175	0	700	15	120
	0	600	20	700	0	40	158
	0	122	190	15	40	0	40
	0	155	25	120	158	40	0;

D=

	10000	9	4	6	1	9	2
	9	10000	9	2	3	9	9
	4	9	10000	5	8	2	1
	6	2	5	10000	6	9	4
	1	3	8	6	10000	4	4
	9	9	2	9	4	10000	4
	2	9	1	4	4	4	10000;

val= 1 1 1;

LEV=1;

PC= 20 15 18;

HC= 8 11 7;

E= 1 1 1 9 5 2;

Ho=7;

PSC=60;

M=1000000;

B=100;

VCAP=50;

Db= 100 80 200;

ENDDATA

!Objective Function;

```

MIN=(@SUM(PRODUCTION(T.L):PC(L)*X(T.L)))+@SUM(ROUTE:DIST*Z*D)+@SUM(PRO
DUCT(L):(Lb(L)*wb(L)))+@SUM(ACCUM(T.K.L):(HC(L)*N(T.L)));

```

```

!Production Constraints;
!Capacity;
@FOR (TIMEPERIOD (T) : @SUM (PRODUCT (L) : X (T . L) ) <= B) ;
!Inventory;
@FOR (PRODUCTION (T . L) | T#EQ#1 : H (T . 1 . L) = (H0 + X (T . L) - E (T . L) -
@SUM (LOCATION (K) : A (T . K . L) ) ) ;
@FOR (PRODUCTION (T . L) | T#GT#1 : H (T . 1 . L) = (H (T - 1 . 1 . L) + X (T . L) - E (T . L) -
@SUM (LOCATION (K) : A (T . K . L) ) ) ;
@FOR (TIMEPERIOD (T) : @SUM (PRODUCT (L) : H (T . 1 . L) ) <= PSC) ;
@FOR (ACCUMM (T . K) | K#GT#1 : U (T . K) <= (SUM) PRODUCT (L) : A (T . K . L) ) ) ;
@FOR (ACCUM (T . K . L) : A (T . K . L) >= (LEV * Q (T . K . L) ) ) ;
!Av Inv Qty;
@for (ACCUM (T . K . L) | T#GT#1 : N (T . L) = (0 . 5 * (H (T - 1 . K . L) + H (T . K . L) ) ) ) ;
@for (ACCUM (T . K . L) | T#EQ#1 : N (T . L) = (0 . 5 * (H0 + H (T . K . L) ) ) ) ;

!Scheduling Constraints;
!Completion time. earliness and lateness;
@FOR (PRODUCTION (T . L) : Cb (L) >= @SUM (PRODUCT (L) : X (T . L) * Gb (L) ) ) ;
@FOR (PRODUCTION (T . L) : Cb (L) + sb (L) + Eb (L) - Lb (L) <= Db (L) ) ;
!Sequencing;
@FOR (TIMEPERIOD (T) : @FOR (PROPRO (L . LL) | L#LT#LL : sb (LL) >= (sb (L) + (
@SUM (PRODUCT (L) : X (T . L) * Gb (L) ) ) ) - @IF (Db (L) #LE#Db (LL) . 0 . M) * yb (LL . L) ;
@bin (yb (L . LL) ) ) ) ;
@FOR (TIMEPERIOD (T) : @FOR (PROPRO (L . LL) | L#LT#LL : sb (L) >= (sb (LL) + (
@SUM (PRODUCT (L) : X (T . L) * Gb (LL) ) ) ) - @IF (Db (LL) #LE#Db (L) . 0 . M) * yb (L . LL) ;
@bin (yb (LL . L) ) ) ) ;
@FOR (PROPRO (L . LL) | L#NE#LL : yb (L . LL) + yb (LL . L) = 1) ;
!Switching;
@FOR (PROPRO (L . LL) | L#EQ#LL : yb (L . LL) = 0) ;

!Distribution Constraints;
!For all except depot;
@FOR (LOCATION (K) | K) GT#1 : @FOR #TIMEPERIOD (T) :
!a vehicle doesn't travel inside itself ;
(Z (T . K . K) = 0;
!a vehicle must enter ;
@FOR (TIMEPERIOD (T) : @SUM (LOCATION (I) | I#NE#K#AND# (I#EQ#1#OR#
(@SUM (PRODUCT (L) : Q (T . I . L) ) ) + (@SUM (PRODUCT (L) : Q (T . K . L) ) ) #LE#
; (VCAP) : Z (T . I . K) ) = 1
!a vehicle must leave;
@FOR (TIMEPERIOD (T) : @SUM (LOCATION (J) | J#NE#K#AND# (J#EQ#1#OR#
(@SUM (PRODUCT (L) : Q (T . J . L) ) ) + (@SUM (PRODUCT (L) : Q (T . K . L) ) ) #LE#
; (VCAP) : Z (T . K . J) ) = 1
!capacity;
) FOR (ACCUM (T . K . L) : @BND@Q (T . K . L) . U (T . K) . VCAP) ) ;
!Sequencing;
@FOR (TIMEPERIOD (T) : @FOR (LOCATION (I) | I#NE#K#AND# I#NE#1#
) U (T . K) >= U (T . I) + (@SUM PRODUCT (L) : *Q (T . K . L) ) ) - VCAP + VCAP
) (Z (T . K . I) + Z (T . I . K) ) - ( (@SUM PRODUCT (L) : Q + ( ( ) T . K . L (
) SUM@) PRODUCT (L) : Q ( ( ( ) T . L . L (
; Z (T . K . I) *
; ( (
; if K is 1st stop!
) FOR@TIMEPERIOD (T) : U (T . K) <= VCAP - (VCAP -
(@SUM (PRODUCT (L) : Q (T . K . L) ) ) ) * Z (T . 1 . K) ) ;
; if K is NOT 1st stop!
) FOR@TIMEPERIOD (T) : U (T . K) >= (@SUM (PRODUCT (L) : Q (T . K . L) ) ) + @SUM (
LOCATION (I) |

```

```
) I#GT#1: (@SUMPRODUCT(L):Q(T.I.L)) *Z(T.I.K));  
;  
  
!Binary;  
@FOR(ROUTE: @BIN(z));  
@FOR(PROPRO: @BIN(yb));  
  
;Enough Capacity!  
@FOR(PRODUCTION(T.L):@SUM(LOCATION(J)|J:GT#1#Z=<())T.1.J(  
)FLOOR((@SUM@LOCATION(I)|I;((GT#1:Q(T.I.L)/VCAP))+0.999#  
END
```

## Appendix B: Input Data and LINGO® Code for the Case Study

### General Formulation

```

SETS:
!K;      LOCATION/1..8/:EM.P.F.G;
!T;      TIMEPERIOD/1..2/;
!L;      PRODUCT/1..7/:PC.HC.val.Db.Cb.Lb.Eb.Gb.sb.wb;
!W;      OMEGA/1..1/:VMAX.VMIN.EMAX.EMIN.Prob;
!(T.L);  PRODUCTION(TIMEPERIOD.PRODUCT):X.E.N;
!(K.K);  CXC(LOCATION.LOCATION):DIST.D;
!(T.K.K); ROUTE(TIMEPERIOD.CXC):Z;
!(T.K);  ACCUMM(TIMEPERIOD.LOCATION):U;
!(T.K.L); ACCUM(TIMEPERIOD.LOCATION.PRODUCT):H.A.Q;
!(T.K.K.W); UNC(TIMEPERIOD.LOCATION.LOCATION.OMEGA):V.OE.UE.JO;
!(L.LL); PROPRO(PRODUCT.PRODUCT):yb;
ENDSETS

```

!Defining Data;

DATA:

