Modelling and determining inventory decisions for improved sustainability in perishable food supply chains

Submitted by

Arjaree Saengsathien to the University of Exeter as a thesis for the degree of Doctor of Philosophy in Engineering

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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ABSTRACT

Since the introduction of sustainable development, industries have witnessed significant sustainability challenges. Literature shows that the food industry is concerned about its need for efficient and effective management practices in dealing with perishability and the requirements for conditioned storage and transport of food products that effect the environment. Hence, the environmental part of sustainability demonstrates its significance in this industrial sector. Despite this, there has been little research into environmentally sustainable inventory management of deteriorating items.

This thesis presents mathematical modelling based research for production inventory systems in perishable food supply chains. In this study, multi-objective mixed-integer linear programming models are developed to determine economically and environmentally optimal production and inventory decisions for a two-echelon supply chain. The supply chain consists of single sourcing suppliers for raw materials and a producer who operates under a make-to-stock or make-to-order strategy. The demand facing the producer is non-stationary stochastic in nature and has requirements in terms of service level and the remaining shelf life of the marketed products.

Using data from the literature, numerical examples are given in order to test and analyse these models. The computational experiments show that operational adjustments in cases where emission and cost parameters were not strongly correlated with supply chain collaboration (where suppliers and a producer operate under centralised control), emissions are effectively reduced without a significant increase in cost. The findings show that assigning a high disposal cost, limit or high weight of importance to perished goods leads to appropriate reduction of expected waste in the supply chain with no major cost increase.

The research has made contributions to the literature on sustainable production and inventory management; providing formal models that can be used as an aid to understanding and as a tool for planning and improving sustainable production and inventory control in supply chains involving deteriorating items, in particular with perishable food supply chains.

Keywords: supply chain management, inventory, production, sustainability, perishability, food supply chain, waste, emission, multi-objective optimisation

DEDICATION

To my family.

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GLOSSARY OF TERMS

3PLs	Third-Party Logistics
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ASC	Agile Supply Chain
BOM	Bill of Materials
CLM	American Council of Logistics Management
CP	Constriant Programming
CSCMP	Council of Supply Chain Management Professionals
CV	Coefficient of Variation
DEA	Data Envelopment Analysis
DES	Discrete-Event Simulation
EOQ	Economic Order Quantity
EPA	Environmental Protection Agency
ERP	Enterprise Resource Planning
FIFO	First-In-First-Out
GHG	Greenhouse Gas
GP	Goal Programming
GPS	Global Positioning Systems
HSC	Hybrid Supply Chain
IOA	Input-Output-Analysis
JIT	Just-In-Time
LCA	Life Cycle Assessment
LIFO	Last-In-Last-Out
LP	Linear Programming

LSC	Lean Supply Chain
MAP	Markovian Arrival Process
MILP	Mixed Integer Linear Programming
MOLP	Multi-Objective Linear Programming
mo-MILP	Multi-Objective Mixed Integer Linear Programming
MPS	Master Production Schedule
MRP	Material Requirements Planning
MRPII	Manufacturing Resource Planning
MTO	Make-to-order
MTS	Make-to-stock
OIR	Old Inventory Ratio
OR	Operational Research
PPP	Profit, Planet and the People
RFID	Radio Frequency Identification
SC	Supply Chain
SCM	Supply Chain Management
SCN	Supply Chain Network
TQM	Total Quality Management
TTI	Time Temperature Integrator Technology
WEEE	Waste Electrical and Electronic Equipment
WIP	Work-In-Process Inventory

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Ren Z., Saengsathien A., Zhang D.Z. (2013). Modeling and optimization of inventory and sourcing decisions with risk assessment in perishable food supply chains, The IEEM International Conference on Industrial Engineering and Engineering Management, 10 – 13 December 2013, Bangkok, Thailand.

Saengsathien A. and Zhang D.Z. (2013). Modelling of production, distribution and inventory decisions in perishable food supply chains, The OR Society, OR 55 Conference Handbook, 3 - 5 September 2013, The University of Exeter, Streatham Campus, Exeter, 103.

Saengsathien A. and Zhang, D.Z. (2012), An inventory and sourcing decisions model with a temporary price discount for improved sustainability in food supply chains, The 17th International Symposium on Inventories Book of Abstracts 20 - 24 Aug 2012, Budapest, Hungary, 149.

Saengsathien A. and Zhang D.Z. (2012) Modeling and determining inventory and sourcing decisions for improved sustainability in food supply chains, The 17th International Working Seminar on Production Economics Proceedings 20 - 24 Feb 2012, Innsbruck, Austria, volume 3, 357-368.

Chapter 1 Introduction

1.1 Introduction

This chapter provides an overview of the research. A brief description of research background is presented in Section 1.2. Research problems and questions are discussed in Section 1.3 and the objectives of this PhD research are given in Section 1.4. Section 1.5 explains the organisation of this thesis and Section 1.6 concludes this chapter.

This chapter gives an introduction to the area of managing a supply chain for perishable food products and, in particular, its relation to the environment. Therefore, the management of this SC that aims towards fulfilling customer and stakeholder requirements in environmental dimension of sustainable development defines its sustainability. The rising significance of environmental sustainability has supported the need of sustainable models for production planning and inventory control such as the ones which were developed in this research. These models can be used as an aid to understanding and as a tool for planning and improving production and inventory control en route for CO_2 emission and perished food reductions.

1.2 Research Background

With the development of globalisation along with more variable and unpredictable customer behaviour, the competitive market has been gradually moving towards the supply chain (SC) level rather than remaining at the company level as it was before (Lambert et al., 1998). A network of companies cooperating together is named as an SC. In order to survive in this competitive environment, the management of an SC has to be optimised in the direction of efficient planning (Chopra and Meindl, 2013). Traditionally, SC planning focuses on the efficiency aspect in minimising cost or maximising the service level of SCs. Due to the uncertainty in SCs, service level is a way of measuring product availability. It is used to evaluate and guarantee the performance of a business.

In addition, SC efficiency can be significantly affected by inventory, one of the drivers of SC performance. Inventory cost comprises a number of costs not giving added value to the product but which assure that customer demand can be satisfied from the ready and available products (Chopra and Meindl, 2013).

Owing to the possibility of demand changes, unreliable demand forecasts, inaccurate data, production delays or replenishment disruptions, there is a chance of having a stock-out. Stock-out is a situation when an item that is to be used for a customer order or for a production order is not in stock when required (Arrow, 1958). Consequently, inventory is held to avoid this. Inventory costs commonly consist of ordering cost and carrying or holding cost (Tersine, 1994). However, in complex environments and for complex products, it can also be relevant to consider other costs such as a stock-out cost, backorder cost, pipeline cost, damage cost, transportation cost and deterioration cost, as well as cost resulting from money tied up in stock (interest charges) (Krajewski et al., 2007, Langley et al., 2009, Slack et al., 2010). With the aim of reducing these costs, managers should act in a way that lowers the amount of inventory needed. This is called inventory management. Therefore, a determination of when the products are ordered and how many products will be ordered per order cycle is required. When making these decisions, managers should bear in mind that a high level of inventory makes inventory costs higher but a low level of inventory may result in lost sales which lead to low customer service level.

Furthermore, there have been increasing demands on companies to pay more attention to the consequences to the environment and resources from the products and services they offer and the processes they deploy (Kleindorfer et al., 2005). This promotes new challenges in integrating issues of sustainability with the traditional efficiency-based SC planning. For that reason, inventory modelling should be aimed at optimising SC profit as a whole, as well as being able to evaluate the sustainability of the SC.

Thus, this research is undertaken to develop a better understanding of the subject area; to identify information, ideas and/or methods that may be relevant to the research project and then to build and/or extend the new production and inventory modelling based on the knowledge gained. Food SC networks are of particular interest. The field of food supply chain management has undergone tremendous changes. In the 20th century, it was once considered the last frontier of cost reduction. Now, it has become a major strategic issue for companies in the new millennium (Bourlakis and Weightman, 2004). Since the research subject of this thesis is the food SC, the typical characteristics of food SCs is discussed below.

1.2.1 Food supply chain

Today, food industries are moving towards an interconnected system linking a mixture of diverse relationships. Food SCs bring together organisations that are responsible for the production, processing, distribution and the disposal of vegetable or animal-based products (van der Vorst, 2000, Trienekens and Zuurbier, 2008, Ahumada and Villalobos, 2009). Exploring the types of products, van der Vorst et al. (2009) distinguish food SCs into:

1. Supply chains for fresh farm products. Growers, breeders, auctions, wholesalers, importers and exporters, retailers and specialty shops and their logistics service suppliers are the potential parties for these chains in which the handling, (conditioned) storing, packing, transportation, and trading of these products are fulfilled; see Figure 1.1. Basically, all of these stages leave the intrinsic characteristics of the product grown or produced on a farm unharmed, except for the product quality that depends on the environmental conditions. Over time, the product quality can either increase (e.g., if fruit ripens) or decrease (e.g., if harvested at a mature stage).
2. Supply chains for processed food products. This type of chain generally uses inputs from the first type to produce consumer products of vegetable or animal-based with higher added value; see Figure 1.2. In most cases, the consumer products are less perishable due to conservation and conditioning processes. This significantly reduces the complexity of the food SC planning and largely eliminates the need for quality change models.

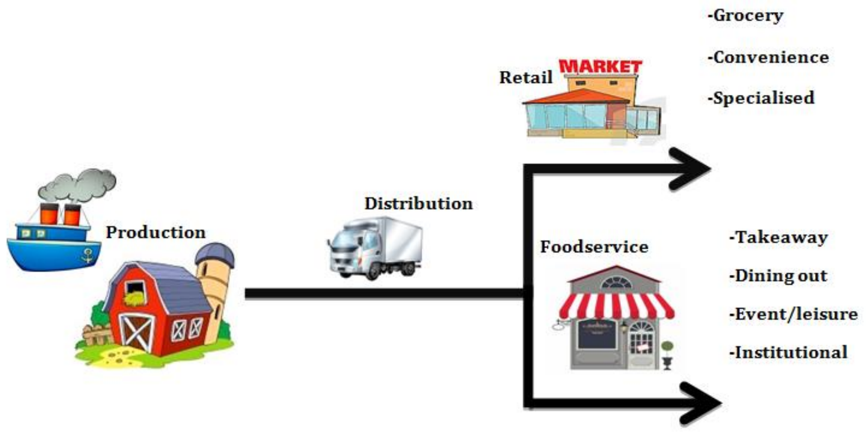


Figure 1.1 A schematic diagram of an SC for fresh food products

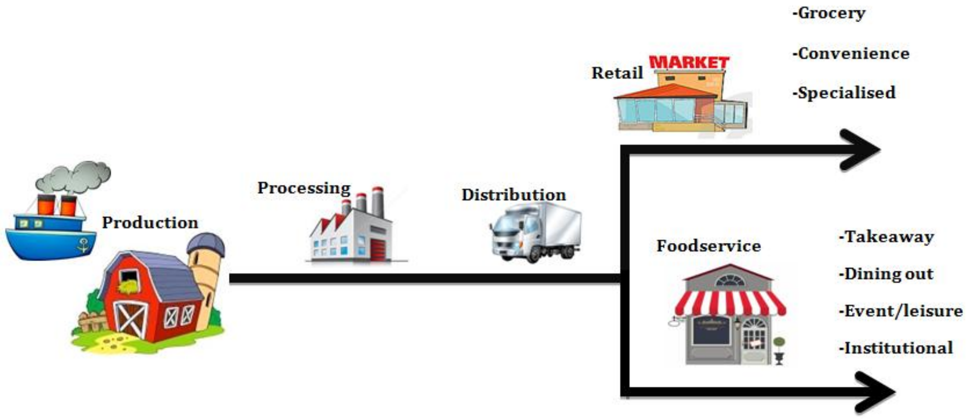


Figure 1.2 A schematic diagram of an SC for processed food products

Food SCs are distinct from other product SCs because there exists the continuous and significant change in the quality of food products while progressing through the SC (Ahumada and Villalobos, 2009, Blackburn and Scudder, 2009, Akkerman et al., 2010). The degree and speed of quality deterioration is determined by specific environmental conditions which may be influenced by the type of packaging, way of loading, and the availability of temperature-controlled packages, vehicles and warehouses (Manzini and Accorsi, 2013). In the following, a list of specific product and process characteristics of food SCs that influence the SC planning process as discussed by van der Vorst (2000), Bourlakis and Weightman (2004) and Jongen and Meulenberg (2005) is introduced.

- Perishability of produce: Shelf life constraints and changes in product quality level as it traverses the SC resulting in possible product shrinkage and stock-outs.

- Seasonality in production.
- Requirement for conditioned transportation and storage means.
- Variability of quality and quantity of supplies of farm-based inputs down to biological variations, seasonality and random factors connected with weather, pests and other biological hazards.
- Necessity for lot traceability of work in process due to quality and environmental requirements and product responsibility.

Along with the concern regarding these specific characteristics, there is the recognition of the environmental impact of food SCs. This has happened due to the increasing interest in green and sustainable SCs. Since the SC revolution in the early 1990s, it has been believed that the best practice calls for integration of environmental management with ongoing operations in SCs attributable to demands from stringent environmental regulations and consumer pressures (Wu and Dunn 1995, Srivastava 2007). Rapid and escalating deterioration of the environment in the directions of ozone layer depletion, rain forest disappearance, pollution level increases, landfill challenges and raw material resource scarcities is the main driver of environmental regulations and consumer pressures.

Therefore, industries should take the environment into account and combine this consideration with their own strategies in order to achieve sustainability in the most cost-effective way. In food SCs, production, distribution and consumption activities impact the environment in different ways, such as the emissions of greenhouse gases and pollution, the use of natural resources and the creation of waste (Mena et al., 2011).

1.2.2 Food supply chain and its sustainability

The perishability of food products results in massive food waste or loss. It has been estimated that approximately one third of the food production is wasted or lost annually (Gustavsson et al., 2011). Product shelf life, identified by the date or other information that is printed on a product label, indicates a limited length of time during which the food is fit for sale and consumption. As a commitment of food supply chain management, perishable food products must be sold to consumers before any spoilage occurs (Wang and Li, 2012). Food waste poses significant environmental impact to the chain as food products have advanced through their value adding activities, accumulating costs and embedded energy (Mena et al., 2011). Additionally, food waste disposal presents an additional environmental burden.

Another challenging, environmentally oriented task in today's food industry is controlling the carbon emissions throughout the food SC. Farm production generates emissions through processes of deforestation, fertiliser production and use and livestock management (CarbonTrust, 2012). Furthermore, growing food out of season can be a high-carbon method of production. Perishable food products often need special handling, transportation and storage technologies for conditioning and preservation purposes (Trienekens and Zuurbier, 2008, Rong et al., 2011). Refrigerated facilities and transporters needed in the food sector largely contribute to green house gas (GHG) emissions through their considerable energy requirement (Bozorgi et al., 2014). As confirmed by Quariguasi Frota Neto et al. (2010), assigning a carbon footprint to material used, energy used, production, consumption and transportation is necessary.

Although these environmental impacts are not new, the growth in food production attributable to demographic and life style trends (Buckley et al., 2007) and increasing globalisation has heightened the urgency to deal with the problems (Mena et al., 2011). These challenges have underlined the need for the efficient and sustainable management of food SCs. This means that businesses must now put their focus on both traditional economical interests and topical issues like the environment.

1.3 Research Problem and Questions

Many of the existing mathematical models of inventory control that followed the classical Economic Order Quantity (EOQ) model of Harris (1915), made the implicit assumption that inventories can be stored for an indefinite period. Deterioration and perishability characteristics started to receive attention from the time when the modelling of inventory in a blood SC was introduced (Pahl et al., 2007). As time has passed, researchers and practitioners have been encouraged to develop and extend models addressing real world applicability to the issue of deteriorating inventory in various dimensions, not only in relation to the lifetime of an item, but also in regards to the type of demand which is the driving force of the entire inventory system.

The profile of demand facing a food producer can be non-stationary stochastic over time (with time-varying randomness) due to promotional activities of the retail organisation, weather conditions, short product life cycles, seasonality etc. (Pauls-Worm et al., 2010, Rossi et al., 2010b). This demand distribution allows for uncertainties in demand within a period but permits fluctuations in the type of uncertainty from period to period which is more plausible from a real life point of view than the common assumption of deterministic demand distribution (with known parameters). Mena et al. (2011) mentioned that irregular demand due to weather and promotions are reasons contributing to food waste. Due to the added complexity caused by demand uncertainty, there are few models developed to address this aspect in a production and inventory system with deterioration (Bakker et al., 2012), which is the focus of this research. Apart from that, few researchers have shown an awareness of the heterogeneity among customers as claimed by Karaesmen et al. (2011). In practice, customers may demand a supply of items that will not expire within a specified time-window but which need not be freshest ones. Therefore, evaluating customer demands with different product shelf life requirements can be an efficient management practice.

It is believed by Karaesmen et al. (2011) that further analysis of supplier-buyer relations and their contracts regarding delivery performance remain fruitful research topics. In the food industry, the producer sells products to customers with a promised availability and a guaranteed remaining shelf life at the time of delivery (Pauls-Worm et al., 2010). Mena et al. (2011) pointed out that retailers' service level requirements contribute to food waste as suppliers usually over stock to prevent penalties. The requirements of the contracts from customers are important considerations for SC planning decisions.

According to the World Bank, demand for food will increase by 50% between 2009 and 2030 (Evans, 2009). As a consequence, food industries have been facing challenges in producing and appropriately distributing enough food to feed a growing population (Mena et al., 2011). The perishability characteristic of food products forces industries to carefully plan their production and inventory in cooperation with their SC partners. Suboptimal planning may result in long waiting times and, consequently, the decreasing quality of items which, in the worst case, will become waste, (Pahl et al., 2007). Mena et al. (2011) confirmed that out of shelf life of products is a reason contributing to food waste. Given the significance of the problem, this research aims to address the reduction of waste, possibly from production and inventory processes, generated in the chain to ensure global food security. Food security refers to the delivery of food product that is uncompromised by intentional contamination, damage, diversion within the SC (Marucheck et al., 2011) or certifiably uncompromised by the inability to guarantee product safety.

Building on the population growth issue mentioned above, higher GHG emissions from food production are expected (Gössling et al., 2011). Recently, emissions have been considered in addition to the cost function for the inventory problem (Bozorgi et al., 2014). Likewise, a thorough analysis of sustainability in warehousing is recommended (Brandenburg et al., 2014). Bouchery et al. (2012) and Brandenburg et al. (2014) suggested that model based research methods are needed to quantitatively investigate this context. Also, there is room in food industries for formal models to be applied (Brandenburg et al., 2014).

The above mentioned problems and issues will undoubtedly affect SC planning decisions. This has necessitated the development of a production and inventory model which can be applied for such a system. It is worth looking at the trade-offs among total cost, wastage and carbon emissions for the food SC whilst being able to satisfy customer requirements and demand.

Based on the issues that have been discussed above, the questions being addressed in this research include:

1. What is the relationship between sustainability and the SC along with potential consequences on the performance of a food SC in particular?

2. How can the sustainability factors be introduced into the production and inventory planning and control problem with efficiency as the primary goal? How can the multi-objective optimisation problem be solved to provide decision support on possible trade-offs between economic and

environmental perspectives when cost, waste and emissions need to be simultaneously minimised?

3. Given production and inventory decision problems under uncertain (erratic) demand, how can practical solutions be constructed using commercial solvers for business use rather than custom-made solution procedures and how can its practical application be improved for the benefit of managers in the food supply chain industry?

1.4 Research Objectives

The overall aim of this research is to contribute to the continuing evolution of supply chain management (SCM) by developing production and inventory models that can be used as tools in the management of perishable inventory in general and food products in particular, ensuring the trade-offs between operational and environmentally sustainable decisions. In this thesis, attempts are made to integrate the specifics of the perishable food industry and sustainability assessment methodology into the standard production and inventory planning and control problem. This study is based on existing theories on SCM that can be utilised to improve the efficiency and sustainability of food SCs.

To address the questions stated in the previous section, a number of objectives have been set for this research. These objectives are:

- To identify the structure of an SC in general and a food SC in particular.

- To clarify the necessity of considering both the financial and sustainability performance measurements concurrently in managing the SC, and to provide a survey on sustainable SCM studies in literature with a focus on perishable inventories.

- To identify where carbon emissions are generated in the SC and their relations to production and inventory processes.

- To investigate modelling techniques used in literature and to review existing SC models and their limitations for solving production and inventory systems with deterioration.

- To build mathematical models for perishable food SCs in make-to-stock and make-to-order production systems which enable optimal or near-optimal production and inventory decisions to be made so that retailers' demand can be fulfilled to meet given due dates with satisfactory trade-offs among total cost/profit, wastage and carbon emissions for SC partners.