Q=

0	0	0	0	0	0	0	0
500	0	175	213	400	375	438	
180	0	0	0	0	0	0	
0	3	0	3	0	0	3	
506	0	13	73	83	0	0	
23	35	35	35	29	0	0	
4	0	0	3	4	0	3	
7	3	3	27	7	27	0	
0	0	0	0	0	0	0	
333	0	117	142	267	250	292	
270	0	0	0	0	0	0	
0	6	0	6	0	0	6	
506	0	13	73	83	0	0	
10	15	15	15	13	0	0	
3	0	0	4	3	0	4	
27	1	13	7	27	7	0;	

DIST=

0	135	156	599	428	396	246	375
135	0	202	678	293	281	381	252
156	202	0	476	446	346	298	345
599	678	476	0	876	714	508	742
428	293	446	876	0	180	508	742
396	281	346	714	180	0	627	48
246	381	298	508	508	627	0	613
375	252	345	742	742	48	613	0;

D=

10000	9	4	6	14	9	24	39
9	10000	9	2	32	9	29	44
4	9	10000	52	38	20	51	29
6	2	52	10000	64	9	44	4
14	32	38	64	10000	4	24	2
9	9	20	9	4	10000	24	1
24	29	51	44	24	24	10000	49

```

          39      44      29      4      2      1      49      10000;
P= 6 7 8 8 9 6 7 8;
EM= 10 12 10 12 10 11 12 10;
F= 9 7 8 8 8 7 6 8;
G= 6 7 8 8 9 6 7 8;
val= 1 1 1 1 1 1 1;
LEV=1;
PC= 20 28 20 20 15 18 25;
HC= 8 11 8 8 6 7 10;
E= 2 5 9 1 1 1 1 2 5 9 1 1 1 1;
Ho=100;
PSC=100000;
M=1000000;
B=10000;
VCAP=2500;
Db=100 1500 1200 2000 2500 2800 3000;
Gb= 1 2 5 5 5 5 5;
wb=1 5 2 1 1 1 1;
ENDDATA

```

!Objective Function;

```

MIN= (@SUM (PRODUCTION (T.L) : PC (L) * X (T.L) )) + @SUM (ROUTE : DIST * Z * D) + @SUM (PRO
DUCT (L) : (Lb (L) * wb (L) )) + @SUM (ACCUM (T.K.L) : (HC (L) * N (T.L) )) + @SUM (OMEGA (W)
: Prob (W) * (@SUM (UNC (T.K.I.W) : (EM (K) * P (K) )) * V (T.K.I.W) )) + @SUM (UNC (T.K.I.W)
: F (K) * OE (T.K.I.W) )) + @SUM (UNC (T.K.I.W) : G (K) * UE (T.K.I.W) ));

```

!Production Constraints;

!Capacity;

```

@FOR (TIMEPERIOD (T) : @SUM (PRODUCT (L) : X (T.L) ) <= B) ;

```

!Inventory;

```

@FOR (PRODUCTION (T.L) | T#EQ#1 : H (T.1.L) = (Ho + X (T.L) - E (T.L) -

```

```

@SUM (LOCATION (K) : A (T.K.L) )) ;

```

```

@FOR (PRODUCTION (T.L) | T#GT#1 : H (T.1.L) = (H (T-1.1.L) + X (T.L) - E (T.L) -

```

```

@SUM (LOCATION (K) : A (T.K.L) )) ;

```

```

@FOR (TIMEPERIOD (T) : @SUM (PRODUCT (L) : H (T.1.L) ) <= PSC) ;

```

```

@FOR (ACCUM (T.K) | K#GT#1 : U (T.K) <= (SUM) PRODUCT (L) : A (T.K.L) )) ;

```

```

@FOR (ACCUM (T.K.L) : A (T.K.L) >= (LEV * Q (T.K.L) ; ( (

```

!Av Inv Qty;

```

@for (ACCUM (T.K.L) | T#GT#1 : N (T.L) = (0.5 * (H (T-1.K.L) + H (T.K.L) )))) ;

```

```

@for (ACCUM (T.K.L) | T#EQ#1 : N (T.L) = (0.5 * (Ho + H (T.K.L) )))) ;

```

!Scheduling Constraints;

!Completion time, earliness and lateness;

```

@FOR (PRODUCTION (T.L) : Cb (L) >= @SUM (PRODUCT (L) : X (T.L) * Gb (L) )) ;

```

```

@FOR (PRODUCTION (T.L) : Cb (L) + sb (L) + Eb (L) - Lb (L) <= Db (L) ) ;

```

!Sequencing;

```

@FOR (TIMEPERIOD (T) : @FOR (PROPRO (L.LL) | L#LT#LL : sb (LL) >= (sb (L) + (

```

```

@SUM (PRODUCT (L) : X (T.L) * Gb (L) )) - @IF (Db (L) #LE#Db (LL) .0.M) * yb (LL.L) ;

```

```

@bin (yb (L.LL) )) ;

```

```

@FOR (TIMEPERIOD (T) : @FOR (PROPRO (L.LL) | L#LT#LL : sb (L) >= (sb (LL) + (

```

```

@SUM (PRODUCT (L) : X (T.L) * Gb (LL) )) - @IF (Db (LL) #LE#Db (L) .0.M) * yb (L.LL) ;

```

```

@bin (yb (LL.L) )) ;

```

```

@FOR (PROPRO (L.LL) | L#NE#LL : yb (L.LL) + yb (LL.L) = 1) ;

```

!Switching;

```

@FOR (PROPRO (L.LL) | L#EQ#LL : yb (L.LL) = 0) ;

```

```

!Distribution Constraints;
!For all except depot;
@FOR (LOCATION(K) | K) GT#1: @FOR#TIMEPERIOD(T) :
!a vehichle doesn't travel inside itself;
Z(T.K.K)=0);
!a vehicle must enter;
@FOR (TIMEPERIOD(T) : @SUM (LOCATION(I) | I#NE#K#AND# (I#EQ#1#OR#
(@SUM(PRODUCT(L) : Q(T.I.L)) + (@SUM(PRODUCT(L) : Q(T.K.L))) #LE#
VCAP) : Z(T.I.K))=1);
!a vehicle must leave;
@FOR (TIMEPERIOD(T) : @SUM (LOCATION(J) | J#NE#K#AND# (J#EQ#1#OR#
(@SUM(PRODUCT(L) : Q(T.J.L)) + (@SUM(PRODUCT(L) : Q(T.K.L))) #LE#
VCAP) : Z(T.K.J))=1);
!capacity;
@FOR (ACCUM(T.K.L) : @BND(Q(T.K.L) . U(T.K) . VCAP));
!Sequencing;
@FOR (TIMEPERIOD(T) : @FOR (LOCATION(I) | I#NE#K#AND# I#NE#1 :
U(T.K) >= U(T.I) + (@SUM(PRODUCT(L) : Q(T.K.L))) - VCAP + VCAP *
(Z(T.K.I) + Z(T.I.K)) - ((@SUM(PRODUCT(L) : Q(T.K.L))) +
(@SUM(PRODUCT(L) : Q(T.L.L))))
*Z(T.K.I) ;
));
!if K is 1st stop;
@FOR (TIMEPERIOD(T) : U(T.K) <= VCAP - (VCAP -
(@SUM(PRODUCT(L) : Q(T.K.L))) * Z(T.1.K));
!if K is NOT 1st stop;
@FOR (TIMEPERIOD(T) : U(T.K) >= (@SUM(PRODUCT(L) : Q(T.K.L))) + @SUM (
LOCATION(I) |
I#GT#1 : (@SUM(PRODUCT(L) : Q(T.I.L))) * Z(T.I.K));
);
!Binary;
@FOR (ROUTE: @BIN (z));
@FOR (PROPRO: @BIN (yb));
!Enough Capacity;
@FOR (PRODUCTION(T.L) : @SUM (LOCATION(J) | J#GT#1 : Z(T.1.J)) >=
@FLOOR ((@SUM (LOCATION(I) | I#GT#1 : Q(T.I.L) / VCAP) + 0.999));
!Stochastic;
@FOR (UNC (T.K.I.W) : V(T.K.I.W) >= (VMIN(W) * Z(T.K.I)));
@FOR (UNC (T.K.I.W) : (VMAX(W) * Z(T.K.I)) <= V(T.K.I.W));
@FOR (UNC (T.K.I.W) : @SUM (LOCATION(K) : (EM(K) * V(T.K.I.W))) = JO(T.K.I.W));
@FOR (UNC (T.K.I.W) : OE(T.K.I.W) >= (JO(T.K.I.W) - (EMAX(W) * Z(T.K.I))));
@FOR (UNC (T.K.I.W) : UE(T.K.I.W) >= (EMIN(W) * Z(T.K.I)) - JO(T.K.I.W));
END