- To develop and propose solution methods for the above models based on centralised and decentralised decision making processes.

- To identify suitable scenarios/cases with which to test the proposed models as well as the success criteria against which the models can be validated.

1.5 Thesis Organisation

An overview of the thesis chapters is given as follows:

Chapter 1 gives an overview of the research conducted. This chapter describes research background, summarises the statement of problem, defines the research questions, establishes the objectives of the study, and overviews the structure of the thesis.

Chapter 2 provides some background knowledge and description of the SC planning problem that is addressed in the research work. It aims to establish the theoretical foundation of this research discussing the evolution and concepts of SCM. Drivers of SC performance are discussed, particularly inventory management. The connection between SCM and sustainability is described.

Chapter 3 details the modelling techniques that were used in literature to handle sustainable SCM problems. It shows how the bulk of published research creates models with which to study the management of SCs towards carbon emissions reduction. It further discusses the necessity of being environmentally sustainable for the perishable food SCs.

Chapter 4 presents an in-depth review of production and inventory models with deterioration in SCM literature. It aims to show the need to carry out this study and the lack of literature already addressing this need. Based on the findings in terms of literature gap, an investigation into an appropriate approach enabling the modelling and optimisation of perishable food SC production and inventory planning and control was carried out. Multi-objective mixed-integer linear programming (mo-MILP) was identified as a promising modelling technique to construct practical solutions using commercial solvers for business use that generate the approximate solutions of the problem involving uncertain demand.

Chapter 5 provides a discussion of research method that was used in the course of this research. Seeing how the research is carried out helps to bring out the research aspects.

Chapter 6 introduces the mathematical model for both make-to-stock and make-to-order production and inventory models in a perishable food SC under the scope of this research. The author summarises and describes the assumptions and notations of the models and then formulates the mathematical models. The solution methods developed and proposed are also described in this chapter.

Chapter 7 introduces numerical tests to examine the validity and the generality of the proposed models using different data from the literature. Implementation of test cases in two sections, one for the make-to-stock production system and one for the make-to-order production system are detailed. The chapter contains results of the implementation of the model in a computer as well as analyses and discussion of these results.

Chapter 8 draws conclusions from the thesis. The major contributions and limitations of this research are also discussed. Finally, the indications for several potential future research directions are presented.

1.6 Summary

A preliminary study involving initial references to the literature in the areas of food SCs, SCM and the sustainability concept was carried out to capture a preview of the subject of the research. It was concluded that there was a need for research in the area of sustainable production and inventory management for food SCs. The aim of this research is to develop models to determine the production and inventory decisions that can be used as tools in the management of perishable inventory in general and food products in particular while the trade-offs between operational and sustainable decisions are optimised.

Chapter 2 Supply Chain Management

2.1 Introduction

This chapter aims to provide a review of relevant literature pertaining to the general topic of SCM where this research is positioned. An overview of SCM concepts and theory including definitions and a range of key issues in managing an SC are given and discussed. Literature was identified and located using online databases of abstracts. Following this, references of interest within the initial papers were located and read.

The evolution of SCM is given in Section 2.2. In Section 2.3, an introduction to SC and SCM is given and the formal definitions of SC and SCM are elaborated on. The objectives of the SC and the importance of its decisions and management are also presented, followed by the difficulties and challenges facing SC managers. Three phases of decision making including strategic, tactical and operational levels are discussed. The author also mentions two possible ways of viewing the processes performed in the SC. Next, the author discusses some drivers of SC performance in Section 2.4. These key SC drivers are considered in this thesis. Section 2.5 investigates the relationship between sustainability and the SC. Lastly, Section 2.6 summarises the chapter.

2.2 The Evolution of Supply Chain Management

Cooper and Ellram (1993) claimed that the route to SCM was evolutionary not revolutionary. An attempt for marketplace advantage, alongside continual advances in communication and transportation technologies, has motivated the continuous evolution of the SC and of the techniques to manage it efficiently and effectively.

It all began in the 1950s. The development of SCM started when responsibility for different activities in the organisation fell under separate, almost independent, departments. van der Vorst (2000) confirmed logistics activities including order processing, transportation and inventory control were treated as separate functions by individual managers each with their own tasks and objectives. Consequently, each function sought to maximise its own objectives which might have come at the expense of others. Mass production with little product or process flexibility was a common operations strategy (Tan, 2001). Esposito and Passaro (2009) also identified this period as the traditional supply phase of customer-supplier relationships evolution. Following that, in the 1970s, people started to recognise manufacturing resource planning, new material management concepts and the impacts of holding a huge work-in-process inventory (WIP) on manufacturing cost, quality, new product development and delivery lead time (Tan, 2001). This was the point when there was a focus on cost reduction rather than performance improvement. In addition, the notion of trade-off analysis was proposed. A trade-off is giving up one thing for another (Yoe, 2002). Therefore, a trade-off analysis is an analytical method for evaluating and comparing alternatives based on decision maker-defined criteria (Daniels et al., 2001).

Favourable options requested at the time of intense global competition in the 1980s were low cost, high quality and reliable products with greater flexibility. For that reason, just-in-time manufacturing (JIT), material requirements planning (MRP), manufacturing resource planning (MRPII), Kanban, lean manufacturing, Total Quality Management (TQM), ISO standards for quality measurement and other management initiatives were employed (Tan, 2001, Al-Mudimigh et al., 2004, Simchi-Levi et al., 2007). JIT is a management philosophy of complete elimination of waste which includes time, resources and materials that constitutes a key element in lean manufacturing. JIT is referred to the production and supply of what is needed, when it is needed, and in the amount needed (Cheng and Podolsky, 1996, Monden, 2011). Kanban system involves the use of product control cards with information of product's name, code and storage location written on in pulling products and components through the process (Suzaki, 1993). MRP is a computer-based production planning and inventory control system for determining the net time phased requirement of dependent items materials from known (e.g. sales orders) or assumed (e.g. sales forecast) independent demand (Rembert, 1992). The product structure records or bill of materials (BOM) records is used to define a relationship between the independent demand items at one level and the dependent demand items at the next lower level which en route to the costing and pulling of materials from inventory for released work orders. While, MRPII further develop MRP systems with the integration of additional data including employee and financial needs. TQM is a management philosophy embracing all activities that emphasises, among other things, continuous improvement, long range thinking, increased employee involvement and teamwork, constant measurement of results, and closer relationships with suppliers (Powell, 1995). Esposito and Passaro (2009) called this period the supply system development phase of customer-supplier relationships evolution.

Procurement professionals' attempt at building strategic partnerships with immediate suppliers initiated the concept of SCM (Tan et al., 1999, Tan, 2001). Simultaneously, the integration of material management and physical distribution activities by transportation and logistics experts was also recognised as SCM (New and Payne, 1995). Although the purchasing and supply perspective of SCM and the transportation and logistics perspective of SCM developed alongside each other, they finally merged into a holistic and strategic approach to operations, materials and logistics management generally referred to as SCM. The term 'Supply Chain Management' was formally introduced by Keith Oliver, a consultant at Booz Allen Hamilton in the early 1980s (Oliver and Webber, 1982). In addition to the purchasing and supply perspective, Chen and Paulraj (2004) proposed that SCM deals with identification and description of the relationship a company develops with its suppliers, planning and control of materials and information flows and both intra- and inter-organisation logistics activities.

The evolution of SCM continued through the 1990s. In accordance with Simchi-Levi et al. (2007), many companies focused their strategies on reducing their own and their SC partners' costs in the 1990s. Strategic partnerships between suppliers and buyers were part of their business strategies. For that reason, Esposito and Passaro (2009) named this period the strategic alliance phase of buyer-supplier relationships evolution. Organisation structures started to align with processes (Al-Mudimigh et al., 2004). Information sharing was engaged for better control of variability in SCs. Many industrial manufacturers were pushed towards outsourcing. Furthermore, the integration of environmental concerns in SC operations was presented attributable to demands from stringent environmental regulations and consumer pressures following the introduction of sustainable development in 1987 (Wu and Dunn 1995, Mebratu, 1998, Srivastava 2007). Later on, in the late 90s, the Internet and the related e-business models were introduced into the business world which required many companies to learn new skills and added complexity to existing SCs. Industries started to recognise that all the trends of cost reduction significantly increase the level of risk in the SC. Consequently, they focussed on strategies that located a right balance between cost reduction and risk management.

By the year 2000, new technologies such as the implementation of enterprise resource planning systems (Giannoccaro and Pontrandolfo), tools for supplier performance assessments, advanced inventory planning systems and others helped create opportunities to improve SC resiliency and responsiveness. This period was recognised as the globalisation phase of buyer-supplier relationships evolution (Esposito and Passaro, 2009). The principles of quality management were then integrated within the SC arena by means of a continuing shift from product-oriented internally driven supply channel quality management practices to externally focused process-based approaches in response to the need to deliver value to customers in often globally scattered SCs (Robinson and Malhotra, 2005). On the whole, the urgency of SC challenges has not diminished over the years and SCM will continue to need attention and innovation in the future.

2.3 Understanding the Supply Chain

A shift from focusing solely on the effectiveness and efficiency of individual business functions to realising the strategic importance of planning, controlling, and designing an SC as a whole is a new practice companies are adopting in today’s global marketplace (Min and Zhou, 2002). They are no longer competing as independent companies with unique brand names but rather as an integral part of SC links seeing that the execution of all members involved contributes to the overall results of the SC. For that reason, managerial ability to integrate and coordinate the complex network of business relationships among SC members is of essential importance (Drucker, 1998, Lambert and Cooper, 2000) .

From a practitioner point of view, an Accenture report in 2010 (in co-operation with Stanford and Insead) states that SCM is critically important or very important to 89% of the surveyed executives (Naslund and Williamson, 2010). It is also considered as increasing in importance when 51% of the executives stated that their investments in SCM have increased significantly over the last three years. Wal-Mart is considered by many authors as a pioneer in implementing SCM, with the ability to create a worldwide integrated network of distributors, warehouses and shops with almost real-time information availability through support from satellite technology, radio frequency identification (RFID) and global positioning systems (GPS) (Russell, 2007). Meanwhile, failing to manage SCs effectively results in serious negative consequences as was seen when Cisco faced a problem with contract manufacturers that led to a write off of $2.25 billion of inventory in 2001 (Lee, 2004). Therefore, SCM concepts and practices are required to be integrated into business processes in an attempt to ensure that customers' demands are met at the right time and place (Giannoccaro and Pontrandolfo 2002, Robinson and Malhotra, 2005).

2.3.1 What Is a Supply Chain and Its Objective?

SC concepts have developed from the period when issues related to material flows were introduced (Forrester, 1961) and have been building up very rapidly since the 1990s as evidenced by remarkable increases in related papers in various journals of interest to both academics and practitioners (Burgess et al., 2006). Apart from the material management and integrated logistics field, Chen and Paulraj (2004) mentioned the quality revolution, a growing interest in industrial markets and networks and influential industrial-specific studies as initial inspirations for SC concepts. An SC is complex in general as it is characterised by numerous activities and processes spread over multiple functions (logistics, inventory, purchasing and procurement, production planning, intra- and inter-organisational relationships and performance measures) and organisations and, at times, over lengthy time horizons (Arshinder et al., 2008).

An SC can be defined as an integrated, interlinked and interdependent network of entities comprised of suppliers, manufacturers, distributors, third party logistic providers and retailers working together either directly or indirectly in order to: (1) acquire raw materials; (2) transform them into final products; (3) add value to these products; (4) distribute and promote these products to retailers who will later provide them to the ultimate users, customers and (5) facilitate information exchange among its SC members (Beamon, 1998, Min and Zhou, 2002) .

The objective of every SC is to maximise the overall value generated for customers. The concept of value has many definitions (Zeithaml, 1988, Monroe, 1990, Anderson et al., 1992, Gale, 1994, Woodruff, 1997). Al-Mudimigh et al. (2004) found some commonalities in these definitions:

- Customer value is related to the use of a product or service.
- Customer value is perceived by customers, not objectively determined by the seller.
- Customer value involves a trade-off between what a customer receives, such as quality, and what he or she gives up, the price, for instance, to acquire and use a product or service.

In brief, value is the amount customers are willing to pay for what a company provides. The creation of value is managed through a value chain which refers to the sequence of activities required to make a finished product from its initial starting material and to bring it to the customer (Chopra and Meindl, 2013). The concept of value-added activities originated from Porter's value chain framework. In the system of dependent activities, those activities involved can be divided into primary (i.e. inbound/outbound logistics, operations, marketing and sales and after sales service) and support (i.e. procurement, technology development, human resources management and firm infrastructure) activities (Porter, 1985). The execution of an activity impacts the costs or effectiveness of other activities. Research on value chains increases the understanding of how different kinds of value chain confer competitive advantage (Recklies, 2001) and what the socioeconomic benefits, disadvantages and risks for various members of such a chain are (Booker et al., 2012).

Figure 2.1 depicts a generic SC characterised by flows of products, information and funds within the context of the total network. The appropriate management of these flows is a key to SC success. An SC starts with the end-customer and works its way upstream via one actor at each industry level. Effective SC strategies must take into account the interactions at various levels in the SC as Hakansson and Snehota (1995) stated: *"What happens between two* *companies does not solely depend on the two parties involved, but on what is going on in a number of other relationships."* Nowadays, the analysis of an SC is preferably being implemented within the context of the total network.

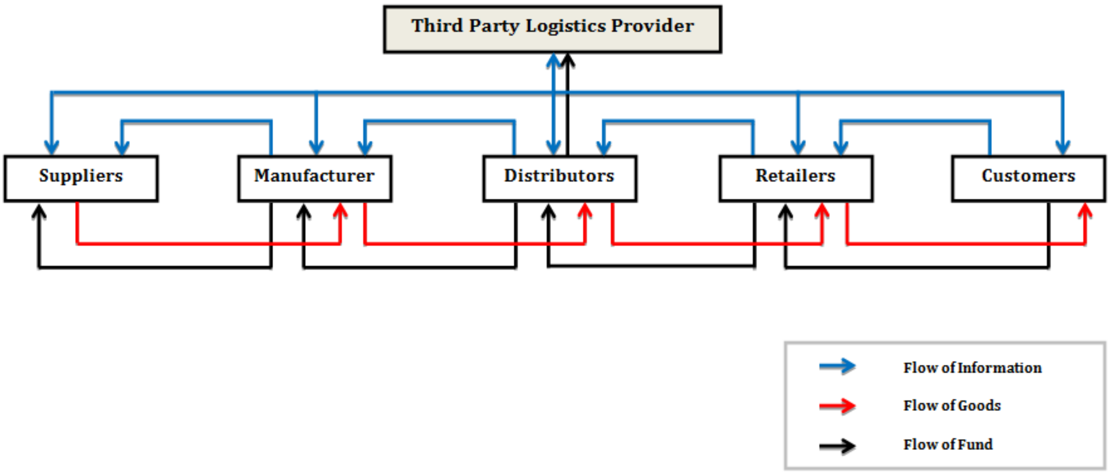


Figure 2.1 The Supply Chain Process

According to Wang et al. (2004), SCs can be classified into three categories: Lean Supply Chain (LSC); Agile Supply Chain (ASC) and Hybrid Supply Chain (Kalchschmidt et al.). An LSC attempts to eliminate waste and non value stops across the chain through the application of continuous improvement processes. Customer responsiveness might be sacrificed by this SC to achieve cost efficiency when required. An ASC endeavours to respond to unpredictable market changes and capitalise on them through the deployment of new technologies and methods, the utilisation of information systems/technologies, the integration of all of the business processes and the enhancement of innovations throughout the company, for instance. Faster delivery and lead time flexibility are goals of this type of SC. Along with the LSC and ASC, an intermediate chain known as the HSC has been proposed (Huang et al., 2002). An HSC tries to achieve mass customisation through its "assemble to order" policy by postponing product differentiation until final assembly. Both lean and agile techniques can be employed mutually in component production. However, only the agile technique is applicable in the company-market interface as adaptability, responsive ability and innovative ability are required.

2.3.2 The Importance of Supply Chain Decisions and Management

Decisions made regarding product, fund and information flows in an SC have determined the success or failure of several business operations (Chopra and Meindl, 2013). The locations of Walmart stores were chosen to cluster close to their distribution centres to facilitate frequent replenishment. Amazon beat its competitors through greater product variety and fewer stocking locations. In 1999, ToysRUs.com failed to fulfil customer orders received from its heavy on-line retailing advertisement (SupplyChainDigest, 2006, Gilmore, 2009). Later on, outsourcing was used as a solution. Another example is Hershey's implementation in 1999 of its new order management system before it was ready (Koch, 2002, SupplyChainDigest, 2006). This caused Hershey to miss its critical Halloween shipments and lose at least $150 million in revenue. Therefore, it is apparent that the right SC decisions are critical to adapt effectively to a changing environment.

Shortened product life cycles, heightened customer expectations, increasing manufacturing costs and globalisation of market economies call for improved SCM. With today's intense global competition, SCM can be employed as a vital tool for enhancing organisational productivity, profitability and performance (Gunasekaran et al., 2004). As such, SCM creates value for companies, customers and stakeholders interacting throughout an SC.

Cooper and Ellram (1993) pointed out differences between previous traditional management and SCM. To put it briefly, SCM involves intra- and inter-organisational integration and coordination, as well as management of those relationships present.

Definitions of SCM

Due to the multidimensional characteristics of SCM, there appeared to be little consensus in literature on the description of SCM or its activities (New, 1997, Mentzer et al., 2001, Lummus et al., 2001, Kauffman, 2002). For that reason, Mentzer et al. (2001) drew comparisons and summarised all of the contrasting aspects among previously proposed definitions of SCM in existing literature and came up with the following single, encompassing definition of SCM:

“Supply chain management is defined as the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long term performance of the individual companies and the supply chain as a whole.”

Burgess et al. (2006) commented that this definition is *“broad, not confined to any specific discipline area and adequately reflecting the breadth of issues that are usually covered under this term.”*

Considering the numerous attempts to define SCM, the one belonging to Simchi-Levi et al. (2007) is recommended and used by many authors:

“Supply chain management is a set of approaches utilised to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying service level requirements.”

This definition prompts several observations. To begin with, the ultimate goal of SCM is to meet customer demand more efficiently and in the most cost-effective way. This can only be achieved when the whole chain commits, integrates and coordinates. Next, SCM makes every effort to supply and provide products and services at the right quantity to the customers of any company throughout the SC at the right time. After all, SCM is rooted in strategic-level decision making but also encompasses tactical and operational aspects within and beyond the organisation.

Stock and Boyer (2009) had the same vision. Their definition is based on a review of 173 definitions of SCM across a range of journals and books as well as a synthesis of reviewed suggestions provided by practitioners, academics and hybrid sources as follows:

“The management of a network of relationships within a firm and between interdependent organisations and business units consisting of material suppliers, purchasing, production facilities, logistics, marketing, and related

systems that facilitate the forward and reverse flow of materials, services, finances and information from the original producer to final customer with the benefits of adding value, maximising profitability through efficiencies, and achieving customer satisfaction."

This latest definition seems to be the most holistic one. It includes important key points in managing an SC. SCM involves interactions relating to the flow of materials, services, funds and information in a network. It is done with the aim of maximum added value or profitability to the whole SC.

Difficulties and challenges in managing an SC

In the reality of intense global competition, SCM concepts and technologies are taken as a way to achieve business excellence. However, there is no rose without a thorn. SCM can be difficult for the following reasons (Simchi-Levi et al., 2007, Chopra and Meindl, 2013):

- SC strategies cannot be determined in isolation without considering the development chain for new product introduction and should be aligned with the specific goals of the company. With an SC consisting of many members, all with their own policies and interests, it is more difficult to coordinate the chain and agree upon SC strategies.
- It is frequently difficult to operate a single facility so that costs are minimised and service levels are maintained. Indeed, the difficulty increases exponentially when an entire system is being considered.
- Globalisation comes with significant fluctuations in exchange rates, global demand and the price of crude oil. It has increased both the opportunities and risks for SCs. Uncertainty and risks are intrinsic in every SC, as in customer demand, and, therefore, can never be forecast completely accurately. For example, travel times will never be exactly certain, and machines and vehicles will breakdown from time to time. SCs need to be designed and managed to mitigate as much uncertainty and as many risks as possible, as well as deal effectively with those that remain.

Moreover, SCM involves challenges such as understanding how SCM can drive competitive advantage, designing and operating an SC towards minimum total costs and constant service levels, developing trust and collaboration among SC partners and identifying best practices to facilitate SC alignment and integration (Robinson and Malhotra, 2005, Simchi-Levi et al., 2007, Mercier, 2014). Last but not least, the environment and sustainability have proven to be other challenges that can no longer be disregarded. Both regulations and the perception of the lack of sustainability as a risk factor help coerce accountability in this regard when designing SC strategy (Chopra and Meindl, 2013).

The SCM challenges are difficult owing to multiple factors (Simchi-Levi et al., 2007). SC requirements vary by product segment, channel and geography. Different facilities in the SC often have different, conflicting objectives. On top of that, demand and cost parameters also vary over time due to the impact of seasonal fluctuations, trends, advertising and promotions, competitors' pricing strategies, and so forth. Companies need to recognise these difficulties and set up SCs accordingly. Furthermore, these requirements evolve over time. As they change, SCs need to adapt. With a changing environment, companies need to constantly be on the lookout to make sure their SC fits the requirements at all times.

2.3.3 Decision Phases in a Supply Chain

To successfully manage the flow of materials, information and funds in an integrated SC, related decisions span a large spectrum from the strategic through the tactical to the operational level in various aspects such as forecasting, procurement, production, distribution, inventory, transportation and customer service depending on frequency of decision and its time frame as follows (Stevens, 1990, Giannoccaro and Pontrandolfo 2002, Simchi-Levi et al., 2007):

- The strategic level deals with decisions that have a long lasting effect on the firm. The focus at this level should be to develop the objectives and policies of the SC, the shape of the SC in terms of key facilities and their locations, the company's competitive package and an outline organisational structure able to bridge functional barriers and operate an integrated SC effectively. This includes decisions regarding SC configuration, product design, outsourcing, supplier selection, strategic partnering and flow of material through the logistics network.

- The tactical level includes decisions that are typically updated anywhere between once every quarter and once every year. The tactical dimension involves determining the tools, approaches and resources necessary to achieve the strategic aims. This includes, for instance, decisions regarding purchasing and production, inventory policy, transportation strategy, demand forecasting, manufacturing subcontracting and timing and size of marketing promotions.
- The operational level refers to daily, routine type decisions. The goal is to handle incoming customer orders in the best possible manner. This includes decisions regarding order allocation, scheduling, lead time quotations, routing, truck loading and order replenishment.

2.3.4 Process Views of a Supply Chain

An SC is a network of entities working together in a sequence of processes and flows to fill a customer need for a product or service. There are two ways to view the processes performed in an SC (Chopra and Meindl, 2013).

- Cycle view: The processes in an SC are divided into a series of cycles including customer order cycle, replenishment cycle, manufacturing cycle and procurement cycle. Each cycle performs at the interface between two successive stages of an SC. A cycle view clearly specifies the roles and responsibilities of each member and the desired outcome of each process in the SC. This is very useful when considering operational decisions.
- Push/pull view: In this view, the processes are divided into two categories depending on how they react to a customer order. Pull processes are executed in response to a customer order. Push processes are initiated and performed in anticipation of customer orders.

2.4 Drivers of Supply Chain Performance

Managing the SC cannot be left to chance given that it is a complicated and challenging task. Actions taken by one SC member can have a positive or negative impact on other SC members. The introduction of cooperation through SCM has helped to moderate the historically adversarial relationships among members (Brown et al., 2005). SCM began while logistics, distribution, marketing, operations, product design, product procurement and operations were gradually integrating. It started once SC members realised that they were part of a value chain extending from raw material extraction to finished product consumption and that all SC participants could benefit by controlling and smoothing the flow of materials, information and funds.

Performance measures used in determining the efficiency and/or effectiveness of an existing system, comparing competing alternative systems and/or designing proposed systems may be categorised as either qualitative or quantitative (Beamon, 1998). Qualitative performance measures usually reflect subjective views of the expected behaviour of the systems including customer satisfaction, flexibility, agility, information and material flow integration, effective risk management, supplier performance, robustness for instance. While, quantitative performance measures may be directly described numerically. Quantitative SC performance measures may be categorised into objectives that are based directly on cost or profit (e.g. cost minimisation, sales maximisation, profit maximisation, inventory investment minimisation, return on investment maximisation and production smoothing) and objectives that are based on some measure of customer responsiveness (e.g. fill rate maximisation, product tardiness minimisation, customer response time minimisation and lead time minimisation).

SC performance can be improved through a better structure of interaction among the logistical and cross functional drivers (Chopra and Meindl, 2013). These drivers include facilities, inventory, transportation, information, sourcing and pricing. Some of the performance drivers which are related to this research are discussed below.

2.4.1 Transportation

The logistics function – sometimes also described as distribution management – connects different parts of the SC together. This function's main focus is the management of physical and information flows. Logistics is seen as a value-adding process that directly supports the primary organisational goal of being competitive by offering a high level of customer service and flexibility in responding to market demands for example (van der Vorst, 2000). The American Council of Logistics Management (CLM) - since renamed the Council of Supply Chain Management Professionals (CSCMP) - defined logistics management in 1998 as (Stock and Lambert, 2001):

"Logistics is that part of the SC process that plans, implements and controls the efficient, effective flow and storage of goods, services and related information from the point-of-origin to the point-of-consumption in order to meet customer requirements."

The logistics distribution problem is to allocate a number of points of consumption to a number of points of supply, including suppliers, manufacturers, warehouses, distribution centres and customers. The connection of these various logistics stakeholders by a mean of transportation facilities is regarded as the logistics distribution network (Ho and Emrouznejad, 2009).

Distribution network configuration is a well recognised and widely studied problem. As a part of an SC, the distribution network refers to the entire chain of intermediaries and transportation logistics which supports the movement and storage of products from the supplier to its various customer segments. Distribution networks of modern enterprises are characterised by significant complexity attributable to their size, span, nature of customer assignation and dynamics of the network flow (Li and Savachkin, 2013). Designing such a network may involve issues related to locations, capacities, production levels and transportation flows which are followed by some key strategic decisions as outlined below (Simchi-Levi et al., 2007):

- Determining the appropriate number of warehouses.
- Determining the location of each warehouse.

- Determining the size of each warehouse.
- Allocating space for products in each warehouse.
- Determining which products customers will receive from each warehouse.

In order to achieve the objective of distribution network configuration, a certain distribution strategy can be applied in distributing products to customers. The following are discussions of some distribution strategies (Simchi-Levi et al., 2007).

- Direct shipping: This is a strategy in which products are shipped from suppliers directly to retail stores, bypassing warehouses and distribution centres. It is suitable when stores require fully loaded trucks and common in the grocery industry where lead time is critical owing to perishability.
- Warehousing: This is the classic distribution strategy in which inventory is kept at the warehouses and provided to customers as required.
- Cross-docking: In this strategy, products are distributed continuously from suppliers through warehouses to customers. It can be used to rapidly consolidate shipments from several sources and realise economies of scale in outbound transportation. Stock coming into a cross-docking centre has already been pre-allocated against a replenishment order generated by a retailer in the SC. Cross-docking essentially eliminates the inventory-holding function of a warehouse while still allowing it to serve its consolidation and shipping functions (Ross and Jayaraman, 2008).

Furthermore, supply chain network (SCN) design is the next important step relating to distribution network configuration. According to Klibi et al. (2010), SCN design involves strategic decisions on the number, location, capacity and operation of the production–distribution facilities of a company, or of a set of collaborating companies, as well as decisions related to the selection of suppliers, subcontractors, and third-party logistics (3PLs), in order to provide products or services to customers. Decisions on day-to-day procurement, production, warehousing, storage, transportation and demand management generate product flows in the network, with associated costs, revenues and service levels. The adequate design of an SCN requires the anticipation of these future activity levels.

2.4.2 Supply Management

Tremendous changes have been occurring in supplier management practices with the ultimate goal of managing their suppliers throughout the entire SC for faster delivery, decreased production lead time, reduced cost and increased quality (Davis, 1993, Battaglia, 1994, Billington, 1994, Hines, 1994).

Collaboration and Strategic Supplier Partnerships

Competition has changed buyer-supplier relationships. Therefore, traditional relationships no longer suffice. Instead closer, more collaborative approaches are needed. Table 2-1 displays the critical elements of a supply partnership in comparison to traditional thinking (Maloni and Benton, 1997). It can be seen that a partnership supply strategy involves sharing information among fewer suppliers in a long term relationship. Furthermore, Kelle and Akbulut (2005) mentioned the traditional way of supply as having a large number of suppliers. This relationship is based on price and involves some advantages such as easy switching between suppliers, having the supplier as the shock absorber and not sharing confidential information. However, it is dominated by disadvantages such as the large amount of inventory, the short-term contracts and arms-length transactions and increased pressure for price reduction. The buyer-supplier partnership has the potential for joint investments in product and process development and an extensive sharing of communication and information. At the same time, it also involves probable disadvantages such as an increase in suppliers’ dependency, loss of direct contact with second tier suppliers, the risk of losing confidential information and increased communication and coordination costs.

Table 2-1 Traditional versus Partnership Supply Strategies taken from (Maloni and Benton, 1997)

Traditional Supply Relationships	Supply Chain Partnerships
• Price emphasis for supplier selection • Short-term contracts for suppliers • Bid evaluation • Large supplier base • Proprietary information • Power driven *problem solving* *improvement* *success sharing*	• Multiple criteria for supplier selection • Long-term alliances with suppliers • Intensive evaluation of value-added by supplier • Few suppliers • Shared information • Mutual *problem solving* *improvement* *success sharing*

Spekman (1988) defined collaboration as *"the process by which partners adopt a high level of purposeful cooperation to maintain a trading relationship over time."* The trading relationship is bilateral. Therefore, mutual commitment to the future and a balanced power relationship are essential to the process. Strategic supplier partnership is defined by Li et al. (2006) as *"the long-term relationship between the organisation and its suppliers."* Long-term relationships allow companies to harness the strengths, competencies and skills of partners to their advantage (Dwyer et al., 1987). A strategic partnership highlights direct, long-term alliances and encourages mutual planning and problem solving efforts (Gunasekaran et al., 2001). It is used to promote shared benefits and mutual gains among SC members and ongoing participation in one or more key strategic areas such as technology, products and markets (Yoshino and Rangan, 1995). It enables organisations to develop closer, more collaborative ties with a few but significant suppliers who are willing to share responsibility for the success of the products. In practice, Xerox reduced its own suppliers by over 50% and demanded a commitment to quality, innovation and cost reduction from those remaining suppliers to maintain closer ties with them (Spekman, 1988). An example of the strategic partnership with suppliers is when suppliers participate at much earlier stages in the product-design process, they may be able to offer more cost-effective design choices, help select the best components and technologies and help in design assessment in returns (Tan et al., 2002). When supplier involvement is put into practice early, SCs achieve on average a 20% reduction in material cost, a 20% improvement in material quality and a 20% reduction in development time (Monczka et al., 2005). An effective supplier partnership can be an essential element of a leading edge SC (Noble, 1997).

The criteria for measuring the success of a partnership includes both soft (i.e. competitive technology and supply chain integration) and hard (i.e. cost, quality, and cycle time) measures of success (Monczka et al., 1998). The following key factors were proved to be important in building a successful strategic supplier partnership:

- Coordination, Trust and Goodwill: It is necessary to foster and nurture a sense of trust with supplier (Niederkofler, 1991, Monczha et al., 1998).
- Bilateral Communication Behaviour: It is important to convey both the depth (i.e. quality and participation) and breadth (i.e. extent of sharing) of information between parties (Ellram and Hendrick, 1995, Landeros et al., 1995, Monczha et al., 1998).
- Conflict Resolution Orientation: It is essential to integrate a joint problem solving process and be flexible (Niederkofler, 1991, Monczha et al., 1998).
- Commodity/Supplier Selection Process: It is critical to formalise the purchasing commodity strategy development process, followed by the supplier assessment and selection process (Monczha et al., 1998).

Strategic Supplier Sourcing

Building on the expertise and commitment of its suppliers, a company is able to gain and sustain market advantage. When buyers are looking to form strategic partnerships with their reduced number of suppliers, the supplier selection process is becoming even more important to these companies. As these long-term relationships develop, the criteria used to select suppliers may be subject to change (Swift, 1995). Strategic sourcing plays an increasingly significant role in products and services seeing that about 70% of the cost of a John Deere tractor and more than 80% of the cost of a given product in the aerospace industry are directly tied to the cost of materials from external suppliers (Ketchen Jr et al., 2008).

Several explanations help clarify why the number of suppliers for different companies may vary (Minner, 2003). They can choose between having a few as an extreme single supplier or multiple suppliers. After JIT and TQM strategies were introduced, long-term relationships with fewer numbers of suppliers were promoted. It requires less effort to coordinate between vendor and buyer while economies of scale and continuous quality improvement can be achieved. This can also benefit the company if high costs of product design and supplier development are incurred. However, several kinds of risks associated with having just a single supplier such as machine breakdowns, labour strikes, capacity limitations and lead time variability can still convince purchasing managers to employ multiple sourcing. Whenever a supplier selection decision is made, the buyer normally establishes a set of evaluation criteria that can be used to compare potential sources (Gregory, 1986). Lehmann and O’Shaughnessy (1982) reported reliability of supply and price as the most important criteria for sourcing routine order products. Cameron and Shipley (1985) as well as Dempsey (1978) identified price, quality and reliable delivery as the prime criteria for industrial raw material purchases. Swift (1995) noted that purchasing managers who have a preference for single sourcing are more interested in the total life cost of the product, the technical support available and the reliability of the product than those who favour multiple sourcers. Additionally, Minner (2003) considered price, quality and supplier service as the three main decisive factors in the supplier selection process.

Supplier selection has been the subject of tons of academic literature from operational research (OR) and related researchers who want to find optimum solution in different ways, and that literature is not included in this piece of research.

2.4.3 Inventory Management

The management of inventory systems is primarily focused on the tactical question of which inventory control policies to use and the operational questions of when and how much inventory to order (Baron, 2010). As customer demand changes over time, future demand can be forecasted using statistical models, historical data, personal experience or intuition. Within an SC, decisions of when and how many to reorder of a new batch of a product arise in response to the demand forecast. These decisions have to be made towards minimising inventory ordering and holding costs (Simchi-Levi et al., 2007). In order to understand the role of inventory, one might start with questioning why inventory should be held in the first place, how to maintain it at the optimum level as well as whether the reorder should be made with more than, less than, or exactly the same amount as the demand forecast?

Inventory

Inventory is the quantity of goods that is obtained and held for some purposes or uses such as meeting a future demand, keeping operations running and so on (Inman, 2009). It is required at different locations and in many nodes of a supply network. Inventory can be kept in the form of raw materials, WIP, and finished goods (BusinessLink). Raw materials supplied by suppliers are used as inputs in production. WIP is a stock of unfinished goods being produced. Finished products are those items ready for current customer sales.

There are several reasons behind the idea of holding inventory (Scott et al., 2011). Inventory is used as a protection against uncertainty. Uncertainty can be caused by variations in customer demand, variations in delivery lead time, or restrictions in quantity and quality of supply. Inventory is held to protect against quality defects. Prompt substitution of faulty items is possible with inventory availability. Inventory is also used as a tool to stabilise production of seasonal items where manufacturing technology is expensive. All things considered, managing inventory is basically about balancing supply and demand.

When managing inventory control, a company has to decide how much stock they would like to keep with the aim towards minimising SC total cost and improving customer service levels. Whether to keep little or no stock or to hold lots of inventory, the size and nature of the business, and the type of stock involved have to be taken into consideration (BusinessLink).

Considering both supply and demand, inventory decisions must be managed. When stock replenishment is made, fixed costs related to this inventory handling are incurred (Hadley and Whitin, 1963, Muller, 2003a, Axsater, 2006).

1. Ordering or set up cost: It is independent of the ordering batch size. Costs required for machine set up, shop floor workers' learning, and order handling administration are examples of this cost.
2. Holding or carrying cost: This cost is any cost relating either to investment in inventory or maintenance of the product in the warehouse. It includes costs incurred from space used, tax, insurance, product handling, deterioration, damage, obsolescence and theft. It also encompasses opportunity cost that is caused by the capital being tied up in the form of inventory.
3. Shortage cost: When an item is ordered but cannot be satisfied, possibly due to a shortage, it results in additional cost. This so called shortage cost brings about two situations for customers to respond to: Either that order is backlogged if the particular customer is willing to wait or the order is lost if that customer decides to choose some other supplier.
4. Price: Apart from ordering cost, holding cost and shortage cost, inventory costs can include the actual value of the products. This is the cost paid per product unit if the product itself is bought from another company. Otherwise, this cost includes costs incurred from the direct labour force, materials and overhead needed in producing the product.

These different inventory types are introduced after either independent or dependent demands. Independent demand is used to describe the demand for items purchased by external customers whereas dependent demand is the demand for items required in production (Orlicky, 1975). Independent demand for finished products generated from the markets commands the company to have the right item in the right quantity with no concern for time and place as the safety stock on-hand can help save the company (Muller, 2003b). A replenishment approach is used for managing these independent demand induced inventories. Stock is replenished with the amount following the forecasted, fairly fixed pattern exhibited from market forces. Order-Point formulae, simple Min-Max inventory system and Economic Order Quantity (EOQ) formula are examples of concepts, formulae and methods used for inventory management.

A replenishment approach used for managing inventory involves the application of two types of inventory policy (Simchi-Levi et al., 2007, Çakici and Groenevelt, 2011, Pearson):

- *Continuous Review Policy*
  It is possible for suppliers to mandate order quantities or impose lower and upper limits on order quantities to achieve economies of scale in handling. In such a case, when *'quantity to order'* is the restriction to the buyer in the inventory replenishment process, a continuous review policy ((*S, Q*) policy) can be used to manage the buyer's inventory decisions. Continuous inventory review involves a system that tracks each item and updates inventory counts each time an item is removed from inventory. A decision of whether and how much to order has to be made when using this policy.
- *Periodic Review Policy*
  Frequently, suppliers also mandate *'time to order'* decisions to achieve economies of scale in their assembly, production or logistics setup (i.e. to conform to a supplier's production schedule or transportation provider's shipping schedule) or because of the restrictions mandated by their own planning processes and suppliers (i.e. to coordinate multiple product orders). When *'time to order'* is the restriction, a periodic review policy ((*R, S*) policy) can be used. Periodic inventory review involves counting and documenting inventory at regular intervals. An appropriate quantity is then ordered after each review.

However, having the right item, in the right quantity, at the right time and in the right place is a concern for the manufacturing unit due to the reliance on another item of this dependent demand on raw materials, parts and assembly in order to complete a finished product. A requirements approach is then suited for inventory management of this dependent demand type. When a demand for an assembled or final product exists, the materials required for its completion are then ordered. Either MRP or a JIT inventory system is then implemented for inventory management purposes.

Manufacturing firms apply various policies for fulfilling customer orders. When inventory is kept in the form of finished goods, demands of final product are then fulfilled from the stock. In that case, the products are referred to in the literature as make-to-stock (MTS) orders. In general, MTS products involve a low variety of customer-specific and less expensive products. The MTS production system focuses on anticipating and planning to meet the demand by the use of forecasting. Therefore, inventory planning, lot size determination and demand forecasting demonstrate as the main operations issues (Soman et al., 2004).

However, increase in diverse types of products and each with its variations along with the cost pressures have led SC managers to focus on running gradually more lean and efficient SCs with minimal inventory. Indeed, industries are to a great extent relying on pull or make-to-order (MTO) production policy to keep inventory at an acceptable level such that cost and waste are minimised (Kaminsky and Kaya, 2006). In addition, it is financially beneficial to store low-value goods instead of higher valued end products (Van Donk, 2001). As no finished goods inventory (including cycle and safety stock) is maintained, a production order with a size of demand quantity is initiated when demand occurs for that period (Rajagopalan, 2002). This initiation of producing more flexible brings about a direct impact of (part of the) customer orders on production orders. The MTO production system focuses on order execution, attaining high due date adherence and capacity planning (Soman et al., 2004). Following the unpredictable nature of demand regarding quantity and/or timing, the firm has an option to accept or reject a particular order, each with an agreed upon due date (i.e. delivery has to be made by this date). The order acceptance/rejection decision has to be based on the characteristics of the already accepted orders and possibility of generating feasible schedule, which includes the new order (Soman et al., 2004). Since capacity is held in reserve to meet customer demand for MTO products, the effective and efficient use of available capacity reveals the most important aspect in MTO (Chen et al., 2009). Hence, capacity investment, inventory holding, average response time (order lateness/tardiness) and service level show the competitive priorities of the manufacturing firm (Soman et al., 2006, Altendorfer, 2010). Furthermore, the manufacturer-supplier relationship dramatically impacts the delivery of products and system performance. Suppliers often have to carry significant amounts of inventory to meet the demands of their customers “just-in-time”.