```

## First Case Study Formulation (20 Scenarios)

SETS:

```

!K; LOCATION/1..8/:EM.P.F.G;
!T; TIMEPERIOD/1..2/;
!L; PRODUCT/1..7/:PC.HC.val.Db.Cb.Lb.Eb.Gb.sb.wb;
!W; OMEGA/1..20/:VMAX.VMIN.EMAX.EMIN.Prob;
!(T.L); PRODUCTION(TIMEPERIOD.PRODUCT):X.E.N;
!(K.K); CXC(LOCATION.LOCATION):DIST.D;
!(T.K.K); ROUTE(TIMEPERIOD.CXC):Z;
!(T.K); ACCUMM(TIMEPERIOD.LOCATION):U;
!(T.K.L); ACCUM(TIMEPERIOD.LOCATION.PRODUCT):H.A.Q;
!(T.K.K.W); UNC(TIMEPERIOD.LOCATION.LOCATION.OMEGA):V.OE.UE.JO;
!(L.LL); PROPRO(PRODUCT.PRODUCT):yb;
ENDSETS

```

!Defining Data;

DATA:

Q=

0	0	0	0	0	0	0
500	0	175	213	400	375	438
180	0	0	0	0	0	0
0	3	0	3	0	0	3
506	0	13	73	83	0	0
23	35	35	35	29	0	0
4	0	0	3	4	0	3
7	3	3	27	7	27	0
0	0	0	0	0	0	0
333	0	117	142	267	250	292
270	0	0	0	0	0	0
0	6	0	6	0	0	6
506	0	13	73	83	0	0
10	15	15	15	13	0	0
3	0	0	4	3	0	4
27	1	13	7	27	7	0;

DIST=

0	135	156	599	428	396	246	375
135	0	202	678	293	281	381	252
156	202	0	476	446	346	298	345
599	678	476	0	876	714	508	742
428	293	446	876	0	180	508	742
396	281	346	714	180	0	627	48
246	381	298	508	508	627	0	613
375	252	345	742	742	48	613	0;

D=

10000	9	4	6	14	9	24	39
9	10000	9	2	32	9	29	44
4	9	10000	52	38	20	51	29
6	2	52	10000	64	9	44	4
14	32	38	64	10000	4	24	2
9	9	20	9	4	10000	24	1
24	29	51	44	24	24	10000	49
39	44	29	4	2	1	49	10000;

P= 6 7 8 8 9 6 7 8;

EM= 10 12 10 12 10 11 12 10;

F= 9 7 8 8 8 7 6 8;

G= 6 7 8 8 9 6 7 8;



```

val= 1 1 1 1 1 1 1;
LEV=1;
PC= 20 28 20 20 15 18 25;
HC= 8 11 8 8 6 7 10;
E= 2 5 9 1 1 1 1 2 5 9 1 1 1 1;
Ho=100;
PSC=100000;
M=1000000;
B=10000;
VCAP=2500;
Db=100 1500 1200 2000 2500 2800 3000;
Gb= 1 2 5 5 5 5 5;
wb=1 5 2 1 1 1 1;

EMAX= 193 200 200 200 184 197 195 183 181 195
182 187 200 184 188 192 199 188 192 192;
EMIN= 55 52 55 54 52 50 52 53 50 55
51 55 53 55 53 54 50 55 52 55;
VMAX= 83 83 86 82 89 96 96 94 83 92
94 87 96 84 85 80 94 94 89 91;
VMIN= 46 50 31 30 49 46 48 33 38 42
41 50 45 45 42 38 36 47 36 35;
Prob= 0.034 0.087 0.019 0.006 0.024 0.068 0.027 0.070 0.057 0.020
0.080 0.007 0.024 0.099 0.049 0.099 0.045 0.0015 0.077 0.098;
ENDDATA

```

!Objective Function;

```

MIN= (@SUM( PRODUCTION(T,L) : PC(L) * X(T,L) )) + @SUM( ROUTE : DIST * Z * D ) + @SUM( PRO
DUCT(L) : ( Lb(L) * wb(L) )) + @SUM( ACCUM(T,K,L) : ( HC(L) * N(T,L) )) + @SUM( OMEGA(W)
: Prob(W) * ( @SUM( UNC(T,K,I,W) : ( EM(K) * P(K) ) * V(T,K,I,W) ) + @SUM( UNC(T,K,I,W)
:F(K) * OE(T,K,I,W) ) + @SUM( UNC(T,K,I,W) : G(K) * UE(T,K,I,W) ) ) );

```

!Production Constraints;

!Capacity;

```

@FOR( TIMEPERIOD(T) : @SUM( PRODUCT(L) : X(T,L) ) <= B );

```

!Inventory;

```

@FOR( PRODUCTION(T,L) | T#EQ#1 : H(T,1,L) = ( Ho + X(T,L) - E(T,L) -

```

```

@SUM( LOCATION(K) : A(T,K,L) ) );

```

```

@FOR( PRODUCTION(T,L) | T#GT#1 : H(T,1,L) = ( H(T-1,1,L) + X(T,L) - E(T,L) -

```

```

@SUM( LOCATION(K) : A(T,K,L) ) );

```

```

@FOR( TIMEPERIOD(T) : @SUM( PRODUCT(L) : H(T,1,L) ) <= PSC );

```

```

@FOR( ACCUM(T,K) | K#GT#1 : U(T,K) = ( @SUM( PRODUCT(L) : A(T,K,L) ) );

```

```

@FOR( ACCUM(T,K,L) : A(T,K,L) >= ( LEV * Q(T,K,L) ; ( (

```

!Av Inv Qty;

```

@for( ACCUM(T,K,L) | T#GT#1 : N(T,L) = ( 0.5 * ( H(T-1,K,L) + H(T,K,L) ) ) );

```

```

@for( ACCUM(T,K,L) | T#EQ#1 : N(T,L) = ( 0.5 * ( Ho + H(T,K,L) ) ) );

```

!Scheduling Constraints;

!Completion time, earliness and lateness;

```

@FOR( PRODUCTION(T,L) : Cb(L) >= @SUM( PRODUCT(L) : X(T,L) * Gb(L) ) );

```

```

@FOR( PRODUCTION(T,L) : Cb(L) + sb(L) + Eb(L) - Lb(L) <= Db(L) );

```

!Sequencing;

```

@FOR( TIMEPERIOD(T) : @FOR( PROPRO(L,LL) | L#LT#LL : sb(LL) >= ( sb(L) + (

```

```

@SUM( PRODUCT(L) : X(T,L) * Gb(L) ) ) - @IF( Db(L) #LE#Db(LL) .0.M) * yb(LL,L) );

```

```

@bin( yb(L,LL) ) );