Additionally, the supplier agreed in carrying inventory to allow acceptance and production of more profitable orders (Carr and Duenyas, 2000).

Concisely, increasing competitive pressures on companies supplying products to customers are leading to an increased emphasis on customer service of having MTS items in stock (to achieve high fill rates) and delivering MTO products quickly and by the promised due date (Kaminsky and Kaya, 2006).

Managing Inventory in a Supply Chain

A multi-echelon or multi-level SC possibly has many players in multiple stages being managed to minimise the total cost of the SC. The goal in a multi-echelon SC inventory system is to decrease total costs and improve service levels by coordinating orders across the SC as well as considering the interaction of various SC levels and the impact this interaction has on the inventory policy.

Consider a simple multi-echelon system with suppliers supplying one producer who converts raw materials into finished products and distributes them to retailers. Each of these forms of inventory held by suppliers, producer and retailers needs its own inventory control mechanism. Managing inventory in this environment is often difficult owing to possible demand uncertainty, inaccurate demand forecasting and order quantity calculation errors. The random or stochastic customer demand leads to extra safety inventory held in the system to prevent future shortages. Given demand fluctuations and forecast errors, an increase in order variability as we travel up in the SC, the *bullwhip effect,* further complicates an optimal order quantity calculation for a multi-echelon SC. Therefore, coordination in the SC is required such that necessary information is shared and the impacts of actions from one SC stage are taken into account on other stages.

According to Simchi-Levi et al. (2007), there are various strategies applicable in reducing inventory levels of the SC in practice. Quantitative approach is one of them and it focuses on the right balance between inventory holding and ordering costs. A number of research studies have been done regarding this topic. This will be discussed in more details in the next two chapters.

2.5 Sustainability and the Supply Chain

“Development that meets the needs of the present without compromising the ability of future generations to meet their own needs” is the definition of sustainable development given by the Brundtland Commission of the United Nations. The 2005 World Summit of the United Nations introduced a framework identifying the “three pillars” of sustainable development that must be reconciled for sustainability to occur i.e. economic, environmental and social sustainability. The environmental dimension of sustainability has probably received the most attention (Akkerman et al., 2010). One of the best-known examples is Life Cycle Assessment (LCA). It is an analytical tool for evaluating the environmental impacts associated with the entire life cycle of a product, process or activity (Hauschild et al., 2005). Although these assessments can be and are used to decrease the environmental load, further standardisation to improve comparative studies and to broaden practical applications, particularly in the food sector, is still needed (Roy et al., 2009b).

2.5.1 The Role of Sustainability in a Supply Chain

Every SC is one connecting piece of the world where it functions. Each survival depends on the health of the surrounding area. That is why the goal of an SC should be developed beyond the interests of its participants to others that may be affected by SC decisions. The growth of emerging markets such as Brazil, China and India has not only improved global living standards but also put pressure on resources and the environment (Chopra and Meindl, 2013). Diminishing raw material resources, overflowing waste sites and increasing levels of pollution highlight the potential escalating deterioration of the environment being experienced (Srivastava, 2007). In maintaining this level of growth, it is important that an SC becomes more sustainable. Sustainability comprises issues related to human health and safety (‘People’) and environmental impact (‘Planet’), within an economic context (‘Profit’) (Bremmers et al., 2011). An increasing focus on sustainability is possibly driven by any of the three factors as follows (Chopra and Meindl, 2013):

- Reducing risk and improving the financial performance of the SC
- Attracting customers who value sustainability.

- Making the world more sustainable.

Paying attention to sustainability is not just about being friendly to the environment but also showing good business sense. However, major barriers to sustainable SCs do exist (Chopra and Meindl, 2013). Sustainability requires efforts that do not provide obvious returns on investment for a company. On top of that, customers themselves have not always backed up words about the importance of sustainability with willingness to pay a premium for green products.

2.5.2 The Quest for Sustainability

In response to the concern for sustainability presented in industries, various approaches have come up (Chopra and Meindl, 2013). In a command-and-control approach, the government or regulators set standards that everybody must adhere to. This approach tends to be inflexible and rarely cost effective. An example is the setting of carbon monoxide emission standards for new automobiles by the United States. Similarly, the European Union has introduced the waste electrical and electronic equipment (WEEE) directive that is geared towards proper recycling and landfill avoidance in the electrical and electronics industry.

Another approach still being debated is market mechanisms in the context of greenhouse gases. One mechanism has been referred to as “cap-and-trade” which is an environmentally effective and economically efficient response to climate change. It constrains the aggregate emissions. A ‘cap’, or ‘limited number’, of tradable emission allowances is created. The cap is reduced approximately three percent each year beginning in 2013 so that total emissions fall (ca.gov, 2014). If SC participants generate fewer emissions than the allowances they own, they can sell their surplus allowances to others that may be polluting above their limit and need additional allowances. The point of this is that those who pollute have to pay more, and those who pollute less can pay less and get money back. Any failure to secure and surrender enough allowances to cover all emissions leads to a significant fine. This mechanism has several challenges relating to the methods used to evaluate the initial allowances awarded to each entity and the fines imposed on companies that fail to comply with the emissions limit.

A second market mechanism to control emissions is an emission tax. Each entity generating green house gases is charged a tax proportional to the size of the emissions. The ideal tax rate would be the exact social cost per unit of pollution (ThinkQuest, 2013). A charge for emissions will encourage companies to reduce their emissions using any idea whose marginal cost is less than the charge. The challenges for this mechanism are in the amount charged for emissions and the extent the charge will hurt the economy.

2.5.3 Key Metrics for Sustainability

Important metrics that should be focused on and which can be used to judge sustainability-related efforts in the SC are divided into four categories (Chopra and Meindl, 2013):

- Energy consumption
- Water consumption
- Waste generation
- Greenhouse gas emissions

In the measurement and reporting of the four categories for every company, the clearly defined scope and the use of absolute or relative measures of performance should be acknowledged. Ideally, all categories should be measured across the entire SC to capture the total impact on the environment. An absolute measurement reports the full impact of the SC in the category being measured. However, a relative measure of performance is more effective at capturing improvement. It is better for firms to use both measures to get a true picture of their performance.

2.5.4 Sustainability and Supply Chain Drivers

SC sustainability can be improved with the aid of key metrics described above (energy consumption, water consumption, waste generation, and greenhouse gas emissions) in the environmental impact measurement for the various SC drivers. In transportation, the SC design can contribute to improved sustainability in terms of emission and waste reduction through an increased aggregation, a proper selection of transportation modes and technologies, a more efficient loading of transportation vehicles and an increase in fuel efficiency for instance (Chopra and Meindl, 2013). Product design also helps to reduce emissions and energy use by means of packaging reduction and greater density allowance during transportation. Also, parameters such as distance, speed or weight in transportation operations impact the environment in the same direction (Soysal et al., 2014). In SCM, the ability to work with suppliers to improve environmental performance is essential while also becoming more difficult in conjunction with increasingly global and fragmented SCs. In inventory, not only raw materials, WIP and finished goods but also landfill wastes should be focused on in terms of sustainability judgment. LCA can be used to reduce the harmful inventory and unlock the unused value in discarded products (Chopra and Meindl, 2013).

2.6 Summary

This chapter presents a review of SCM. It includes the evolution of SCM, the definitions of SC and its management, key drivers of SC performance and the priority for a sustainable SC. A basic knowledge of SCM history helps develop better understanding of the concepts and increase awareness of the current situations and managerial advancement. The SC is defined as a network comprising all companies involved, either directly or indirectly, in fulfilling a customer request. SCM is a set of approaches utilised to efficiently manage a network of relationships that facilitate the flow of materials, services, finances and information from original producer to final customer with the benefits of minimising system-wide costs and achieving customer satisfaction. Three decision making phases, namely SC strategy or design, SC planning or tactics and SC operations have to be managed.

However, the management of the SC is difficult. Some reasons behind this are: SC strategies cannot be determined in isolation; an SC is a complex network of facilities; uncertainty and risks are intrinsic in every SC; system parameters vary over time; different facilities in the SC often have different, conflicting objectives and an SC is dynamic and its requirements evolve over time. The challenges involved are understanding how to achieve competitive advantage, minimum total costs and constant service levels; developing trust and collaboration among partners and identifying best practices.

Some logistical and cross functional drivers employed to achieve the desired SC performance in a responsive and efficient direction must be considered. These performance drivers include facilities, inventory, transportation, information, sourcing and pricing. The author discussed some drivers related to this research.

Inventory, being one of the drivers, commonly presents difficulties in SCs due to a mismatch between supply and demand. When managing inventory, a company has to decide how much stock it would like to keep with the aim towards minimising SC total cost and improving customer service levels by answering two questions: when the product or service should be ordered and how many products or services should be ordered.

Following globalised SCs and the growth of emerging countries, efforts are required for a more sustainable way of using the world’s resources and protecting the environment. Two approaches that support sustainability in the context of greenhouse gases are the command-and-control approach and market mechanisms. There are four key metrics that can be used to measure environmental sustainability for an SC: energy consumption, water consumption, waste generation and greenhouse gas emissions. These metrics can be matched with various SC drivers to identify possible opportunities for increased sustainability.

Chapter 3 Sustainable Management and its Relevance to Food Supply Chains: a Literature Review

3.1 Introduction

This chapter provides a literature review of the work that has been done on sustainable SCM. Its objective is to demonstrate that there is a need for the development of a formal model in the area of production and inventory planning within environmentally sustainable food SCM. Section 3.2 starts with an overview of literature on sustainable SCM. This section elaborates on the relevant modelling techniques, SC decisions and their associated carbon emissions and the significance of being environmentally sustainable to the perishable food sector. Section 3.3 discusses and analyses the relevant studies. The author concludes this chapter with a summary of the main findings.

3.2 Sustainable Supply Chain Management

Seuring and Müller (2008) define sustainable SCM as the management of SC that aim towards fulfilling customer and stakeholder requirements in all three dimensions of sustainable development, i.e., economic, environmental and social.

Sustainability has become a highly relevant topic within both academia and industry. This is driven by an insight that SC performance should be measured not just by profits, but also by the impact of the chain on environmental and social systems (Pagell and Wu, 2009). Given the complexity and practical relevance, environmentally and socially sustainable operations will continue to be an important and rich research stream (Tang and Zhou, 2012). Hassini et al. (2012) reported that factors related to market forces, policy and regulations, science and technology, product development, process capability, sourcing and operations, transport and logistics, marketing and public relations and social issues are the major external and internal pressures that may push an SC to adopt sustainable operations. The interactions among the economic, enviromental and social dimensions can be described through the Profit, Planet and People (PPP) ecosystem as illustrated in Figure 3.1.

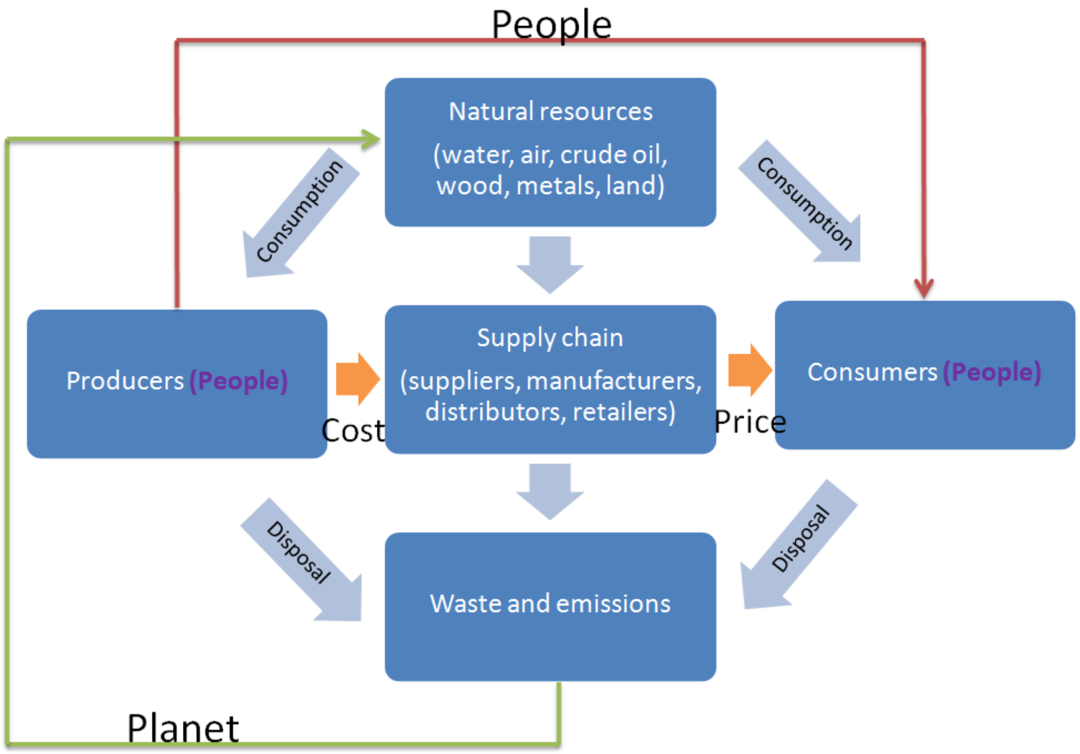


Figure 3.1 The PPP ecosystem: profit, planet, and people adapted from Tang and Zhou (2012)

This PPP ecosystem begins with the demand for products generated by consumers. The amount of products or services that consumers are willing and able to purchase at a given price during a given period of time represents consumer demand. Each SC partner uses natural resources and employs producers to produce and distribute the products. Aiming at SC performance optimisation, the flow as depicted by the orange arrows in Figure 3.1 involves all kinds of business activities, strategic to operational level decisions and incurred costs and revenues. However, these activities consume natural resources and inevitably generate wastes and emissions. This results in a number of serious environmental effects on the entire planet (the green arrow in Figure 3.1). The desire to minimise these negative impacts along with legal requirements and consumer pressures shape the organisation and SC operations and bring about changes in SC decisions towards less resources consumption, less waste disposal and lower generation of greenhouse gases (Akkerman et al., 2010).

Considerable research effort is being devoted to understanding and facilitating the incorporation of sustainability into SCM. The methodologies and approaches employed in dealing with sustainable SCM problems range from thought papers and perspectives, frameworks and approaches, reviews and empirical studies to mathematical modelling approaches (Srivastava, 2007). Formal mathematical models are simplified representations or abstracts of reality that are based on a set of variables and their causal relationship (Brandenburg et al., 2014).

Seeing that sustainable SCM requires the understanding and identification of complex trade-offs, managers in many industries need a framework and practical tools that can help them set priorities and make decisions that are both financially and sustainably sound (Gupta and Palsule-Desai, 2011). Moreover, reviews on sustainable SCM such as the ones done by Carter and Easton (2011), Dekker et al. (2012), Hassini et al. (2012) and Wilding et al. (2012) help confirm that providing tangible outputs such as an appropriate framework or model intersecting environmental and/or social performance and economic performance is required. These research contributions highlight the possibility for firms to address the multitude of decisions and to clearly demonstrate their environmental and ethical behaviour. This confirms a rich opportunity for researchers and practitioners to collaborate on developing formal models that serve as decision support tools for managers to more fully understand and integrate sustainable SCM into business thought and practice (Gupta and Palsule-Desai, 2011).

3.2.1 Modelling techniques for sustainable SCM

Model-based quantitative research is when models of causal relationships between control variables and performance variables are developed, analysed and tested (Bertrand and Fransoo, 2002). The models developed in this type of research can both explain (part of) the behaviour of real-life SC processes and capture (part of) the decision-making problems that are faced by managers (Akkerman et al., 2010). They are built with an aim to support decision-making on strategic and tactical levels, which often includes extensive scenario analysis, as well as on an operational level that needs quick solutions and the possibility to re-plan on an ad-hoc basis. However, a compromise between model complexity and reality is necessary due to the broad spectrum of an SC. The scope of the model should be defined in such a way that is reflective of key real-world dimensions, yet not too complicated to solve (Min and Zhou, 2002).

After an investigation of research developments and directions for formal modelling in forward sustainable SCM, Seuring (2013) and Brandenburg et al. (2014) derived categories of models and tools that are employed in quantitative sustainable SCM as listed in Table 3-1.

Table 3-1 Modelling and its analytic categories based on Seuring (2013) and Brandenburg et al. (2014)

Modelling	Analytic Categories
Model goal	Win-win situations, minimum performance for environmental and social issue, trade-offs
Model purpose	Deterministic, stochastic
Model type	Analytical, heuristics, hybrid, mathematical programming, simulation
Model technique	Artificial intelligence, business game, discrete-event simulation (DES), game theory, algebraic equations, Markov chains/queuing, meta-heuristics, multi-criteria decision making, multi-objective, simple heuristics, single objective, spreadsheet calculation, system dynamics, systemic models
Solution approach	Analytic hierarchy process/analytic network process (AHP/ANP), ant colony optimization, Bayesian networks, case based reasoning, data envelopment analysis (DEA), differential evolution, dynamic programming, fuzzy logic, genetic algorithm, tabu search, simulated annealing, goal programming, greedy randomized adaptive search procedure, input-output-analysis (IOA), LCA, linear programming/mixed integer linear programming (LP/MILP), metrics, neural networks, nonlinear programming, petri net, particle swarm optimization, queuing, rough set, simulated annealing, variation inequality.

The overall target of managing an SC is usually a cost minimisation effort. Further goal relations can be set to sustainably manage SC (Seuring, 2013). Win-win situations can be aimed for when making decisions on choices of investments and improvements as well as analysing on a macro-level. In some models, minimum performance level of environmental and social standards is adhered to. The overall contribution of these models is to evaluate the consequences of introducing some sort of minimum performance criteria. For instance, environmental issues can be taken as minimum standards against which economic decisions have then to be made.

A decision goal dominating this stream of research is to find trade-offs between sustainability and the economic dimensions which are most often taken as a starting point for building models and planning respective actions. Trade-offs would be based on societal decisions based on Pareto optimality. Pareto optimality explores and gives a set of best alternatives which is called the Pareto optimal set (Coello Coello, 2006, Dekker et al., 2012, Pareto, 2014). The vectors of the decision variables corresponding to the solutions included in the Pareto optimal set are called non-dominated. The plot of the objective functions whose non-dominated vectors are in the Pareto optimal set is called the Pareto front. As illustrated in Figure 3.2, a Pareto optimal solution on the Pareto front can be seen as an optimal trade-off between the objectives A1 and A2.

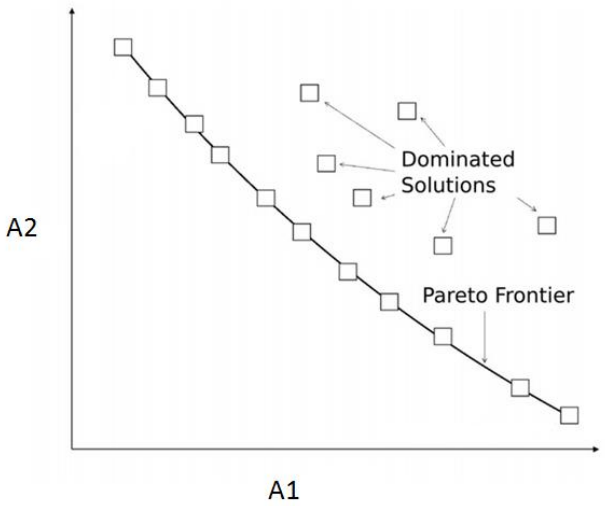


Figure 3.2 Example of a Pareto front

Deterministic models treat future scenarios as occurring with certainty through an assumption of known and fixed model parameters. Stochastic models take into account the uncertain and random elements in the SC such as customer demands, lead times, and production fluctuation (Min and Zhou, 2002).

Methodologically, the models can be grouped into five main types. An analytical model is used to support rational analysis of SC. Analytical approaches relevant for the food sector have appeared mainly in the context of inventory management of perishable products (Akkerman et al., 2010). Heuristics is a simplification process that attempts to quickly find a good solution to a decision problem. Decision makers recognise patterns in the situations they face and apply rules of appropriate behaviour to those situations (Shapiro, 2006). Heuristics are widely used to solve complex problems. Hybrid models are the combination of different modelling approaches with complementary strengths that can be combined in hybrid algorithms. However, as their modelling styles may be different and possibly incompatible, the issue of problem formulation may perhaps exist (Hooker, 2011). Mathematical programming methods provide powerful and comprehensive tools for accommodating large quantities of numerical data describing the SCs (Shapiro, 2007). In mathematical programming for SC planning problems, variables that are manipulated, such as shipping quantities or production batch sizes, would usually be referred to as decision variables while performance variables such as logistics costs, service level or emissions level would be referred to as objectives (Akkerman et al., 2010). Simulation is commonly used for scenario generation and analysis (Srivastava, 2007). It permits managers and analysts to study the dynamic behaviour of an SC with an easier decision logic employed than that of a mathematical programming model (Shapiro, 2007). The simulation model has already been proven to be useful for measuring the bullwhip effect (Min and Zhou, 2002).

The resulting category system of modelling approaches, which is depicted in Figure 3.3, is based on the classification of Brandenburg et al. (2014). The selection of a specific technique used for problem formulation depends on a multitude of factors such as the nature of the problem, the nature and availability of data, familiarity with the technique, compatibility between the analysis and solution techniques envisaged, previous related works and the wish to use new emergent techniques (Srivastava, 2007).

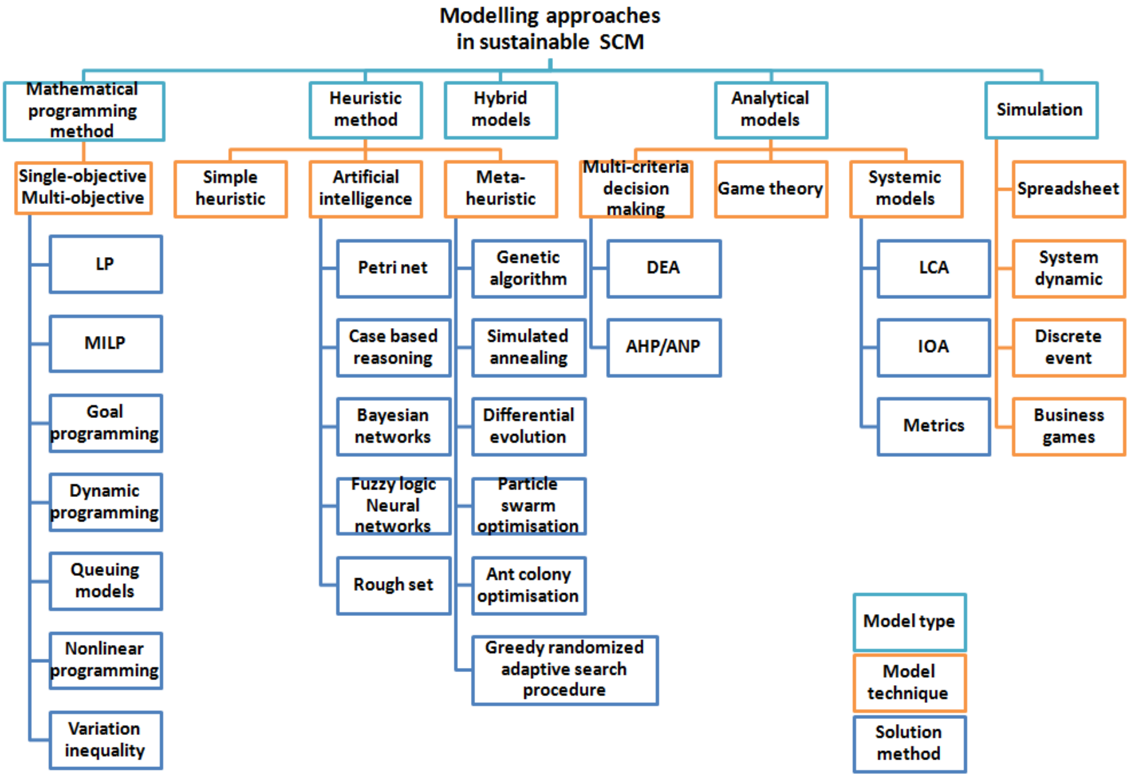


Figure 3.3 Analytic categories of modelling adapted from Brandenburg et al. (2014)

A variety of techniques is employed for different types of models. In inventory management, EOQ-type algebraic formulae are dominant (Srivastava, 2007). Markov chains have been used in inventory-related problem formulations. Computer programming and software packages such as spreadsheets have been used for input, interface and computations. Multi-criteria decision making showcases the idea of meeting different criteria at the same time (Seuring, 2013). Cardinal rankings of options for each criterion and cardinal weightings for the criteria are employed in the decision making process to identify a single most preferred option, to rank options, to short-list a limited number of options for subsequent detailed appraisal, or simply to distinguish acceptable from unacceptable possibilities (Dodgson, 2009, Steele et al., 2009). The value of multi-objective optimisation lies in providing a set of alternative options (trade-off solutions or compromise policies) for system improvements rather than a single prescriptive solution (Dekker et al., 2012). In order to determine the set of options that all fit a predetermined definition for an optimum, Pareto optimality is normally adopted (Marler and Arora, 2004, Coello Coello, 2006). If there is no other feasible solution which would decrease some criterion without causing a simultaneous increase in at least one other criterion, that solution to a multi-objective optimisation is the Pareto optimal (Coello Coello, 2006). Many classical multi-objective optimisation methods such as weighted sum approach, ε-constraint method, weighted metric method, value function method, goal programming method, weighted goal programming etc. convert the problem into a single-objective optimisation one that only provide a Pareto-optimal solution in each individual simulation run (Shankar et al., 2013). To manage a set of conflicting objectives, goal programming (GP) minimises the (weighted) sum of deviations between the target values (i.e. specific numeric goals) and the realised results (Charnes and Cooper, 1977, Rifai, 1996). Cakravastia et al. (2002) employed the weighted GP to measure two objectives into a single objective of the end customer's level of dissatisfaction.

Despite the extensive literature on multi-objective programming, determining eco-efficient frontiers using multi-objective mixed integer programming models is quite new (Dekker et al., 2012).

Looking at modelling solution approaches, linear programming is the most common technique used for problem formulation, followed by dynamic programming. Dynamic programming is used when inventory control, waste disposal and cost considerations are taken into account (Srivastava, 2007). It is an iterative, recursive method for efficiently identifying optimal solutions to sequential optimisation problems (Shapiro, 2007). Linear programming models were originally devised to optimise the allocation of scarce resources to economic activities in a complex system (Shapiro, 2007). All data regarding the future, such as costs, capacities, sales and so on are assumed to be known with certainty. This important assumption could seriously limit the validity of any LP solution to an SC problem. However, multiple scenarios of an uncertain future can be constructed and an LP model can be optimised for each scenario. LP models can also be adapted to measure trade-offs among conflicting objectives by tracing out the efficient frontier of solutions.

Mixed-integer programming models are generalisations of LP models in which some variables, called integer variables, are constrained to take on nonnegative integer values with binary variables (Shapiro, 2007). These variables are employed in models to address operational problems of sequencing and routing decisions; tactical problems of fixed costs, economies of scale, and a variety of logical policy restrictions; and strategic problems of the timing, sizing, phasing and location of investment options in an SC. This method is capable of finding good solutions and can yield optimal solutions. However, it takes a long time to process.

With an attempt to handle the complexity of decision making and to give an emphasis to the influence of decision makers, the analytical hierarchy process (AHP) is one of the dominant approaches (Seuring, 2013). AHP allows taking different decision criteria that are connected in a logical manner into account and evaluating them without necessarily connecting all of them into one quantitative model. This approach may also be called multi-objective decision making that simplifies and structures decisions through managerial judgments.

Additionally, having the environment as a focal point, LCA based approaches and impact criteria clearly dominate (Seuring, 2013). These solution approaches, in addition to dealing with the environmental issues, make respective SC related decisions clearer.

It is worth noting that the ultimate choice of modelling approach from those shown above is driven as well by the sustainability aspects to be considered (Brandenburg et al., 2014). The environmental part of sustainability in an SC will be discussed in what follows.

3.2.2 Carbon-efficient supply chains

Among formal sustainable SCM models, most of them neglect the social factor. Holistic models covering all sustainability dimensions have gained attention in the last ten years but are often employed for macroscopic analyses (Brandenburg et al., 2014). Therefore, the environmental dimension of sustainability has received much more effort from researchers and practitioners. Energy demand and CO_2 emissions are among the frequently mentioned topics (Seuring, 2013). Following the regulation imposed by governments on carbon emissions, the interactions of firms can be modelled under different schemes of carbon tax, agreed carbon target or emissions trading (Tang and Zhou, 2012).

Sundarakani et al. (2010) consider carbon emission as heat flux. This heat flux increases as a product enters each of the SC participants with its intensity depending on the performance of various product and process drivers of the SC as shown in Figure 3.4. The processes consume energy and emit carbon and other wastes.

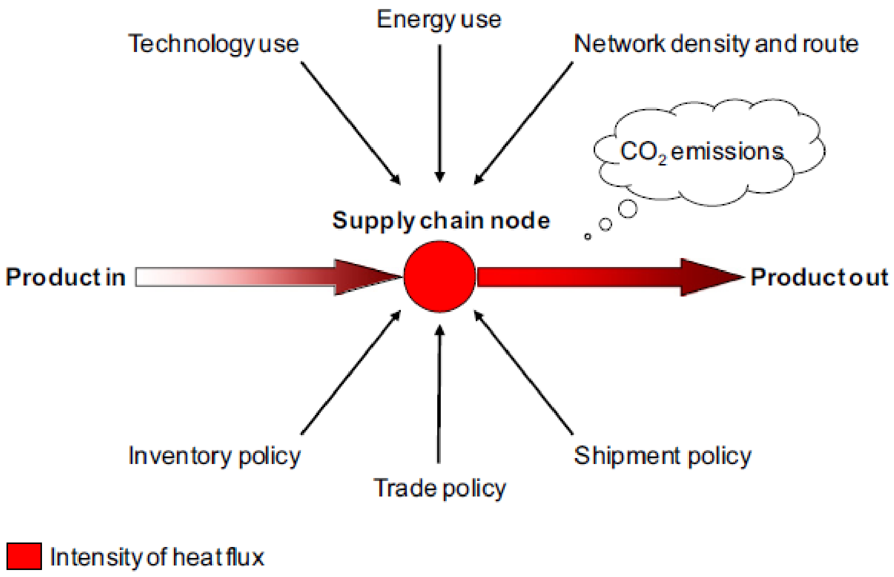


Figure 3.4 Driving forces of green SC taken from Sundarakani et al. (2010)

The emissions associated with each SC process and decision can be put into a group as in Table 3-2 and may correspond to direct emissions from fuel consumption, indirect emissions from the consumption of electricity or the sum of both.

Table 3-2 SC decisions and their emissions based on Sundarakani et al. (2010), Dekker et al. (2012) and Benjaafar et al. (2013)

SC decision phase	Decisions regarding	Associated emissions
Strategic	Number, location and capacity of facilities	Transportation, production, warehouse operations, investment in technology
	Production	Concepts - JIT, the way products are assembled and transported (e.g. importing finished products, transporting parts and assembling locally or repackaging)
	Sourcing	Near shoring vs. far shoring
	Transportation	Mode of transportation; speed of transportation; distance travelled; choice of fuel used; concepts such as consolidation and direct trips vs. milk runs
Tactical	Pricing and emission trading	Revenue management, choice of carbon emission trading schemes
	Procurement	Choice of environmental investments with suppliers
Operational	Inventory holding	The storage of each unit held in inventory in each period
	Ordering	Transportation
	Production	Process setup, the production of each unit
	Transportation	Route navigation, vehicle routing, the handling of each unit

Firms put their efforts into reducing emissions due to physical processes by replacing energy inefficient equipment and facilities, redesigning products and packaging, searching for less polluting sources of energy or introducing energy saving programs (Benjaafar et al., 2013). However, business practices and operational policies are also another potentially significant source of emissions requiring attention. Production operations and transportation are the two major sources of emissions owing to the fuel and energy consumption involved (Tang and Zhou, 2012).

Emissions from production and inventory decisions

Abdallah et al. (2012) supported that the manufacturing process was where most carbon emissions and resource consumption occurred through an LCA that was performed under different carbon trading scenarios in a PC industry case. Carbon embedded in raw materials supplied, emission levels based on travelled distance and weight transported and the amount of emissions from facilities were the main sources of carbon emissions considered in this two-level multi-commodity facility location problem. Benjaafar et al. (2013) looked into procurement, production and inventory planning under different regulatory emission control policies and showed that making operational adjustments in cases where emission and cost parameters were not strongly correlated and with SC collaboration as an alternative (or a supplement) to costly investments in carbon-reducing technologies can lead to effective emissions reduction without a significant increase in costs. Soysal et al. (2014) found that either energy consumption from production and/or inventory related operations or fixed emission factor per unit produced or stocked is considered in quantitative models with production and inventory related emissions.

As inventory management has been extended to include sustainability that links inventory and ordering behaviour to emissions, several inventory models have been developed that include considering an environmental constraint to be satisfied and considering the environmental function as an objective function, as well as adding some modifications to the classical inventory models like the EOQ model and the lot sizing problem. Table 3-3 gives an overview of the inventory models developed by researchers in response to the emerging interest in sustainability.

Table 3-3 Emissions included inventory models

Studies	Emissions consideration
Venkat (2007)	Impact of batch size in terms of carbon emissions
Chen and Monahan (2010)	Accounted for demand and environmental uncertainties in firms' decisions of production planning and inventory control under regulatory and voluntary pollution control approaches
Tao et al. (2010)	Included green cost into EPQ and EOQ models
Bonney and Jaber (2011)	Included vehicle emissions cost into EOQ model but left out emissions from storage
El Saadany et al. (2011)	Accounted for customers' pressure through price and products' environmental quality dependent demand in two-echelon SC model
Hua et al. (2011)	EOQ model under cap and trade system with emissions from logistics and warehousing activities
Bouchery et al. (2012)	Accounted for decision makers' preferences with trade-offs in multi-objective EOQ model under different regulatory policies regarding emissions from ordering and inventory holding
Song and Leng (2012)	Included emission constraint in Newsvendor problem under four regulatory policies
Absi et al. (2013)	Included different types of carbon emission constraints into lot-sizing model for maximum impact allowed per unit of product
Arslan and Turkay (2013)	Included environmental criteria e.g. carbon emission and working hours into EOQ model under different environmental management policies through additional objectives and/or constraints
Benjaafar et al. (2013)	Lot sizing model under four regulatory policy settings regarding emissions from ordering, production and inventory holding
Chen et al. (2013)	Included carbon footprint constraint into EOQ model under four environmental regulations with emissions from ordering, production/purchasing and inventory holding
Jaber et al. (2013)	Included manufacturing emissions into two-echelon

	SC model under different emissions trading schemes
Bozorgi et al. (2014)	Included emissions from and unit capacities of inventory holding and transportation in EOQ model

Emissions from transportation decisions

Transportation CO_2 emissions amount to some 14% of total emissions, both at a global and an EU level (Stern et al., 2006). Piecyk and McKinnon (2010) studied the most relevant factors for carbon emissions in road transport. The relationship between the weight of goods produced/consumed and freight-related carbon emissions can be defined with reference to key variables that are influenced by a range of logistics-related decisions, product characteristics and external factors (Figure 3.5). Generally, the emissions resulting from transportation activities can be calculated using either fuel-based or distance-based methodologies. Ubeda et al. (2011) created a list of some criteria for determining the feasibility of each approach, as can be seen in Table 3-4, based on the Greenhouse Gas Protocol Initiative (2005). Regardless of the methodology used, the load carried is an important parameter that influences carbon emissions (McKinnon, 2000).

In quantitative models with emission consideration for logistics management, researchers basically employ two approaches to measure the emissions from transportation operations (Soysal et al., 2014). The first approach, which is preferred most, is using fixed emission or environmental impact factors per distance unit and/or per weight unit, per product, per vehicle, which are obtained through other environmental studies. The second approach is estimating emissions indirectly by calculating total energy consumed from transportation operations while considering the aforementioned parameters such as distance, speed or weight.

Table 3-4 Fuel-based method vs. distance-based methods based on Ubeda et al. (2011)

	Fuel-based method	Distance-based method
Advantage	More reliable	Easy to obtain data
Drawback	Not easy to calculate	High levels of uncertainty
Calculating emissions	• Collect data on distance travelled by vehicle type and fuel type • Convert distance travelled data into fuel use values based on fuel economy factors • Convert fuel estimate to CO_2 emissions by multiplying fuel use values by fuel-specific factors	• Collect data on distance travelled by vehicle type and fuel type • Convert distance estimate to CO_2 emissions by multiplying distance travelled by distance-based emission factor

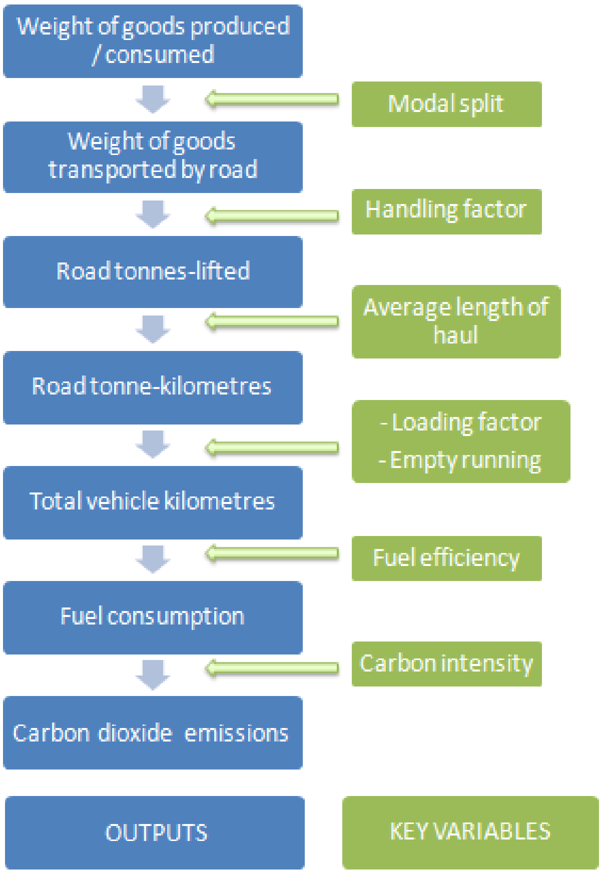


Figure 3.5 Relationship between logistical variables and environmental impacts based on Piecyk and McKinnon (2010)

Furthermore, determining how frequently supply deliveries are made could be as important in mitigating carbon emissions as the energy efficiency of the vehicles used to make these deliveries (Benjaafar et al., 2013). Ubeda et al. (2011) did a case study on the Spanish food distribution sector to study how the environment would be affected positively from some operational changes in logistics system.

Emissions from SC decisions

Consider a situation when a firm requires shipments from its suppliers with short notice, suppliers then have little choice but to keep large inventories. For certain products such as those requiring refrigeration, the associated carbon footprint can be significant (Benjaafar et al., 2013). Therefore, aligning an individual firm's operational strategies with those of their upstream suppliers and downstream customers would generate the largest sustainable benefit (Tang and Zhou, 2012). Moreover, involving SC partners in joint efficiency initiatives, such as joint shipments or production schedules towards SC coordination, may result in lower emissions.

The literature on carbon footprint management in SCs is quite limited with a small number of studies focusing on the measurement method of carbon emissions in SCs. Cholette and Venkat (2009) employed a web-based tool to calculate the energy consumption and carbon emissions associated with each transportation link and storage echelon under different SC configurations in a wine SC. An analytical model was developed by Sundarakani et al. (2010) to measure carbon emissions across the closed loop end-to-end SC as shown in Figure 3.6. A multi-objective LP model for sustainable SC design under the emission trading scheme that considers the LCA principle was introduced by Chaabane et al. (2012). Carbon dioxide equivalent quantity (CO_2e) is used in the environmental objective function to evaluate carbon emissions resulting from operation strategies, manufacturing and transportation activities. Tseng and Hung (2014) attempted to place a value on the social costs of emitting carbon that gives estimation on the monetary value of the damage made by the emission of one extra ton of CO_2 at some point in time. They proposed a mixed integer nonlinear model to optimise production and distribution operations under different social cost rates that tend to increase gradually in an apparel manufacturing SC network.