```

```

@FOR (TIMEPERIOD (T) :@FOR (PROPRO (L,LL) |L#LT#LL: sb (L) >= (sb (LL) + (
@SUM (PRODUCT (L) :X (T, L) *Gb (LL) ) ) -@IF (Db (LL) #LE#Db (L) .0 .M) *yb (L,LL) ;
@bin (yb (LL, L) ) ) ) ;
@FOR (PROPRO (L,LL) |L#NE#LL:yb (L,LL) +yb (LL, L) =1) ;
!Switching;
@FOR (PROPRO (L,LL) |L#EQ#LL:yb (L,LL) =0) ;

!Distribution Constraints;
!For all except depot;
@FOR (LOCATION (K) |K) GT#1:@FOR#TIMEPERIOD (T) :
!a vehicle doesn't travel inside itself;
Z (T,K,K)=0) ;
!a vehicle must enter;
@FOR (TIMEPERIOD (T) :@SUM (LOCATION (I) |I#NE#K#AND# (I#EQ#1#OR#
(@SUM (PRODUCT (L) :Q (T, I, L) ) ) + (@SUM (PRODUCT (L) :Q (T, K, L) ) ) #LE#
VCAP) :Z (T, I, K) )=1) ;
!a vehicle must leave;
@FOR (TIMEPERIOD (T) :@SUM (LOCATION (J) |J#NE#K#AND# (J#EQ#1#OR#
(@SUM (PRODUCT (L) :Q (T, J, L) ) ) + (@SUM (PRODUCT (L) :Q (T, K, L) ) ) #LE#
VCAP) :Z (T, K, J) )=1) ;
!capacity;
@FOR (ACCUM (T, K, L) :@BND (Q (T, K, L) . U (T, K) . VCAP) ) ;
!Sequencing;
@FOR (TIMEPERIOD (T) :@FOR (LOCATION (I) |I#NE#K#AND# I#NE#1 :
U (T, K) >=U (T, I) + (@SUM (PRODUCT (L) :Q (T, K, L) ) ) -VCAP+VCAP*
(Z (T, K, I) +Z (T, I, K) ) - ((@SUM (PRODUCT (L) :Q (T, K, L) ) ) +
(@SUM (PRODUCT (L) :Q (T, L, L) ) ) )
*Z (T, K, I) ;
) ) ;
!if K is 1st stop;
@FOR (TIMEPERIOD (T) :U (T, K) <=VCAP- (VCAP-
(@SUM (PRODUCT (L) :Q (T, K, L) ) ) ) *Z (T, 1, K) ) ;
!if K is NOT 1st stop;
@FOR (TIMEPERIOD (T) :U (T, K) >= (@SUM (PRODUCT (L) :Q (T, K, L) ) ) +@SUM (
LOCATION (I) |
I#GT#1: (@SUM (PRODUCT (L) :Q (T, I, L) ) ) *Z (T, I, K) ) ) ;
) ;
!Binary;
@FOR (ROUTE: @BIN (z) ) ;
@FOR (PROPRO: @BIN (yb) ) ;
!Enough Capacity;
@FOR (PRODUCTION (T, L) :@SUM (LOCATION (J) |J#GT#1:Z (T, 1, J) ) >=
@FLOOR ( (@SUM (LOCATION (I) |I#GT#1:Q (T, I, L) ) /VCAP) +0.999) ) ;
!Stochastic;
@FOR (UNC (T, K, I, W) :V (T, K, I, W) >= (VMIN (W) *Z (T, K, I) ) ) ;
@FOR (UNC (T, K, I, W) : (VMAX (W) *Z (T, K, I) ) <=V (T, K, I, W) ) ;
@FOR (UNC (T, K, I, W) :@SUM (LOCATION (K) : (EM (K) *V (T, K, I, W) ) ) =JO (T, K, I, W) ) ;
@FOR (UNC (T, K, I, W) :OE (T, K, I, W) >= (JO (T, K, I, W) - (EMAX (W) *Z (T, K, I) ) ) ) ;
@FOR (UNC (T, K, I, W) :UE (T, K, I, W) >= (EMIN (W) *Z (T, K, I) ) -JO (T, K, I, W) ) ;
END

```

## First Case Study Formulation (30 Scenarios)

SETS:

```

!K; LOCATION/1..8/:EM.P.F.G;
!T; TIMEPERIOD/1..2/;
!L; PRODUCT/1..7/:PC.HC.val.Db.Cb.Lb.Eb.Gb.sb.wb;
!W; OMEGA/1..30/:VMAX.VMIN.EMAX.EMIN.Prob;
!(T.L); PRODUCTION(TIMEPERIOD.PRODUCT):X.E.N;
!(K.K); CXC(LOCATION.LOCATION):DIST.D;
!(T.K.K); ROUTE(TIMEPERIOD.CXC):Z;
!(T.K); ACCUMM(TIMEPERIOD.LOCATION):U;
!(T.K.L); ACCUM(TIMEPERIOD.LOCATION.PRODUCT):H.A.Q;
!(T.K.K.W); UNC(TIMEPERIOD.LOCATION.LOCATION.OMEGA):V.OE.UE.JO;
!(L.LL); PROPRO(PRODUCT.PRODUCT):yb;
ENDSETS

```

!Defining Data;

DATA:

Q=

0	0	0	0	0	0	0
500	0	175	213	400	375	438
180	0	0	0	0	0	0
0	3	0	3	0	0	3
506	0	13	73	83	0	0
23	35	35	35	29	0	0
4	0	0	3	4	0	3
7	3	3	27	7	27	0
0	0	0	0	0	0	0
333	0	117	142	267	250	292
270	0	0	0	0	0	0
0	6	0	6	0	0	6
506	0	13	73	83	0	0
10	15	15	15	13	0	0
3	0	0	4	3	0	4
27	1	13	7	27	7	0;

DIST=

0	135	156	599	428	396	246	375
135	0	202	678	293	281	381	252
156	202	0	476	446	346	298	345
599	678	476	0	876	714	508	742
428	293	446	876	0	180	508	742
396	281	346	714	180	0	627	48
246	381	298	508	508	627	0	613
375	252	345	742	742	48	613	0;

D=

10000	9	4	6	14	9	24	39
9	10000	9	2	32	9	29	44
4	9	10000	52	38	20	51	29
6	2	52	10000	64	9	44	4
14	32	38	64	10000	4	24	2
9	9	20	9	4	10000	24	1
24	29	51	44	24	24	10000	49
39	44	29	4	2	1	49	10000;

P= 6 7 8 8 9 6 7 8;

EM= 10 12 10 12 10 11 12 10;

F= 9 7 8 8 8 7 6 8;

G= 6 7 8 8 9 6 7 8;

```

val= 1 1 1 1 1 1 1;
LEV=1;
PC= 20 28 20 20 15 18 25;
HC= 8 11 8 8 6 7 10;
E= 2 5 9 1 1 1 1 2 5 9 1 1 1 1;
Ho=100;
PSC=100000;
M=1000000;
B=10000;
VCAP=2500;
Db=100 1500 1200 2000 2500 2800 3000;
Gb= 1 2 5 5 5 5 5;
wb=1 5 2 1 1 1 1;

EMAX= 187 186 197 180 193 200 200 200 184 197
      195 183 181 195 195 182 187 200 184 188
      192 199 188 192 192 196 200 189 196 185;
EMIN= 54 54 51 53 55 52 55 54 52 50
      52 53 50 55 55 51 55 53 55 53
      54 50 55 52 55 53 50 55 54 55;
VMAX= 81 89 80 95 83 83 86 82 89 96
      96 94 83 100 92 94 87 96 84 85
      80 94 94 89 91 85 96 81 91 86;
VMIN= 30 32 45 40 46 50 31 30 49 46
      48 33 38 47 42 41 50 45 45 42
      38 36 47 36 35 36 43 30 34 36;
Prob= 0 0 0 0.03995 0.02325 0.03246 0.00377
      0.01845 0.03839 0.03434
      0.01384 0.04494 0.04552 0 0.03066 0.05694
      0.04108 0.04696 0.04353 0.00291
      0.00666 0.02508 0.04079 0.05152 0.00647
      0.00147 0.04615 0.06194 0.04376 0.04288;