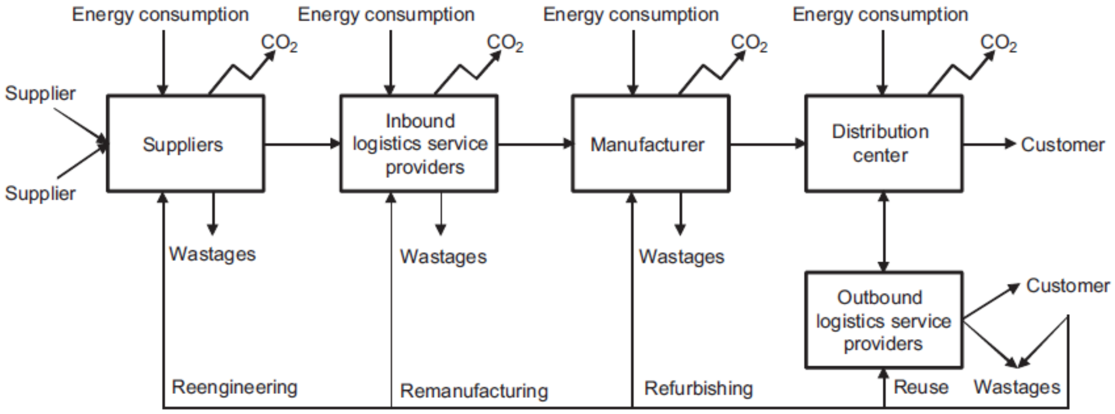


Figure 3.6 Stages of the closed loop end-to-end SC taken from Sundarakani (2010)

Benjaafar et al. (2013) reported an implicit assumption used by any public policy that emissions are measurable and quantifiable. Working under this assumption towards regulatory policy compliance and consumer communication, firms are documenting the carbon footprint of their activities with support from emerging emissions measuring standards, availability of independent third parties for emission verification and certification and availability of emission data such as ones provided by GHG Protocol, the Environmental Protection Agency (Nepal et al.) and the Office of National Statistics in the U.K..

PAS 2050 (BSI, 2011) is an example of a publicly available specification that provides a method for assessing the life cycle of GHG emissions of products. According to The Guide to PAS 2050: 2011, the footprinting process can be carried out in a sequential series of steps as illustrated in Figure 3.7. When starting on scoping activities, the following are necessary:

- an up-to-date bill of materials or standard operating procedure for product/packaging or service providers;
- production/energy use/waste statistics for operational activities;
- information on the distribution of product
- and a list of suppliers and supplier locations.

A carbon footprint can be a basis for reducing carbon emissions and energy use while also conveying a message of which parts of the life cycle, which materials and which processes should be target for reduction. When assigning a carbon footprint label, schemes must be devised to correctly and fairly attribute carbon emissions for products sharing the same production facilities, warehouses or transportation vehicles (Benjaarfar et al., 2013).

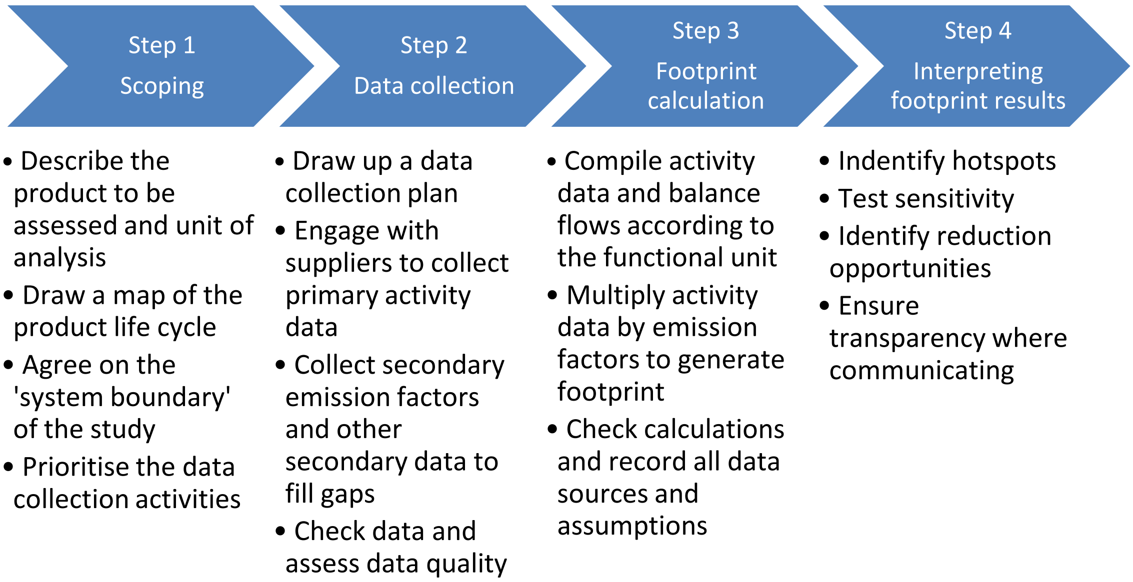


Figure 3.7 The stepwise footprinting process taken from The Guide to PAS 2050: 2011

3.2.3 Managing an environmentally sustainable SC of perishable food

Food SCs are complex global networks, creating pathways from farms to consumers, involving production, processing, distribution and even the disposal of food (Van der Vorst, 2000, Trienekens and Zuurbier, 2008, Ahumada and Villalobos, 2009). This business sector contributes to some 23% of global resource use, 18% of greenhouse gas emissions and 31% of acidifying emissions (EEA, 2010). According to Manzini and Accorsi (2013), the most important environmental impacts generated within a generic food SC are presented in Figure 3.8. Resource inputs (e.g. land, water, energy and fossil fuel) generate outputs (e.g. waste, emission to air and soil loss) as impacts on the environment at different levels of the chain (e.g. procurement, food processing, handling and consumption).

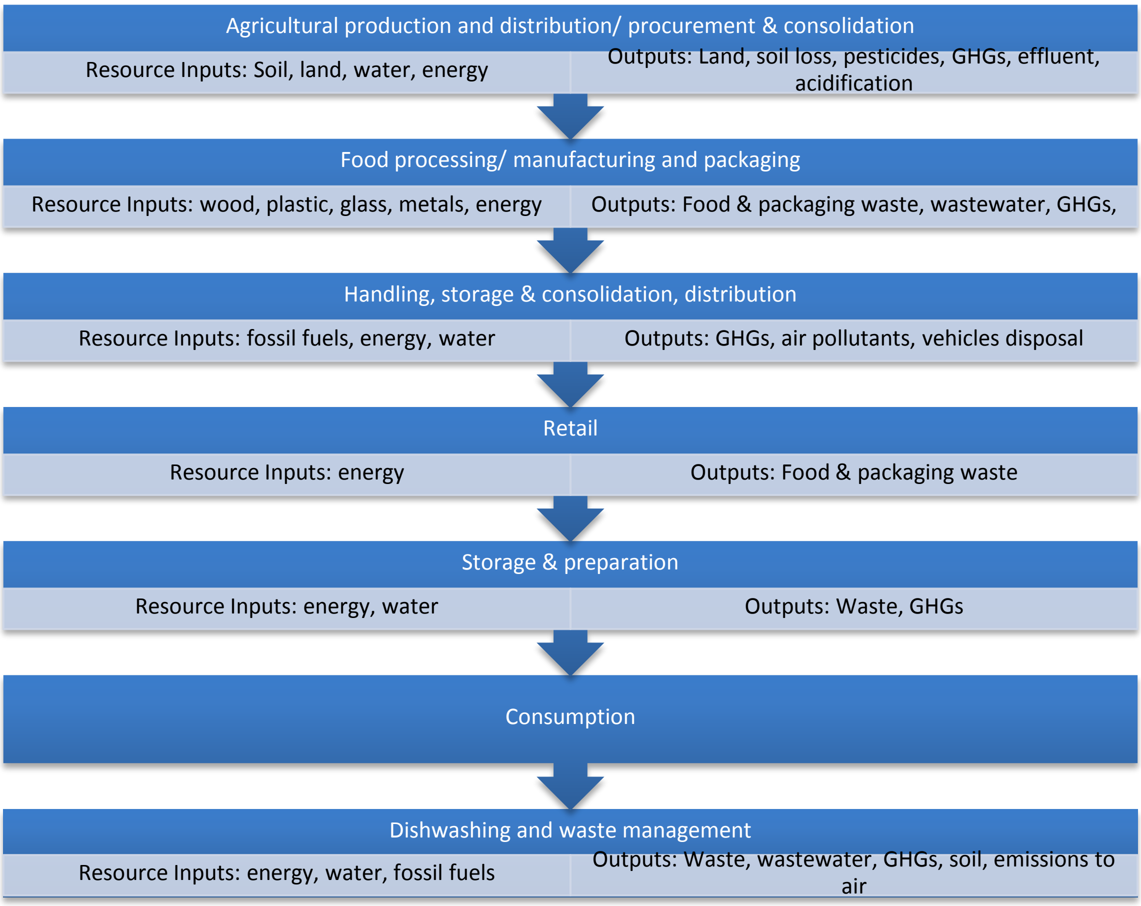


Figure 3.8 Food SC environmental impacts adapted from Manzini and Accorsi (2013)

Bourlakis et al. (2014) classified 18 sustainability measures relevant to food SCs as shown in Table 3-5. These measures can be grouped into five categories in a performance measurement framework adapted from literature contributions, namely: consumption, flexibility, responsiveness, product quality and total SC. The framework takes into account the characteristics of seasonality in production, product safety and sensory properties found in food chains, allows chain-wide measurement and accommodates the inclusion of non-financial measures which are important in the sustainability context.

Table 3-5 Sustainability SC performance measures adapted from Bourlakis et al. (2014)

Performance element	Sustainability measures	Description
Consumption	1.Production/ operational/raw materials cost	A measure of firm’s direct internal resource consumption in making the product that reflect the extent of firm’s achievement in deploying less resource intensive and more sustainable farming techniques and/or processing technologies.
	2. Storage cost	A measure of both energy consumption in making product available to other chain members and consumers in a fit-for-purpose condition and of resource consumption incurred when product is ‘idle’.
	3. Delivery cost	A measure of both energy consumption in making the product available to subsequent chain members and of responsible logistics management that reflect the extent of ‘scale and spread’ of a firm’s logistics operation.
	4. Waste	Waste minimisation is frequently identified as a core measure in food production caused by lost or wasted food. Wastewater, solid by-products, air pollutants and surplus heat are also common types of waste.
	5. Financial cost	A measure of resource consumption in administration operations which is likely to be minimised if the firm promotes employee well-being.
	6. Gross profit margin	A measure of the ability to grow and to provide returns for responsible investment given that sustainability performance is linked to market gains and economic viability.
Flexibility	7. Flexibility in extra volume orders 8. Flexibility in delivering in extra point of sales	Measures of a firm’s ability to re-route product and/or alter delivery volumes and the ability to deal with changes in demand or supply.
Resposiveness	9. Responsiveness in the arranged lead time 10. Responsiveness of delivery in terms of	Measures of the firm’s accuracy and ability to consistently get the right product in the righ place at the right time that reflect the ability of the chain members to avoid wasted product as it progresses through

	arranged point of sale	the food chain, and to deliver a high level of customer service.
	11. Responsiveness of delivery in terms of the ordered type of product (exact code, quality, etc.)	
Quality	12. Quality of the firm’s product	A measure used to address environmental anxieties via both customers’ and SC members’ confidence in the quality and safety of food products.
	13. Product conservation time (product shelf life)	In order to avoid exceeding the conservation time, the firm is required to plan the nature and timing of operations and delivery better.
	14. Consistency of traceability system	A measure of the firm’s ability to provide confidence to the consumers and other firms at each successive value-adding stage about the products’ quality, origin and safety, to provide rapid response in immediate product recall and to facilitate chain members’ mapping of product flows within the chain.
	15. Storage and delivery conditions	A measure of resource consumption as energy is needed for the temperature control process.
	16. Quality of packaging	A measure used to address demands from regulatory agencies and/or consumers for recyclable or returnable packaging and for clearer information on the nutritional and dietary characteristics of the food products.
Total SC	17. Firm’s perception of its own SC performance	Measures of consumer confidence in the food products with reputational implications and consequences to the firm’s longevity and sustainability.
	18. Firm’s perceptions of market opinion regarding its SC performance	

In relation to the high perishability of food products and excessive inventories, food waste/loss is an unwanted consequence (van Donselaar et al., 2006 and Yu and Nagurney, 2013). In most countries, around 30% of food products, including 20–60% of the total amount of agricultural fresh produce is said to be wasted throughout the SC (Widodo et al., 2006). Food waste problems could be caused by an increasing demand for fresh products, short product shelf-life, or lack of information sharing, just to name a few (Mena et al., 2011). Sufficient time and temperature should be given for the product to reach customer hands before the sell-by-date.

In an attempt to reduce the amount of wastes generated by reason of the perishable nature of food along the network flow, it is important to be aware that a large amount of energy is needed for the temperature control process during storage and transportation. This energy use implies the consumption of resources which directly influences the sustainability of the food SC considered, together with its economic performance (Zanoni and Zavanella, 2012).

Jones (2002) used transport-related fossil-fuel energy consumption and associated carbon dioxide emissions as the main criteria to compare the environmental efficiency of alternative fresh produce food SCs considering the global sourcing of food produce, centralised distribution systems and shopping by car. Apaiah et al. (2006) explored the potential of using an analysis of energy requirements, called an exergy analysis, to study and compare the environmental impact of food SCs due to its ability to identify problem areas in chains and aid in identifying losses and inefficient uses of natural resources. Exergy described as a thermodynamic unit that gives a numerical value to energy quality is used more or less the same as in LCA to measure the ability of a source to produce useful work.

Ahumada and Villalobos (2009) offered an updated review of production and distribution planning models in an agri-food SC and confirmed attention gained by argument and different approaches. Akkerman et al. (2010) presented a comprehensive review of food quality, food safety and sustainability aspects in quantitative operations management research on food distribution management and the challenges faced by the industry. Owing to the rising awareness of sustainability, this emphasizes the richness of decision-making options in food SCs that could be revisited with environmental sustainability in mind. Table 3-6 gives an overview of the studies that have been done.

Table 3-6 Quantitative models that incorporate environmental sustainability

Studies	Model type	Decisions	Environmental consideration	Application area
Akkerman et al. (2009)	MILP	(PT)I*	CO_2eq	Meal elements
Van der Vorst et al. (2009)	Sim.	P(TI)	CO_2	Pineapples
Oglethorpe (2010)	GP	(PTI)	CO_2	Pork
Rong et al. (2011)	MILP	PT	Waste disposal cost	Bell peppers
You et al. (2012)	mo-MILP	(PTI)	CO_2eq	Cellulosic ethanol sector
Zanoni and Zavanella (2012)	Analytical model	PTI	Energy consumption	Cold chain
Yu and Nagurney (2013)	Variation inequality	PTI	Waste disposal cost	Fresh produce
Bozorgi et al. (2014)	Exact algorithms	(TI)	CO_2	Cold chain
Govindan et al. (2014)	mo-hybrid	(PT)I	CO_2eq	Perishable food
Soysal et al. (2014)	MOLP	P(T)I	CO_2	Beef
Ting et al. (2014)	DSS	T	Quality assurance	Wine

* Parentheses refer to emission source, for instance, (P) refers to emissions from production or (PT) refers to emissions from production and transportation.

P: Production/Processing; T: Transportation; I: Inventory; CO_2: Carbon dioxide; CO_2eq: Carbon dioxide equivalent; MILP: Mixed-integer linear programming; mo-MILP: multi-objective MILP; mo-hybrid: multi-objective hybrid; Sim: Simulation; GP: Goal programming; MOLP: Multi-objective linear programming; DSS: Decision support system

Akkerman et al. (2009) presented a modelling approach for the sustainable production and distribution of professionally prepared meals using an environmental impact factor for producing one product unit and transporting one shipment of product combined with aspect of product quality. Oglethorpe (2010) introduced and illustrated the use of goal programming for alternative food SC strategies at local, regional and national levels. Emissions depend on weight of output produced and stocked, distance unit travelled and energy consumption for refrigeration of product, machine use, heating and lighting. The cold item inventory problem and associated emissions were studied by Bozorgi et al. (2014) who used the development of a set of exact algorithms to find the optimal order quantity based on both cost and emission function minimisation. They are compared against each other and the trade-off between the functions is analysed to provide insights. Govindan et al. (2014) proposed a multi-objective hybrid approach to integrate sustainability in decision-making into distribution for SC network design. The environmental impacts associated with opening facilities and shipping products, as well as variable environmental impacts produced by operational activities for each product produced and transported are considered.

Dealing with the change in food product quality, van der Vorst et al. (2009) embedded food quality models and sustainability indicators of energy use for transportation and inventory that are calculated and converted to realised emissions in discrete event simulation models to provide a new and improved means for analysing and redesigning food SCs of different scenarios. Zanoni and Zavanella (2012) examined food SC configuration problems considering the influence of temperature and storage time on product quality, costs and sustainability of the chain. The model proposed allows the understanding of the relationships among quality degradation, temperature and energy consumption. It addresses a possible approach to the chain optimisation in a cold chain of frozen French fried potatoes as an example. Ting et al. (2014) proposed a SC quality sustainability decision support system (QSDSS) to support managers in food manufacturing firms in defining good logistics plans in order to maintain the quality and safety of food products with a case study of a Hong Kong red wine company.

A model developed by Rong et al. (2011) combines decision-making on traditional logistical issues such as production volumes and transportation flows with decisions on storage and transportation temperatures so as to capture product quality degradation explicitly. Waste disposal cost is incurred when food quality fails to satisfy the quality requirement. Yu and Nagurney (2013) included the discarding costs associated with the disposal of spoiled food products into the proposed network-based model under oligopolistic competition in different scenarios prior/during/after a food borne disease outbreak with a case in the cantaloupe market. The model incorporates both product differentiation attributable to product freshness and food safety concerns and food deterioration through the introduction of arc multipliers. Each post-production link in the SC network, including a processing link, a shipment/distribution link, or a storage link, is assigned a multiplier (throughput factor) in order to capture the decay between initial and final product flow in number of units.

You et al. (2012) addressed the optimal design and planning of cellulosic ethanol SCs under all sustainability dimensions measured by the total cost; the life cycle greenhouse gas emissions considering an emission factor per output produced, distributed and stored; and the number of accrued local jobs. A multi-objective mixed-integer linear programming (mo-MILP) model that accounts for major characteristics of the chains, including supply seasonality and geographical diversity, biomass degradation etc. was developed and solved with an ε-constraint method and the resulting Pareto frontiers then revealed the trade-offs. Another model that is solved with the ε-constraint method is from Soysal et al. (2014) who developed a multi-objective linear programming (MOLP) model for a generic beef logistics network problem considering transportation emissions (affected by road structure, vehicle and fuel types, weight loads of vehicles and travelled distances), return hauls and product perishability. Trade-off relationships between multiple objectives are observed by the derived Pareto frontier that presents the cost of being sustainable from the point of reducing transportation emissions.

Under the ε-constraint method, one objective is selected for optimisation, whereas the others are reformulated as constraints. The method is used to solve the bi-criterion optimisation problem and generate the Pareto frontier to observe the dependency between the two objectives at a time. The right hand side value of the additional constraint is ε which represents the limit of a performance criterion, an objective not selected for optimisation. While deriving the Pareto frontier, initially, the optimal lower and upper bounds of this performance criterion are determined. The model is solved without the additional constraint and the resulting value of the performance criterion in that instance is set as an upper bound of the ε. To obtain the lower bound, an alternate objective is selected for optimisation. Afterwards, the additional constraint is activated and the right hand side value of the ε is progressively reduced in each instance with identical intervals between lower and upper bounds. In this way, we obtain an approximation of the Pareto frontier for the proposed model together with the optimal solutions for different values of a performance criterion.

3.3 Literature discussion

Along with attempting to implement sustainable operations, due to pressures facing companies, an SC should measure its performance by profits and its impact on the environment and society.

Considerable research effort has been expended on this sustainable SCM issue, which has proven to be a continuingly important research stream. As SC managers need a framework and practical tools to support their decisions, this demonstrates a rich opportunity for researchers to develop formal models for handling various chain activities in sustainable ways.

The relative wealth of literature on quantitative modelling for sustainable SCM indicates the extent to which the models and practical tools have been a focus of sustainable SCM research to date. Finding a trade-off point between sustainability and the economic dimensions based on Pareto optimality has been widely selected as the decision goal (Seuring, 2013). This literature review has illustrated a range of techniques and solution approaches employed within model-based quantitative research. A challenge for researchers is to develop appropriate stochastic modelling approaches to capture a more realistic uncertain decision environment for sustainable SCM (Brandenburg et al., 2014).

Through this review, it can be found that extensive research has been done in terms of the environmental dimension of sustainability. It is clear that carbon-efficient SCM is a key area for future research and a means to progress the efforts to reduce global emissions. Considering business practices, operational policies and coordination as the driving sources of emissions is underexplored in the reviewed literature and yet could hold the key to addressing the issues associated with curbing carbon emissions. There has been limited research into how production, inventory, transportation and general SC decisions can be harnessed to achieve environmental sustainability. Significant development in inventory issues is considered lacking (Hassini et al., 2012) and research literature to date has been limited in terms of inventory operations related emissions. This oversight may be because the emissions from inventory storage is particularly difficult to measure or less visible than transportation of products (Dekker et al., 2012), or it may not represent a vital source of emissions for firms involving products without deterioration. It is clear from the reviewed literature that energy consumption from SC activities or fixed emissions or environmental impact factor per a choice of unit conforming to the SC activity is considered in quantitative models as the measurement of the SC environmental sustainability (Soysal et al., 2014). Overall, it has to be concluded that studying carbon footprint measurement and integrating this environmental concern with the decision-making should offer interesting insights to better understand, quantify and analyse the impact of carbon emissions across SCs.

As is apparent from the reviewed literature, food industries and sustainability have both relevance and a growing presence within the SCM field. While several sustainability measures relevant to food SCs are considered in the reviewed literature, there are few practical measures commonly used in the research such as those related to consumption and product quality categories in the performance measurement framework explicitly owing to the perishable nature of food products. While the small body of sustainable SCM literature recognises the relevance of the waste problem to a perishable food SC, only selected studies take a more explicit approach towards modelling food waste across the SC. Properly modelling the changes in food properties, such as quality degradation or a decrease in lifetime throughout the network, would be of significant benefit. Related to this is an effort to reduce energy consumption in the temperature control process as well as associated carbon emissions along the chain, which would allow for better environmental efficiency. This is an area that deserves further, informed research.

Among the available literature, one approach (Bozorgi et al., 2014) explicitly mentions environmental sustainability in an inventory model of cold chain items. However, Bozorgi's approach towards environmental sustainability is related to emissions during transportation and warehousing, and not on perishability. Some recent approaches look at temperature and its influence on quality degradation of perishable food in relation to sustainable SCs (van der Vorst et al., 2009, Rong et al., 2011, Zanoni and Zavanella, 2012, Yu and Nagurney, 2013). Rong et al. (2011) and Yu and Nagurney (2013) take the food waste problem into account by considering the waste disposal cost. However, including the amount of food wasted along the SC in the modelling approach can be useful as waste also means resource consumption and could be used to evaluate the impact of decisions on the nature and timing of operations and delivery.

The inclusion of environmental impacts produced by operational activities in a multi-objective approach was seen in some recent work (You et al., 2012, Govindan et al., 2014, Soysal et al., 2014), but still seems to be in its infancy. Govindan et al. (2014) proposed a hybrid metaheuristic algorithm with the use of Pareto front as an archieve. In an alternative approach, You et al. (2012) and Soysal et al. (2014) used an ε-constraint method and the Pareto frontiers to observe trade-off relationships between cost and emissions objectives. Regarding the trade-offs in a multi-objective model, Bouchery et al. (2012) approached the inventory problem by using an interactive procedure that accounted for decision makers' preferences for non-perishable products.

In sum, there are still significant opportunities for researchers to identify efficient ways to improve sustainability measures, to address the issues associated with curbing carbon emissions, to reduce the impacts of food waste problems and to develop models that would improve the possibility for a practical approach to sustainability through decision-making in a stochastic environment to minimise the environmental impact of SC operations, which are currently lacking.

3.4 Summary

The interactions among profit, planet and people bring about SC decisions towards less resource consumption, less waste disposal and lower generation of greenhouse gases. The management of a sustainable SC requires practical and solid tools such as an appropriate framework and model that can help SC managers to address the multitude of decisions, to set priorities, to make decisions that are both financially and sustainably sound and to demonstrate their environmental and ethical behaviour.

Different categories of models and tools capable of reflecting key real-world dimensions and holding moderate solving difficulties are employed by literature in dealing with the SCM sustainability problem in accordance with the sustainability aspects considered, the goal relations set by the management, the purpose of the model environment studied, the type of the problem situation analysed, the technique used for problem formulation and the solution approach applied to obtain an answer to the problem.

Following the regulation imposed on carbon emissions, the interactions of firms can be modelled under different schemes of carbon tax, agreed carbon target or emissions trading. In an SC, the processes involved in different phases of decisions, i.e. strategic, tactical, and operational decisions, do consume energy and emit carbon and other wastages. The amount of carbon emissions depends on the performance of various product and process drivers of the SC whilst having production operations and transportation as the two major sources.

Approaches employed in literature to measure carbon emissions from production and inventory operations and transportation activities, as well as emissions in SCs involving chain partners, have been described and discussed. Under an assumption that emissions are measurable and quantifiable, firms are documenting the carbon footprint of their activities with a variety of support.

When measuring the environmental impacts generated within a food SC, a performance measurement framework comprised of five categories, namely consumption, flexibility, responsiveness, product quality and total SC can be used. Literature considering environmental sustainability in food sector including review papers and quantitative models developed has been investigated.

Chapter 4 Managing Inventory System with Deterioration: a Literature Review

4.1 Introduction

This chapter provides a literature review of the work that has been done on deteriorating inventory management. It aims to demonstrate the promising research directions and possible approaches in formulating these research problems. Section 4.2 starts with an overview of literature on existing quantitative models for inventory systems with deterioration. This section elaborates on the existing variations of the inventory problems considered by researchers regarding the product lifetime, customer demand, replenishment policy and numbers of echelon considered. Section 4.3 describes the current relationship between perishable food producers and their main customers, supermarkets. This section mentions reasons and challenges related to the need for research in this area. Section 4.4 discusses and analyses relevant studies. The author concludes this chapter with Section 4.5.

4.2 Inventory system with deterioration

Inventory holding refers to producing ahead of demand and sales realisations (Pahl and Voß, 2014). The total investment in inventories is enormous and accounts for nearly half of the total logistics cost (Lancioni, 2000). Owing to this significance, the management of inventory offers high potential for improvement and results in a relatively rich amount of literature on theoretic inventory models. In inventory planning and control, the performance measures adopted should encourage the positive aspects of holding inventory such as providing flexibility, providing resources for production, providing responsive customer service and acting as a buffer. However, at the same time, they should encourage the reduction of negative implications including high energy usage, high resource usage, pollution production and the unsustainability of the activities, for instance (Bonney and Jaber, 2011). Note that inventory arises in many different situations. It is unlikely that the same inventory planning and control considerations will apply equally to all categories of inventory.

Some type of products may undergo change in value in storage. They may become partially or entirely unfit for consumption in due course. This change or deterioration can be defined as any process that prevents an item from being used for its intended original purpose. Following its utility, the deteriorating item can be characterised into either an item whose functionality/physical fitness deteriorates over time (e.g. fresh food, medicine or gasoline) or an item whose functionality does not degrade, but where demand deteriorates over time as customers' perceived utility decreases (e.g. fashion clothes, high technology products or newspapers) (Pahl and Voß, 2014). Both categories pertain to the same problem but require different actions seeing that items that lose their functional characteristics and quality often cannot (or should not) be kept in inventory but items that lose perceived utility can be kept in inventory and may be sold on a secondary market.

The functionality/physical fitness deterioration includes spoilage for perishable food products, decay for radioactive substances, degradation for electronic components, loss of potency for photographic films and pharmaceutical drugs, and physical depletion for pilferage or evaporation of volatile liquids such as gasoline and alcohol (Raafat, 1991). An item is considered perishable if it requires specific storage conditions to slow down the high deterioration rate when at ambient, i.e. room temperature, storage conditions (van Donselaar et al., 2006). Perishable goods can be seen as items with a fixed, maximum lifetime when they become obsolete at some point in time due to their nature or external factors that predetermine their shelf lives. However, most authors working in the field of deterioration and perishability use these terms interchangeably (Pahl and Voß, 2014).

The main objective of inventory management for deteriorating items is to obtain optimal returns during the useful lifetime of the product (Pahl et al., 2007). This leads to three main issues: determining reasonable and appropriate methods for issuing inventory, replenishing inventory and allocating inventory. The choice of inventory valuation methods adopted in issuing inventory (i.e. the order in which the items are to be issued), such as methods based on time sequence including FIFO (first-in, first-out) and LIFO (last-in, first-out), depends on both the intrinsic characteristics of the inventory (e.g. lifetime, quantity, variety, issuing frequency etc.) and the influence on the company (e.g. inventory balance, cost of goods sold etc.) (Yu and Nagurney, 2013). Considering the replenishment of inventory, the penalty for ordering too much is the future penalty of outdating, marginal order cost, opportunity cost and a unit holding cost charged against each unit on hand at the end of the period, yet a penalty cost for excess demand will be charged when ordering too little (Nahmias, 2011). This penalty cost approach is employed in almost all deterministic studies done on deteriorating items while service level is used in stochastic models (Ghiami et al., 2013). When looking at the inventory allocation of deteriorating items for different customer types, the problem formulation would be application dependent. Allowing for several customers that demand different levels of item freshness (i.e. different residual life of items) in addition to high product availability, an allocation of items may need to consider different service levels and storage requirements for different customer types (Baron, 2010).

Consideration of perishability in the SC has received increased attention in both practice and academic research. The first comprehensive review on perishable products is found in Nahmias (1982). Raafat (1991) did a survey restricted to the study of continuously deteriorating models. Goyal and Giri (2001) presented an excellent review of the classification of products with deterioration and the policies needed to manage them. Li et al. (2010) and Bakker et al. (2012) provided a review of inventory models with deterioration that had been published since the review of Goyal and Giri. Readers are referred to Pahl et al. (2007), Ahumada and Villalobos (2009), Akkerman et al. (2010), Baron (2010), Karaesmen et al. (2011), Amorim et al. (2013) and Pahl and Voß (2014) for extensive reviews/surveys on papers managing production and distribution decisions of perishable inventories.

After Whitin (1957) initially introduced deterioration into the mathematical modelling of inventory control in relation to deteriorating fashion items after a prescribed storage period, many variations have existed that differ in assumptions and specifications of the models for deteriorating inventory. This has been done in an attempt to accommodate various realistic factors for complex decision models which may require considerable computational efforts. In the modelling of deterioration, customer demand plays a key role as it also affects the physical reduction of inventory. Therefore, deteriorating inventory models available in the relevant literature can be broadly distinguished along with the lifetime of products and characteristics of demand.

Readers are referred to Appendix A for a summary of literature on deteriorating inventory management reviewed by the author. The contents in this section are mainly derived from those published research works. Most deterministic studies done on deteriorating items seek to maximise the profit or minimise the cost. An attempt to achieve the required service level is seen in stochastic models.

4.2.1 The product lifetime

Deterioration reflects the physical condition, the productive or marketable life of products. A challenge of limited lifetime makes it difficult for SC members to simultaneously project demand, plan manufacturing, and meet supply in a timely manner (Govindan et al., 2014).

Depending on the category and storage facilities available, products deteriorate in different manners in terms of the initial point and rate. For example, the value of food products can decrease incrementally, while the death rate of plants in a nursery decreases with age (Banerjee and Agrawal, 2008). In accordance with deterioration patterns, inventory models can be classified into the following three categories (Bakker et al., 2012):

1. Models for inventory with a fixed lifetime, i.e. a predetermined deterministic shelf life of, for example, two days or one season.
2. Models for inventory with a time- or inventory-dependent deterioration rate.
3. Models for inventory with an age-dependent deterioration rate (which implies a probabilistic distributed lifetime, e.g. Weibull).

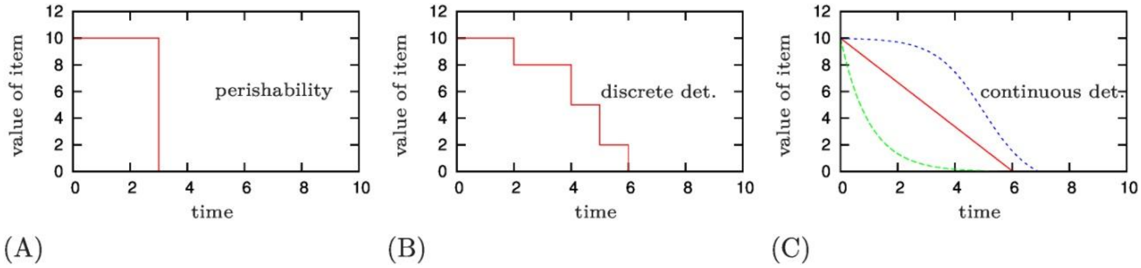


Figure 4.1 Courses of deterioration adapted from Pahl and Voß (2014)

Inventory with a fixed lifetime

Fixed lifetime inventory is a fundamental type in deteriorating inventory problems. Some attention has been focused on deteriorating items with expiration dates as well as perishable items with fixed time to perishability (see Figure 4.1A). The lifetime is determined, printed and affixed to the packaging of product in the form of a “use by/consume by” label under an assumption that the product will be maintained under time and temperature conditions that are “reasonably as expected during transportation and storage” (Kouki et al., 2013). An item must be disposed of if it is still left unused when the end of its lifetime is reached (i.e. an item becomes outdated).

A random lifetime product is a product with an exact lifetime that cannot be predetermined while in stock (Goyal and Giri, 2001). This uncertain time to deteriorate is represented by distributions such as exponential, Weibull, normal etc. and makes the inventory management more difficult than the fixed lifetime counterpart.

Inventory with time-dependent deterioration rate

Items may deteriorate with respect to time in either discrete or continuous fashion as shown in Figure 4.1B-4.1C. Considering the deterioration as a function of time is practical in situations, for instance, involving seasonality, items whose deterioration depends on time spent in storage, fast deteriorating items whose deterioration starts then accelerates with time (e.g. dairy products), items that experience sudden perishability due to disaster (i.e. exponential times between the disasters), fixed lifetime items in which aging of the fresh stock begins only after all remaining old units are depleted, or items whose demand drops (i.e. facing loss in value) when a new version or generation is introduced (Baron, 2010, Mishra and Sahab Singh, 2011, Pahl and Voß, 2014).

In the existing literature on inventory modelling with a time-dependent deterioration rate, exponential time decay has been utilised to describe either the decrease in quantity or the degradation in quality. Although the approaches are conceptually different, they both measure the loss of products by deterioration (Goyal and Giri, 2001). The decrease in quantity represents the number of units of deteriorated product. By assuming the time to deterioration of a product follows an exponential distribution, a fraction of stock on hand is lost each period regardless of the age distribution of inventory. On the other hand, the degradation in quality emphasises that all the products deteriorate at the same rate simultaneously. With an assumption that the loss in product value is well-fit by an exponential decay function, product quality decreases with respect to time.

The dynamics of quality degradation play an important role in modelling quality in food SCs. While much of the literature focuses on perishable products with fixed shelf life, for many fresh produce items, the moment of spoilage varies significantly with different temperatures and under other environmental conditions (Blackburn and Scudder, 2009, Rong et al., 2011, Zanoni and Zavanella, 2012, Fauza et al., 2013). In general, quality degradation of food products in storage or transport is dependent on storage time, storage temperature and various constants (e.g., activation energy or gas constant). This prediction of quality levels through time aids in the adoption of a markdown policy for retailers for the items affected by quality degradation. It is interesting to see how temperature affects shelf life in the modelling. However, in reality, sometimes it is not practical to change the temperature level as a temperature range that a company should abide by for storing different types of products has already been specified with the longest shelf life as the goal.

Inventory with inventory-dependent deterioration rate

The rate of deterioration of some items such as peaches, apples etc. depends on the on-hand inventory. In addition to natural deterioration, such as evaporation of some products, there is another type of deterioration commonly taking place due to self contact (i.e. when fresh produce is stored together, bruising or other damage is possible) or collision (Maity and Maiti, 2009). This incurs loss to the growth rate of the inventory.

Inventory with age-dependent deterioration rate

Age-dependent deterioration is considered by assuming the lifetime to be a random variable. The time to deterioration can be assumed to be normally distributed over time. Normally distributed shelf life is chosen as it is one of the most important probability phenomena in the real world due to the classical central limit theorem and it is also one of the most commonly used lifetime distributions in reliability contexts (Chen and Lin, 2002). If the number of aggregated inventory units is sufficiently large, the time of deterioration will be approximately distributed as a standard normal random variable regardless of the distribution of the individuals.

An assumption of non-instantaneous deterioration holds true in a situation when items have a span in which the quality or the original condition is maintained, that is to say that during that period there is no deterioration occurring (Ouyang et al., 2006, Wu et al., 2006, Chung, 2009, Chung, 2010). Researchers have discovered that many products that start deteriorating appreciably only after a certain period (e.g. after they are produced) and for which the rate of deterioration increases over time have a deterioration rate best described by a Weibull distribution (Chakrabarty et al., 1998, Chang et al., 2002, Giri et al., 2003, Banerjee and Agrawal, 2008, Pahl and Voß, 2014). The time of deterioration is a random variable following either a two-parameter (i.e. scale and shape parameters) Weibull distribution or a three-parameter (i.e. scale, shape and location parameters) Weibull distribution. The two-parameter Weibull distribution, which is a generalised form of exponentially decaying function, can be used to model either an increasing or decreasing rate of deterioration, according to the choice of the parameters. A three-parameter Weibull distribution enables one to handle the rate of deterioration that is any of the three types: incremental, decreasing or constant (Banerjee and Agrawal, 2008).

Mathematical formulation

A rich literature on modelling of deteriorating inventory shows how the deterioration of products has been captured in the research problem up till now. To integrate deterioration into mathematical models, the model type (deterministic or stochastic) and the considered time horizon (infinite or finite) lead to specific methods (Pahl and Voß, 2014). The lifetime characteristics can be modelled in various ways as below.

The deterioration can be captured in value per unit outdated through an increase in holding cost, a charge on deterioration cost or a partial return of money if there is a salvage value. The cost of deteriorated items is acknowledged and can be equal to the unit cost, the disposal cost or in proportion to the carrying cost.

The deterioration can be implicitly captured either by using the rate of deterioration (e.g. shrinkage factor due to perishability or percentage of inventory that is lost) on on-hand inventory to measure the decrease in quantity, named by Pahl and Voß (2014) as fraction formulation, or by having the planning horizon set as shorter than/equivalent to the expected product lifetime periods when spoilage is not considered in the model. The use of fraction formulation by assuming that all products in inventory undergo the same transformation independent of their age or their production period is limiting seeing that deterioration is not avoided when deriving optimal replenishment decisions. Therefore, formulations that restrict products' lifetimes are required.

The deterioration can be captured explicitly through the use of formulations for lifetime restriction that might involve the modification of the inventory balance equation of related optimisation models. The index transformation method as addressed by Pahl and Voß (2014) restricts the considered time periods by the lifetime of items. The considered production time periods can be constrained by specifying that just enough products must be produced to carry on satisfying customer demand for the length of the variable lifetime of the product after the production run stops. The duration of inventory holding can be restricted by allowing the product to be held in stock only to the maximum period of product lifetime (Xu and Sarker, 2003, Soysal et al., 2014). However, this approach excludes perishability by limiting and prohibiting periods in inventory. Responding to this need, a constraint is formulated via a modification of the inventory balance equation. By subtracting items that are past their lifetimes when updating the inventory level helps enforce that the outdated inventories are removed. Another approach used to integrate the maximum storage time for perishable inventory is to observe the inventory state (i.e. the total number of on-hand inventory and their age distribution) at each period. Also, a (continuous) decrease in product value over time can be observed such that its quality level can be predicted throughout the system. Another stochastic method to integrate deterioration assumes that the age values of ordered items arriving in inventory are given by a vector of age classes of items and defined to be independent and identically distributed random variables. Also, the shrinkage of inventory might be assumed as a virtual outdating process similar to the virtual waiting time process in queuing theory (Pahl and Voß, 2014).

4.2.2 The demand characteristics

The customer arrival rate per time period may be deterministic or stochastic, each individual demand may be deterministic or stochastic and each individual demand may also be discrete or continuous (Baron, 2010). Demand plays a key role in the modelling of deteriorating inventory. Aiming towards meeting customer demand, companies employ demand forecasts as a prediction of customer behaviour. The following variations of demand labelled from the point of view of real life situations have been recognised and studied by researchers (Goyal and Giri, 2001). It is assumed that demand is known with certainty in a deterministic demand process. Stochastic demand process incorporated randomness and unpredictability.

A deterministic demand distribution can be categorised into:

1. Uniform demand, i.e. demand is a constant, fixed number of items
2. Time-varying demand
3. Stock-dependent demand
4. Price-dependent demand

A combination of the above is also possible. In the case of stochastic demand models, a further distinction is made between a specific type of probability distribution and an arbitrary probability distribution. Although modelling in a deterministic setting is more straightforward, a stronger focus on stochastic modelling of deteriorating inventory is suggested in order to better represent inventory control in practice since customer demand is variable in time and uncertain in amount. The demand rates for many products may vary by day, week and season depending on weather conditions, social needs, physical needs, trends, advertising or marketing efforts, actions that competitors have taken, events affecting that geographical region and a whole host of other factors (Langley et al., 2009, Chopra and Meindl, 2013). Therefore, it is likely that companies may face non-stationary stochastic demand for their products.