```

ENDDATA

!Objective Function;

```

MIN= (@SUM (PRODUCTION (T.L) : PC (L) * X (T.L) )) + @SUM (ROUTE : DIST * Z * D) + @SUM (PRO
DUCT (L) : (Lb (L) * wb (L) )) + @SUM (ACCUM (T.K.L) : (HC (L) * N (T.L) )) + @SUM (OMEGA (W)
: Prob (W) * (@SUM (UNC (T.K.I.W) : (EM (K) * P (K) ) * V (T.K.I.W) ) + @SUM (UNC (T.K.I.W)
: F (K) * OE (T.K.I.W) ) + @SUM (UNC (T.K.I.W) : G (K) * UE (T.K.I.W) )));

```

!Production Constraints;

!Capacity;

```

@FOR (TIMEPERIOD (T) : @SUM (PRODUCT (L) : X (T.L) ) <= B);

```

!Inventory;

```

@FOR (PRODUCTION (T.L) | T#EQ#1 : H (T.1.L) = (Ho + X (T.L) - E (T.L) -

```

```

@SUM (LOCATION (K) : A (T.K.L) ));

```

```

@FOR (PRODUCTION (T.L) | T#GT#1 : H (T.1.L) = (H (T-1.1.L) + X (T.L) - E (T.L) -

```

```

@SUM (LOCATION (K) : A (T.K.L) ));

```

```

@FOR (TIMEPERIOD (T) : @SUM (PRODUCT (L) : H (T.1.L) ) <= PSC);

```

```

@FOR (ACCUM (T.K) | K#GT#1 : U (T.K) = (< (SUM) PRODUCT (L) : A (T.K.L) ));

```

```

@FOR (ACCUM (T.K.L) : A (T.K.L) >= (LEV * Q (T.K.L); ( (

```

!Av Inv Qty;

```

@for (ACCUM (T.K.L) | T#GT#1 : N (T.L) = (0.5 * (H (T-1.K.L) + H (T.K.L) )));

```

```

@for (ACCUM (T.K.L) | T#EQ#1 : N (T.L) = (0.5 * (Ho + H (T.K.L) )));

```

!Scheduling Constraints;

```

!Completion time, earliness and lateness;
@FOR (PRODUCTION (T, L) : Cb (L) >=@SUM (PRODUCT (L) : X (T, L) *Gb (L) ) ) ;
@FOR (PRODUCTION (T, L) : Cb (L) +sb (L) +Eb (L) -Lb (L) <=Db (L) ) ;
!Sequencing;
@FOR (TIMEPERIOD (T) :@FOR (PROPRO (L, LL) | L#LT#LL : sb (LL) >= (sb (L) + (
@SUM (PRODUCT (L) : X (T, L) *Gb (L) ) ) ) -@IF (Db (L) #LE#Db (LL) .0.M) *yb (LL, L) ) ;
@bin (yb (L, LL) ) ) ) ;
@FOR (TIMEPERIOD (T) :@FOR (PROPRO (L, LL) | L#LT#LL : sb (L) >= (sb (LL) + (
@SUM (PRODUCT (L) : X (T, L) *Gb (LL) ) ) ) -@IF (Db (LL) #LE#Db (L) .0.M) *yb (L, LL) ) ;
@bin (yb (LL, L) ) ) ) ;
@FOR (PROPRO (L, LL) | L#NE#LL : yb (L, LL) +yb (LL, L) =1) ;
!Switching;
@FOR (PROPRO (L, LL) | L#EQ#LL : yb (L, LL) =0) ;

!Distribution Constraints;
!For all except depot;
@FOR (LOCATION (K) | K) GT#1 :@FOR#TIMEPERIOD (T) :
!a vehicle doesn't travel inside itself;
Z (T, K, K) =0) ;
!a vehicle must enter;
@FOR (TIMEPERIOD (T) :@SUM (LOCATION (I) | I#NE#K#AND# (I#EQ#1#OR#
(@SUM (PRODUCT (L) : Q (T, I, L) ) ) + (@SUM (PRODUCT (L) : Q (T, K, L) ) ) #LE#
VCAP) : Z (T, I, K) ) =1) ;
!a vehicle must leave;
@FOR (TIMEPERIOD (T) :@SUM (LOCATION (J) | J#NE#K#AND# (J#EQ#1#OR#
(@SUM (PRODUCT (L) : Q (T, J, L) ) ) + (@SUM (PRODUCT (L) : Q (T, K, L) ) ) #LE#
VCAP) : Z (T, K, J) ) =1) ;
!capacity;
@FOR (ACCUM (T, K, L) :@BND (Q (T, K, L) . U (T, K) . VCAP) ) ;
!Sequencing;
@FOR (TIMEPERIOD (T) :@FOR (LOCATION (I) | I#NE#K#AND# I#NE#1 :
U (T, K) >=U (T, I) + (@SUM (PRODUCT (L) : Q (T, K, L) ) ) -VCAP+VCAP*
(Z (T, K, I) +Z (T, I, K) ) - ( (@SUM (PRODUCT (L) : Q (T, K, L) ) ) +
(@SUM (PRODUCT (L) : Q (T, L, L) ) ) )
)*Z (T, K, I) ;
) ) ;
!if K is 1st stop;
@FOR (TIMEPERIOD (T) :U (T, K) <=VCAP- (VCAP-
(@SUM (PRODUCT (L) : Q (T, K, L) ) ) ) *Z (T, 1, K) ) ;
!if K is NOT 1st stop;
@FOR (TIMEPERIOD (T) :U (T, K) >= (@SUM (PRODUCT (L) : Q (T, K, L) ) ) +@SUM (
LOCATION (I) |
I#GT#1 : (@SUM (PRODUCT (L) : Q (T, I, L) ) ) *Z (T, I, K) ) ) ;
) ;
!Binary;
@FOR (ROUTE : @BIN (z) ) ;
@FOR (PROPRO : @BIN (yb) ) ;
!Enough Capacity;
@FOR (PRODUCTION (T, L) :@SUM (LOCATION (J) | J#GT#1 : Z (T, 1, J) ) >=
@FLOOR ( (@SUM (LOCATION (I) | I#GT#1 : Q (T, I, L) ) /VCAP) ) +0.999) ) ;
!Stochastic;
@FOR (UNC (T, K, I, W) :V (T, K, I, W) >= (VMIN (W) *Z (T, K, I) ) ) ;
@FOR (UNC (T, K, I, W) : (VMAX (W) *Z (T, K, I) ) <=V (T, K, I, W) ) ;
@FOR (UNC (T, K, I, W) :@SUM (LOCATION (K) : (EM (K) *V (T, K, I, W) ) ) =JO (T, K, I, W) ) ;
@FOR (UNC (T, K, I, W) :OE (T, K, I, W) >= (JO (T, K, I, W) - (EMAX (W) *Z (T, K, I) ) ) ) ;
@FOR (UNC (T, K, I, W) :UE (T, K, I, W) >= (EMIN (W) *Z (T, K, I) ) -JO (T, K, I, W) ) ;
END

```

## First Case Study Formulation (40 Scenarios)

```

SETS:
!K;      LOCATION/1..8/:EM.P.F.G;
!T;      TIMEPERIOD/1..2/;
!L;      PRODUCT/1..7/:PC.HC.val.Db.Cb.Lb.Eb.Gb.sb.wb;
!W;      OMEGA/1..40/:VMAX.VMIN.EMAX.EMIN.Prob;
!(T.L);  PRODUCTION(TIMEPERIOD.PRODUCT):X.E.N;
!(K.K);  CXC(LOCATION.LOCATION):DIST.D;
!(T.K.K); ROUTE(TIMEPERIOD.CXC):Z;
!(T.K);  ACCUMM(TIMEPERIOD.LOCATION):U;
!(T.K.L); ACCUM(TIMEPERIOD.LOCATION.PRODUCT):H.A.Q;
!(T.K.K.W); UNC(TIMEPERIOD.LOCATION.LOCATION.OMEGA):V.OE.UE.JO;
!(L.LL);  PROPRO(PRODUCT.PRODUCT):yb;
ENDSETS

!Defining Data;
DATA:
Q=
    0      0      0      0      0      0      0
    500    0      175    213    400    375    438
    180    0      0      0      0      0      0
    0      3      0      3      0      0      3
    506    0      13     73     83     0      0
    23     35     35     35     29     0      0
    4      0      0      3      4      0      3
    7      3      3      27    7      27     0
    0      0      0      0      0      0      0
    333    0      117    142    267    250    292
    270    0      0      0      0      0      0
    0      6      0      6      0      0      6
    506    0      13     73     83     0      0
    10     15     15     15     13     0      0
    3      0      0      4      3      0      4
    27     1      13     7      27     7      0;

DIST=
    0      135    156    599    428    396    246    375
    135    0      202    678    293    281    381    252
    156    202    0      476    446    346    298    345
    599    678    476    0      876    714    508    742
    428    293    446    876    0      180    508    742
    396    281    346    714    180    0      627    48
    246    381    298    508    508    627    0      613
    375    252    345    742    742    48    613    0;

D=
    10000  9      4      6      14     9      24     39
    9      10000 9      2      32     9      29     44
    4      9      10000 52     38     20     51     29
    6      2      52     10000 64     9      44     4
    14     32     38     64     10000 4      24     2
    9      9      20     9      4      10000 24     1
    24     29     51     44     24     24     10000 49
    39     44     29     4      2      1      49     10000;

P= 6 7 8 8 9 6 7 8;
EM= 10 12 10 12 10 11 12 10;
F= 9 7 8 8 8 7 6 8;
G= 6 7 8 8 9 6 7 8;
val= 1 1 1 1 1 1 1 1;

```

```

LEV=1;
PC= 20 28 20 20 15 18 25;
HC= 8 11 8 8 6 7 10;
E= 2 5 9 1 1 1 1 2 5 9 1 1 1 1;
Ho=100;
PSC=100000;
M=1000000;
B=10000;
VCAP=2500;
Db=100 1500 1200 2000 2500 2800 3000;
Gb= 1 2 5 5 5 5 5;
wb=1 5 2 1 1 1 1;

EMAX= 195 191 199 194 199 181 194 185 182 200
      190 191 180 194 198 190 190 190 188 192
      180 186 198 198 199 191 181 183 192 196
      188 192 180 183 189 197 198 181 189 189;

EMIN= 55 54 51 53 54 50 53 54 55 51
      55 53 55 53 54 52 51 51 51 52
      51 51 54 55 50 53 51 55 54 52
      55 52 54 54 51 55 50 50 52 50;
VMIN= 39 30 43 39 43 43 31 31 48 32
      42 41 35 45 35 45 34 38 44 31
      33 30 30 45 45 49 38 34 32 37
      45 31 38 32 31 35 40 32 38 40;
VMAX= 100 95 100 93 87 84 92 100 87 84
      100 93 96 97 89 85 87 97 98 91
      83 98 94 98 100 85 86 86 85 87
      80 85 92 100 98 91 96 93 81 98;

Prob= 0.01063 0.02391 0.0016 0.02073 0.03322
      0.01412 0.03817 0.03703 0.03773 0.03183
      0.03818 0.00285 0.03856 0.02452 0.00574
      0.01356 0.00122 0.03558 0.01838 0.01067
      0.02455 0.02045 0.02858 0.02148 0.00082
      0.00725 0.00875 0.07109 0.03818 0.00638
      0.03401 0.02408 0.02714 0.02781 0.00612
      0.02034 0.03873 0.00089 0.03752 0.02152;

```

ENDDATA

!Objective Function;

```

MIN= (@SUM (PRODUCTION (T.L) : PC (L) * X (T.L) )) + @SUM (ROUTE : DIST * Z * D) + @SUM (PRO
DUCT (L) : (Lb (L) * wb (L) )) + @SUM (ACCUM (T.K.L) : (HC (L) * N (T.L) )) + @SUM (OMEGA (W)
: Prob (W) * (@SUM (UNC (T.K.I.W) : (EM (K) * P (K) ) * V (T.K.I.W) )) + @SUM (UNC (T.K.I.W)
: F (K) * OE (T.K.I.W) ) + @SUM (UNC (T.K.I.W) : G (K) * UE (T.K.I.W) ) ) ) ;

```

!Production Constraints;

!Capacity;

```

@FOR (TIMEPERIOD (T) : @SUM (PRODUCT (L) : X (T.L) ) <= B) ;

```

!Inventory;

```

@FOR (PRODUCTION (T.L) | T#EQ#1 : H (T.L) = (Ho + X (T.L) - E (T.L) -
@SUM (LOCATION (K) : A (T.K.L) ) ) ;

```

```

@FOR (PRODUCTION (T.L) | T#GT#1 : H (T.L) = (H (T-1.L) + X (T.L) - E (T.L) -
@SUM (LOCATION (K) : A (T.K.L) ) ) ;

```

```

@FOR (TIMEPERIOD (T) : @SUM (PRODUCT (L) : H (T.L) ) <= PSC) ;

```

```

@FOR (ACCUM (T.K) | K#GT#1 : U (T.K) = (< (SUM) PRODUCT (L) : A (T.K.L) ) ) ;

```

```

@FOR (ACCUM (T.K.L) : A (T.K.L) >= (LEV * Q (T.K.L) ; ( ( (

```

```

!Av Inv Qty;
@for (ACCUM(T.K.L) | T#GT#1:N(T.L) = (0.5* (H(T-1.K.L) +H(T.K.L) ) ) );
@for (ACCUM(T.K.L) | T#EQ#1:N(T.L) = (0.5* (Ho+H(T.K.L) ) ) );

!Scheduling Constraints;
!Completion time, earliness and lateness;
@FOR (PRODUCTION(T.L) :Cb(L) >=@SUM (PRODUCT(L) :X(T.L) *Gb(L) ) );
@FOR (PRODUCTION(T.L) :Cb(L) +sb(L) +Eb(L) -Lb(L) <=Db(L) );
!Sequencing;
@FOR (TIMEPERIOD(T) :@FOR (PROPRO(L.LL) | L#LT#LL: sb(LL) >= (sb(L) + (
@SUM (PRODUCT(L) :X(T.L) *Gb(L) ) ) ) -@IF (Db(L) #LE#Db(LL) .0.M) *yb(LL.L) ;
@bin (yb(L.LL) ) ) );
@FOR (TIMEPERIOD(T) :@FOR (PROPRO(L.LL) | L#LT#LL: sb(L) >= (sb(LL) + (
@SUM (PRODUCT(L) :X(T.L) *Gb(LL) ) ) ) -@IF (Db(LL) #LE#Db(L) .0.M) *yb(L.LL) ;
@bin (yb(LL.L) ) ) );
@FOR (PROPRO(L.LL) | L#NE#LL: yb(L.LL) +yb(LL.L) =1) ;
!Switching;
@FOR (PROPRO(L.LL) | L#EQ#LL: yb(L.LL) =0) ;

!Distribution Constraints;
!For all except depot;
@FOR (LOCATION(K) | K) GT#1: @FOR#TIMEPERIOD(T) :
!a vehicle doesn't travel inside itself;
Z(T.K.K) =0) ;
!a vehicle must enter;
@FOR (TIMEPERIOD(T) :@SUM (LOCATION(I) | I#NE#K#AND# (I#EQ#1#OR#
(@SUM (PRODUCT(L) :Q(T.I.L) ) ) + (@SUM (PRODUCT(L) :Q(T.K.L) ) ) #LE#
VCAP) :Z(T.I.K) ) =1) ;
!a vehicle must leave;
@FOR (TIMEPERIOD(T) :@SUM (LOCATION(J) | J#NE#K#AND# (J#EQ#1#OR#
(@SUM (PRODUCT(L) :Q(T.J.L) ) ) + (@SUM (PRODUCT(L) :Q(T.K.L) ) ) #LE#
VCAP) :Z(T.K.J) ) =1) ;
!capacity;
@FOR (ACCUM(T.K.L) :@BND (Q(T.K.L) . U(T.K) . VCAP) );
!Sequencing;
@FOR (TIMEPERIOD(T) :@FOR (LOCATION(I) | I#NE#K#AND# I#NE#1:
U(T.K) >=U(T.I) + (@SUM (PRODUCT(L) :Q(T.K.L) ) ) -VCAP+VCAP*
(Z(T.K.I) +Z(T.I.K) ) - ((@SUM (PRODUCT(L) :Q(T.K.L) ) ) +
(@SUM (PRODUCT(L) :Q(T.L.L) ) ) )
)*Z(T.K.I) ;
) );
!if K is 1st stop;
@FOR (TIMEPERIOD(T) :U(T.K) <=VCAP- (VCAP-
(@SUM (PRODUCT(L) :Q(T.K.L) ) ) ) *Z(T.I.K) );
!if K is NOT 1st stop;
@FOR (TIMEPERIOD(T) :U(T.K) >= (@SUM (PRODUCT(L) :Q(T.K.L) ) ) +@SUM (
LOCATION(I) |
I#GT#1: (@SUM (PRODUCT(L) :Q(T.I.L) ) ) *Z(T.I.K) ) ) ;
) );
!Binary;
@FOR (ROUTE: @BIN (z) );
@FOR (PROPRO: @BIN (yb) );
!Enough Capacity;
@FOR (PRODUCTION(T.L) :@SUM (LOCATION(J) | J#GT#1: Z(T.I.J) ) >=
@FLOOR ( (@SUM (LOCATION(I) | I#GT#1:Q(T.I.L) /VCAP) ) +0.999) );
!Stochastic;
@FOR (UNC(T.K.I.W) :V(T.K.I.W) >= (VMIN(W) *Z(T.K.I) ) );
@FOR (UNC(T.K.I.W) : (VMAX(W) *Z(T.K.I) ) <=V(T.K.I.W) );

```



```
@FOR (UNC (T.K.I.W) : @SUM (LOCATION (K) : (EM (K) * V (T.K.I.W) ) ) = JO (T.K.I.W) ) ;  
@FOR (UNC (T.K.I.W) : OE (T.K.I.W) >= (JO (T.K.I.W) - (EMAX (W) * Z (T.K.I) ) ) ) ;  
@FOR (UNC (T.K.I.W) : UE (T.K.I.W) >= (EMIN (W) * Z (T.K.I) ) - JO (T.K.I.W) ) ;  
END
```

## First Case Study Formulation (50 Scenarios)

```

SETS:
!K;      LOCATION/1..8/:EM.P.F.G;
!T;      TIMEPERIOD/1..2/;
!L;      PRODUCT/1..7/:PC.HC.val.Db.Cb.Lb.Eb.Gb.sb.wb;
!W;      OMEGA/1..50/:VMAX.VMIN.EMAX.EMIN.Prob;
!(T.L);  PRODUCTION(TIMEPERIOD.PRODUCT):X.E.N;
!(K.K);  CXC(LOCATION.LOCATION):DIST.D;
!(T.K.K); ROUTE(TIMEPERIOD.CXC):Z;
!(T.K);  ACCUMM(TIMEPERIOD.LOCATION):U;
!(T.K.L); ACCUM(TIMEPERIOD.LOCATION.PRODUCT):H.A.Q;
!(T.K.K.W); UNC(TIMEPERIOD.LOCATION.LOCATION.OMEGA):V.OE.UE.JO;
!(L.LL);  PROPRO(PRODUCT.PRODUCT):yb;
ENDSETS

!Defining Data;
DATA:
Q=
    0      0      0      0      0      0      0
    500    0      175    213    400    375    438
    180    0      0      0      0      0      0
    0      3      0      3      0      0      3
    506    0      13     73     83     0      0
    23     35     35     35     29     0      0
    4      0      0      3      4      0      3
    7      3      3      27    7      27     0
    0      0      0      0      0      0      0
    333    0      117    142    267    250    292
    270    0      0      0      0      0      0
    0      6      0      6      0      0      6
    506    0      13     73     83     0      0
    10     15     15     15     13     0      0
    3      0      0      4      3      0      4
    27     1      13     7      27     7      0;
DIST=
    0      135    156    599    428    396    246    375
    135    0      202    678    293    281    381    252
    156    202    0      476    446    346    298    345
    599    678    476    0      876    714    508    742
    428    293    446    876    0      180    508    742
    396    281    346    714    180    0      627    48
    246    381    298    508    508    627    0      613
    375    252    345    742    742    48    613    0;
D=
    10000  9      4      6      14     9      24     39
    9      10000 9      2      32     9      29     44
    4      9      10000 52     38     20     51     29
    6      2      52     10000 64     9      44     4
    14     32     38     64     10000 4      24     2
    9      9      20     9      4      10000 24     1
    24     29     51     44     24     24     10000 49
    39     44     29     4      2      1      49     10000;
P= 6 7 8 8 9 6 7 8;
EM= 10 12 10 12 10 11 12 10;
F= 9 7 8 8 8 7 6 8;
G= 6 7 8 8 9 6 7 8;
val= 1 1 1 1 1 1 1 1;

```

```

LEV=1;
PC= 20 28 20 20 15 18 25;
HC= 8 11 8 8 6 7 10;
E= 2 5 9 1 1 1 1 2 5 9 1 1 1 1;
Ho=100;
PSC=100000;
M=1000000;
B=10000;
VCAP=2500;
Db=100 1500 1200 2000 2500 2800 3000;
Gb= 1 2 5 5 5 5 5;
wb=1 5 2 1 1 1 1;

EMAX= 195 191 199 194 199 181 194 185 182 200
      190 191 180 194 198 190 190 190 188 192
      180 186 198 198 199 191 181 183 192 196
      188 192 180 183 189 197 198 181 189 189
      185 192 185 195 200 191 198 181 189 196;
EMIN= 55 54 51 53 54 50 53 54 55 51
      55 53 55 53 54 52 51 51 51 52
      51 51 54 55 50 53 51 55 54 52
      55 52 54 54 51 55 50 50 52 50
      55 53 51 51 55 50 53 55 54 52;
VMAX= 100 95 100 93 87 84 92 100 87 84
      100 93 96 97 89 85 87 97 98 91
      83 98 94 98 100 85 86 86 85 87
      80 85 92 100 98 91 96 93 81 80
      87 100 94 84 84 95 91 96 88 94;
VMIN= 39 30 43 39 43 43 31 31 48 32
      42 41 35 45 35 45 34 38 44 31
      33 30 30 45 45 49 38 34 32 37
      45 31 38 32 31 35 40 32 38 46
      39 36 31 49 33 32 35 48 49 50;
Prob= 0 0 0 0.01063 0.02391 0.0016 0.02073
      0.03322 0.01412 0.03817
      0.03703 0.03773 0.03183 0 0.03818 0.00285
      0.03856 0.02452 0.00574 0.01356
      0.00122 0.03558 0.01838 0.01067 0.02455
      0.02045 0.02858 0.02148 0.00082 0.00725
      0.00875 0 0.03073 0.03589 0.00138 0.00163
      0.00146 0.03818 0.00638 0.03401
      0.02408 0.02714 0.02781 0.00612 0.02034
      0.03873 0.00089 0.03752 0.02152 0.00553;

ENDDATA

!Objective Function;
MIN= (@SUM (PRODUCTION (T.L) : PC (L) * X (T.L) )) + @SUM (ROUTE : DIST * Z * D) + @SUM (PRO
DUCT (L) : (Lb (L) * wb (L) )) + @SUM (ACCUM (T.K.L) : (HC (L) * N (T.L) )) + @SUM (OMEGA (W)
: Prob (W) * (@SUM (UNC (T.K.I.W) : (EM (K) * P (K) ) * V (T.K.I.W) ) + @SUM (UNC (T.K.I.W)
: F (K) * OE (T.K.I.W) ) + @SUM (UNC (T.K.I.W) : G (K) * UE (T.K.I.W) )));

!Production Constraints;
!Capacity;
@FOR (TIMEPERIOD (T) : @SUM (PRODUCT (L) : X (T.L) ) <= B);
!Inventory;
@FOR (PRODUCTION (T.L) | T#EQ#1 : H (T.L) = (Ho + X (T.L) - E (T.L) -
@SUM (LOCATION (K) : A (T.K.L) ));

```

```

@FOR (PRODUCTION (T.L) | T#GT#1 : H (T.1.L) = (H (T-1.1.L) + X (T.L) - E (T.L) -
@SUM (LOCATION (K) : A (T.K.L) ) ) ;
@FOR (TIMEPERIOD (T) : @SUM (PRODUCT (L) : H (T.1.L) ) <= PSC ;
@FOR (ACCUMM (T.K) | K#GT#1 : U (T.K) = < (SUM) PRODUCT (L) : A (T.K.L) ) ) ;
@FOR (ACCUM (T.K.L) : A (T.K.L) >= (LEV * Q (T.K.L) ; ( (
!Av Inv Qty;
@for (ACCUM (T.K.L) | T#GT#1 : N (T.L) = (0.5 * (H (T-1.K.L) + H (T.K.L) ) ) ) ;
@for (ACCUM (T.K.L) | T#EQ#1 : N (T.L) = (0.5 * (Ho + H (T.K.L) ) ) ) ;

!Scheduling Constraints;
!Completion time, earliness and lateness;
@FOR (PRODUCTION (T.L) : Cb (L) >= @SUM (PRODUCT (L) : X (T.L) * Gb (L) ) ) ;
@FOR (PRODUCTION (T.L) : Cb (L) + sb (L) + Eb (L) - Lb (L) <= Db (L) ) ;
!Sequencing;
@FOR (TIMEPERIOD (T) : @FOR (PROPRO (L.LL) | L#LT#LL : sb (LL) >= (sb (L) + (
@SUM (PRODUCT (L) : X (T.L) * Gb (L) ) ) - @IF (Db (L) #LE#Db (LL) . 0 . M) * yb (LL.L) ;
@bin (yb (L.LL) ) ) ) ;
@FOR (TIMEPERIOD (T) : @FOR (PROPRO (L.LL) | L#LT#LL : sb (L) >= (sb (LL) + (
@SUM (PRODUCT (L) : X (T.L) * Gb (LL) ) ) ) - @IF (Db (LL) #LE#Db (L) . 0 . M) * yb (L.LL) ;
@bin (yb (LL.L) ) ) ) ;
@FOR (PROPRO (L.LL) | L#NE#LL : yb (L.LL) + yb (LL.L) = 1 ) ;
!Switching;
@FOR (PROPRO (L.LL) | L#EQ#LL : yb (L.LL) = 0 ) ;

!Distribution Constraints;
!For all except depot;
@FOR (LOCATION (K) | K) GT#1 : @FOR #TIMEPERIOD (T) :
!a vehicle doesn't travel inside itself;
Z (T.K.K) = 0 ) ;
!a vehicle must enter;
@FOR (TIMEPERIOD (T) : @SUM (LOCATION (I) | I#NE#K#AND# (I#EQ#1#OR#
(@SUM (PRODUCT (L) : Q (T.I.L) ) ) + (@SUM (PRODUCT (L) : Q (T.K.L) ) ) ) #LE#
VCAP) : Z (T.I.K) ) = 1 ) ;
!a vehicle must leave;
@FOR (TIMEPERIOD (T) : @SUM (LOCATION (J) | J#NE#K#AND# (J#EQ#1#OR#
(@SUM (PRODUCT (L) : Q (T.J.L) ) ) + (@SUM (PRODUCT (L) : Q (T.K.L) ) ) ) #LE#
VCAP) : Z (T.K.J) ) = 1 ) ;
!capacity;
@FOR (ACCUM (T.K.L) : @BND (Q (T.K.L) . U (T.K) . VCAP) ) ;
!Sequencing;
@FOR (TIMEPERIOD (T) : @FOR (LOCATION (I) | I#NE#K#AND# I#NE#1 :
U (T.K) >= U (T.I) + (@SUM (PRODUCT (L) : Q (T.K.L) ) ) - VCAP + VCAP *
(Z (T.K.I) + Z (T.I.K) ) - ((@SUM (PRODUCT (L) : Q (T.K.L) ) ) +
(@SUM (PRODUCT (L) : Q (T.L.L) ) ) )
* Z (T.K.I) ;
) ) ;
!if K is 1st stop;
@FOR (TIMEPERIOD (T) : U (T.K) <= VCAP - (VCAP -
(@SUM (PRODUCT (L) : Q (T.K.L) ) ) ) * Z (T.1.K) ) ;
!if K is NOT 1st stop;
@FOR (TIMEPERIOD (T) : U (T.K) >= (@SUM (PRODUCT (L) : Q (T.K.L) ) ) + @SUM (
LOCATION (I) |
I#GT#1 : (@SUM (PRODUCT (L) : Q (T.I.L) ) ) * Z (T.I.K) ) ) ;
) ;
!Binary;
@FOR (ROUTE : @BIN (z) ) ;
@FOR (PROPRO : @BIN (yb) ) ;
!Enough Capacity;

```

```

@FOR (PRODUCTION (T.L) : @SUM (LOCATION (J) | J#GT#1 : Z (T.L.J) ) >=
@FLOOR ( ( @SUM (LOCATION (I) | I#GT#1 : Q (T.I.L) /VCAP ) +0.999 ) );
!Stochastic;
@FOR (UNC (T.K.I.W) : V (T.K.I.W) >= (VMIN (W) *Z (T.K.I) ) );
@FOR (UNC (T.K.I.W) : (VMAX (W) *Z (T.K.I) ) <=V (T.K.I.W) );
@FOR (UNC (T.K.I.W) : @SUM (LOCATION (K) : (EM (K) *V (T.K.I.W) ) ) =JO (T.K.I.W) );
@FOR (UNC (T.K.I.W) : OE (T.K.I.W) >= (JO (T.K.I.W) - (EMAX (W) *Z (T.K.I) ) ) );
@FOR (UNC (T.K.I.W) : UE (T.K.I.W) >= (EMIN (W) *Z (T.K.I) ) -JO (T.K.I.W) );
END

```