Uniform demand

In uniform demand, papers make an implicit assumption that the demand rate is constant over an infinite planning horizon. This assumption is only valid during the maturity phase of a product life cycle but not during the introduction and growth phase when firms face increasing demand with little competition (Dye and Ouyang, 2011). Furthermore, some papers assume the demand of deteriorating products occurs continuously over time and at a constant rate despite markdown, provided that the markdowns are aligned with the products' decreasing expected lifetime (Zanoni and Zavanella, 2007).

Time-varying demand

When the introduction of attractive products has an effect on customers' preference, the time-varying demand rate describes a downward sales trend for the products currently on the market. Considering deteriorating inventory, the physical loss of the materials plus the ageing of products with time may lead to the loss of consumer confidence in the quality of such products. This phenomenon represents the demand rate as a negative function of time. An example of this demand application can be seen in the retail grocery industry when the demand rate for some products varies on different weekdays. The demand rate is a function of time that reflects a situation when sales fluctuate through time or a change in sales through different phases of a product's life cycle in the market (Chen and Lin, 2002, Chen and Chen, 2005, Roy and Maiti, 2010, Maihami and Kamalabadi, 2012, Ghiami et al., 2013, Pahl and Voß, 2014).

In developing deteriorating inventory models, two kinds of time-varying demand have been considered so far: (a) discrete-time and (b) continuous-time (e.g. linear, power-form, log-concave or exponential). Some researchers suggest that the demand rate can be well approximated by a linear form. A linear trend demand implies a steady increase (or decrease) in demand (Ghosh and Chaudhuri, 2006, Dye and Ouyang, 2011). Demand for a product that is progressively gaining popularity is usually assumed a non-decreasing linear function of time (Banerjee and Agrawal, 2008). Another functional form adopted in inventory modelling is exponentially increasing (or decreasing) demand. The demand rate is assumed a linear function of the unit selling price that is an exponentially declining function with time (Lin et al., 2009). However, in real market situations, demand is unlikely to vary with a rate which is as high as the exponential (Ghosh and Chaudhuri, 2006). Quadratic time dependence seems to be a better representation of time-varying market demand (Khanra and Chaudhuri, 2003, Ghosh and Chaudhuri, 2006) The possible demand patterns accommodated in the quadratic form are accelerated growth in demand (e.g. seasonal products towards the beginning of the season), accelerated decline in demand (e.g. seasonal products towards the end of the season) and other types including ramp type growth, logistic growth, etc. Demand for some products, such as Christmas season consumer products, rate a ramp type function of time. The demand rate is any function of time (e.g. linear or exponential) up to the time-point of its stabilisation where the demand becomes a constant until the end of the inventory cycle (Giri et al., 2003, Skouri et al., 2011). The ramp type demand rate is commonly seen when a new brand of consumer goods is introduced into the market (Deng et al., 2007). Furthermore, the studies of market information revealed that trapezoidal demand, which is a piecewise time-dependent demand function, is more applicable than ramp type demand rate model in the stages of product life cycle (Cheng et al., 2011).

Stock-dependent demand

It is often recognised that demand for certain items depends largely on the instantaneous inventory level (Zhou and Yang, 2003, Balkhi and Benkherouf, 2004). It has been observed in supermarkets that the demand is usually influenced by the amount of stock displayed on the shelves (Hou, 2006). Therefore, each of products may be displayed in large quantities to generate greater demand. The problems of space allocation for each product, investment on the increased inventory levels and the deteriorating nature of products have influenced many marketing researchers and practitioners to analyse product assortment and shelf-space allocation models with stock-dependent consumption rates (Maity and Maiti, 2009). As it is desirable to maintain a large inventory for potential profits obtained from the increased demand, it is clear that the objective for an inventory system with this demand rate must be to maximise profit (Chang et al., 2010c).

Price-dependent demand

When the customers' purchasing capacity is taken into consideration, the price of a product mainly determines the volume of demand of that item in the market (Mahapatra and Maiti, 2005). The demand rate is a function of price that reflects a situation when sales increase as the price decreases (Maihami and Kamalabadi, 2012). The demand rate can be any non-negative, continuous, convex, decreasing function of the selling price (Chang et al., 2006, Hou and Lin, 2006, Dye, 2007). However, with today's global competition, many firms have no pricing power such that the selling price is hardly changed (Chern et al., 2008).

Stochastic demand distribution

Demand functions for products are generally uncertain down to external factors such as changes in trends or events affecting that geographical region, or internal factors such as marketing efforts. In this situation, an assumption is made that the demand is unknown but its probability distribution can be identified. Hence, the manager facing stochastic customer demand does not operate with perfect knowledge of the future.

Stochastic demand may lead to chaotic production processes in peak situations and idle times in low demand situations. For that reason, various safety factors including better forecasting, human resource flexibility, over capacity or safety stock can be held in order to guarantee satisfactory customer service levels. Another line of research in the stochastic inventory models has focused on a service objective given that shortage costs or opportunity costs may be hard to determine in applied situations. The service level can be defined as a minimum probability that at the end of every period the net inventory will not be negative (i.e. the company is able to fulfil customer demand).

Specific type of probability distribution

Different forecasted demand functions and their mathematical representations have been adopted in the modelling of a deteriorating inventory problem. In a situation when the inventory is depleted at the demand rate, the demand function can be assumed to follow normal distribution with particular mean and standard deviation values (Shen et al., 2011). Demands in different periods are assumed random and sensitive to selling price but independent of each other (Pang, 2011). The market demand for the product is assumed to fluctuate over the selling price and its freshness level having one realisation of random factor in the freshness parameter. The demand rate can then be expressed in the multiplicative functional-form (Chakravarthy and Daniel, 2004). The demand process is assumed to be modelled by a Brownian motion with certain drift and variance values (Benkherouf et al., 2003). Demand arrival is assumed to follow a renewal process with random batch sizes (Gürler and Özkaya, 2008).

In a situation when the requested item may require extra processing, the inventory managers need to consider the queue length and the waiting time in addition to the mean inventory level and holding time to evaluate the system performance and hence to implement various control policies. (Cai et al., 2010, Yadavalli et al., 2011) . In this inventory model, the inventory is depleted at the rate at which the service is completed. The arrival of customers can follow a Markovian arrival process (MAP) or are assumed Poisson-distributed. The service time has exponential distribution or any general distribution depending upon the state of the system (Berman and Sapna, 2002).

Arbitrary probability distribution

Some authors considered the demand rate to follow an arbitrary probability distribution function by assuming the demand rate to be any positive function, to follow some probability distribution or to have a random fuzzy variable (Yang et al., 2011).

Non-stationary stochastic demand distribution

Taking a step closer to the real situations, non-stationary demand distribution can be used to represent sales of companies experiencing short product life cycles, seasonality or customer buying patterns, for instance. In this approximation, the demand per period is assumed a random quantity and the randomness is allowed to vary from one period to the next.

Inventory models have been developed so far over a prescribed non-stationary stochastic demand. A single-item, single-echelon production planning and inventory control problem with service level constraints has been considered by Pauls-Worm et al. (2010), Rossi et al. (2010b), Rossi (2013) and Pauls-Worm et al. (2014). Their papers extend the model of Tarim and Kingsman (2004) towards a model that includes non-stationary stochastic demand for a perishable product with an attempt to produce more implementable near optimal solutions to a stochastic dynamic lot-size problem.

The problem of making inventory decisions under non-stationary stochastic demand was considered by Bookbinder and Tan (1988) for non-deteriorating products. They developed a model adopting “static-dynamic” uncertainty strategy in solving the single-stage probabilistic lot-sizing problems that consider setup cost and service-level constraints. This strategy operates according to the non-stationary (R^n, S^n) replenishment policy. A series of review times R^n denoting the number of periods between two consecutive replenishments (i.e. replenishment interval time) and associated order-up-to-levels S^n are determined at the beginning of the planning horizon representing the static aspect of the strategy. Subsequently, the actual order quantities are decided only after observing the realised demand which confirms the dynamic aspect of the strategy. Tarim and Kingsman (2004) considered Bookbinder and Tan’s heuristic approach as a basis for the formulation of a mixed integer programming (MIP) model for the simultaneous determination of the number and timing of the replenishment orders that provide an optimal solution.

Tarim and Kingsman (2004) approached the problem with a chance-constrained programming model that can be expressed as the minimisation of the total expected cost, $E\{TC\}$, over the N-period planning horizon subject to the service-level constraints, as given below:

Minimise

$$E\{TC\} =$$

$$\int_{d_1}\int_{d_2}\dots\int_{d_N}\sum_{t=1}^{N}(a\delta_t + hI_t + vX_t) \times g_1\,(d_1)g_2(d_2)\dots g_N(d_N)d(d_1)d(d_2)\dots d(d_N) \tag{4.1}$$

subject to

$$\delta_t = \begin{cases} 1\; if\; X_t > 0, \\ 0\; otherwise, \end{cases} \qquad t = 1, \dots, N, \tag{4.2}$$

$$I_t = I_0 \sum_{i=1}^{t}(X_i - d_i)\,, \quad t = 1, \dots, N, \tag{4.3}$$

$$Pr\{I_t \geq 0\} \geq \alpha, \qquad t = 1, \dots, N, \tag{4.4}$$

$$X_t, I_t \geq 0, \qquad t = 1, \dots, N, \tag{4.5}$$

where X_t is the replenishment order placed and received (without lead time) in period t, δ_t a binary variable that takes the value of 1 if a replenishment order is placed in period t and 0 otherwise, I_t the inventory level at the end of period t, I_0 the stock on hand at the beginning of period 1, d_t the demand in period t, a the fixed procurement cost, v the marginal cost of purchasing an item, h the linear holding cost incurred on any unit carried over in inventory from one period to the next. The demand d_t in period t is considered as a random variable with known probability density function $g_t(d_t)$. The distribution of demand may vary from period to period. Demands in different time periods are assumed independent.

A fixed procurement cost is incurred each time a replenishment order is placed regardless of the order size. A variable purchasing cost is charged in relation to the size of the order. A replenishment order is assumed to arrive instantaneously at the beginning of the period before observing the demand. A linear holding cost is charged on the inventory at the end of each period. The probability that at the end of each and every time period the net inventory will not be negative is set to be at least α. It is implicitly assumed that since normally the desired service level is quite high, the value α incorporates the perception of the cost of backorders, so that shortage cost can be ignored in the model.

The general stochastic programming formulation above is then modified to incorporate the replenishment cycle policy. Consider a review schedule, which has m reviews over the N period planning horizon with orders arriving at $\{T_{1,}T_{2,}\dots,T_{m,}\}$, where $T_m \leq N$.

$$I_t = R_{T_i} - \sum_{k=T_i}^{t} d_k, \quad T_i \leq t < T_{i+1}, \quad i = 1, \dots, m \tag{4.6}$$

Note that R_{T_i} may be interpreted as an order-up-to-level to which stock should be raised after receiving an order at the ith review period T_i and $R_{T_i} - \sum_{k=T_i}^{t} d_k$ is the end of period inventory. This leads to the definition of order-up-to-levels R_t, which is $X_t + I_{t-1}$. In order to determine the number of reviews, m, the

T_i, and the associated $R_{T_i}$for $i = 1, \dots, m$, constraints (4.7)-(4.9) are given. If there is no replenishment scheduled for period t, then R_t equals the opening inventory level in period t and must be equal to I_{t-1}. In addition, R_t must be equal to the order-up-to-level if there is a review and the receipt of an order.

$$I_t = R_t - d_t, \qquad t = 1, \dots, N, \tag{4.7}$$

$$R_t \geq I_{t-1}, \qquad t = 1, \dots, N, \tag{4.8}$$

$$R_t - I_{t-1} \leq \boldsymbol{M}\delta_t, \qquad t = 1, \dots, N, \tag{4.9}$$

where $\boldsymbol{M}$ is a large positive number. The values for the order-up-to-level variables, R_t, when $\delta_t = 1$ are then those that give the minimum expected total cost $E\{TC\}$.

From constraint (4.6), the required service level in each period denoted in constraint (4.4) can then be written alternatively as

$$Pr\left\{R_{T_i} \geq \sum_{k=T_i}^{t} d_k\right\} \geq \alpha, \qquad t = 1, \dots, N, \tag{4.10}$$

which implies

$$G_{d_{T_i}+d_{T_{i+1}}+\cdots+d_t}\left(R_{T_i}\right) \geq \alpha, \qquad T_i \leq t < T_{i+1}, \quad i = 1, \dots, m \tag{4.11}$$

and

$$I_t \geq G^{-1}_{d_{T_i}+d_{T_{i+1}}+\cdots+d_t}(\alpha) - \sum_{k=T_i}^{t} d_k, \qquad T_i \leq t < T_{i+1}, \quad i = 1, \dots, m \tag{4.12}$$

The right-hand side of constraint (4.12) can be calculated or possibly read from a table, once the form of $g_t(.)$ is selected.

In constraint (4.12), $G^{-1}_{d_{T_i}+d_{T_{i+1}}+\cdots+d_t}(.)$ can only be calculated after the replenishment periods T_i are known. But, as these are chosen to minimise the expected total cost, the stock replenishment periods cannot be determined until the appropriate $G^{-1}_{d_{T_i}+d_{T_{i+1}}+\cdots+d_t}(.)$ values to use in the model are known. There is an obvious circularity here in trying to solve the problem. Bookbinder and Tan avoided this circularity by separating the determination of the timing of the replenishment orders and the adjustments to those orders yet the optimality is sacrificed. However, there is an alternative way to overcome this problem which is to formulate it as a mixed integer linear programming (MILP) model.

Since the problem has a finite planning horizon of N periods, $G^{-1}_{d_{T_i}+d_{T_{i+1}}+\cdots+d_t}(.)$ can be calculated for all relevant cases. If the binary integer variable P_{tj} is defined as taking a value of 1 when the most recent order prior to period t was in period $t-j+1$ and zero elsewhere, then $G^{-1}_{d_{T_i}+d_{T_{i+1}}+\cdots+d_t}(\alpha)$ can be expressed as

$$G^{-1}_{d_{T_i}+d_{T_{i+1}}+\cdots+d_t}(\alpha)=\sum_{j=1}^{t}G^{-1}_{d_{t-j+1}+d_{t-j+2}+\cdots+d_t}(\alpha)P_{tj}, \qquad t=1,\dots,N \qquad (4.13)$$

and similarly constraint (4.12) can be expressed as

$$I_t \geq \sum_{j=1}^{t}\left(G^{-1}_{d_{t-j+1}+d_{t-j+2}+\cdots+d_t}(\alpha)-\sum_{k=t-j+1}^{t}d_k\right)P_{tj}, \qquad t=1,\dots,N \qquad (4.14)$$

The result $P_{t1}=1$ means that the stock review was at the start of period t itself. At most, there can be only one most recent order received prior to period t. Thus, the P_{tj} must satisfy

$$\sum_{j=1}^{t}P_{tj}=1, \qquad t=1,\dots,N \qquad (4.15)$$

The following constraint is designed in compliment to constraint (4.15) to uniquely identify the period in which the most recent order prior to period t took place:

$$P_{tj} \geq \delta_{t-j+1}-\sum_{k=t-j+2}^{t}\delta_k, \quad t=1,\dots,N, \quad j=1,\dots,t \qquad (4.16)$$

Note that the “static–dynamic uncertainty” strategy is adopted as the decision rule for the above stochastic optimisation problem. Given that an analysis is completed at the beginning of the horizon before any of the demands become known, the expectation operator must be applied to the stochastic variables in the constraint equations and objective function. Therefore, the deterministic equivalent model may be obtained by taking expectations. The mixed integer programming model then is

$$\text{Minimise } E\{TC\}=\sum_{t=1}^{N}(a\delta_t+hE\{I_t\}+vE\{R_t\}-vE\{I_{t-1}\}), \qquad (4.17)$$

subject to

$$E\{I_t\}=E\{R_t\}-E\{d_t\}, \qquad t=1,\dots,N, \qquad (4.18)$$

$$E\{R_t\}\geq E\{I_{t-1}\}, \qquad t=1,\dots,N, \qquad (4.19)$$

$$E\{R_t\}-E\{I_{t-1}\}\leq M\delta_t, \qquad t=1,\dots,N, \qquad (4.20)$$

$$E\{I_t\} \geq \sum_{j=1}^{t}\left(G^{-1}_{d_{t-j+1}+d_{t-j+2}+\cdots+d_t}(\alpha) - \sum_{k=t-j+1}^{t} E\{d_k\}\right) P_{tj}\,, \quad t = 1, \dots, N, \tag{4.21}$$

$$\sum_{j=1}^{t} P_{tj} = 1, \qquad t = 1, \dots, N, \tag{4.22}$$

$$P_{tj} \geq \delta_{t-j+1} - \sum_{k=t-j+2}^{t} \delta_k\,, \qquad t = 1, \dots, N, \tag{4.23}$$

$$E\{I_t\}, E\{R_t\} \geq 0, \quad \delta_t, P_{tj} \in \{0,1\}, \qquad t = 1, \dots, N, \;\; j = 1, \dots, t. \tag{4.24}$$

Several extensions of Tarim and Kingsman's model exist. Rossi et al. (2010a) and Rossi et al. (2012a) incorporated a stochastic delivery lead time and developed both complete and fast heuristic approaches. Rossi et al. (2010a) further addressed the problem with stochastic supplier lead time. Random variables are divided into two sets and each is dealt with in a separate fashion. The scenario-based approach is employed for the random variables $\{l_t | t = 1, \dots, N\}$ which represent lead times. A deterministic equivalent modelling approach is employed for the random variables $\{d_t | t = 1, \dots, N\}$ which represent demand. They modelled the situation in which the lead time is deterministic and dynamic (i.e. it may take a different deterministic value in each period) that corresponds to what is observed within any given scenario.

An inventory holding cost is charged based on the current inventory position to reflect interest incurred on both the actual amount of items in stock and the outstanding orders since companies may assess holding cost on their total invested capital. The inventory position at the end of period t denoted as P_t directly follows that

$$P_t = I_t + \sum_{\{i|1 \leq i \leq t, l_i + i > t\}} X_i\,, \qquad t = 1, \dots, N, \tag{4.25}$$

where X_i is the size of the replenishment order placed in period i, $X_i \geq 0$ (received in period $i + l_i$). Substituting for the inventory position, constraint (4.4) becomes

$$Pr\left\{P_t \geq \sum_{\{i|1 \leq i \leq t, l_i > t-i\}} X_i\right\} \geq \alpha, \qquad t = 1, \dots, N, \tag{4.26}$$

where l_t is the lead time length of the order placed in period t, a discrete random variable with a probability mass function $f_t(.)$.

Some modifications to the service level constraints are made following the inclusion of positive supplier lead time. The target stock is adjusted to include the stock necessary to cover the demand during the supplier lead time. The lead time in each period varies and assumes a given deterministic value. This dynamic deterministic lead time L_t is then generalised in the case in which the lead time is stochastic and assumes a different distribution from period to period; refer to Rossi et al. (2010a) for the formulations. Define $T_{p(t)}$ as the latest review before period t in the planning horizon, for which all the former replenishment orders, including the one placed in $T_{p(t)}$, are delivered within period t, therefore

$$p(t) = max\left\{i \middle| \forall j \in \{1, \dots, i\}, T_j + L_{T_j} \le t, \quad i = 1, \dots, m\right\}, \quad t = 1, \dots, N \tag{4.27}$$

$$I_t = R_{T_{p(t)}} + \sum\nolimits_{\left\{i \middle| i>p(t), L_{T_i}+T_i \le t\right\}} \left(R_{T_i} - R_{T_{i-1}} + d_{T_{i-1}} + \cdots + d_{T_i-1}\right) - \sum\nolimits_{k=T_{p(t)}}^{t} d_k \tag{4.28}$$

for all $t = 1, \dots, N$. Depending on the values assigned to L_t, it is not possible to provide the required service level for some initial periods. In general, the required service level α starting from the period t, for which the value $t + L_t$ is minimum. Let A be this period. Notice that it will never be optimal to place any order in a period t such that $t + L_t > N$, since such an order will not be received within the given planning horizon. Substituting I_t, constraint (4.11) becomes

$$G_s\left(R_{T_{p(t)}} + \sum\nolimits_{\left\{i \middle| i>p(t), L_{T_i}+T_i \le t\right\}} \left(R_{T_i} - R_{T_{i-1}}\right)\right) \ge \alpha, \qquad t = A, \dots, N \tag{4.29}$$

Where $s = \sum_{k=T_{p(t)}}^{t} d_k - \sum_{\left\{i \middle| i>p(t), L_{T_i}+T_i \le t\right\}} \left(d_{T_{i-1}} + \cdots + d_{T_i-1}\right)$, and $G_s(.)$ is the cumulative distribution function of s.

When perishability and FIFO issuing policy are taken into account, Pauls-Worm et al. (2010, 2014) formulated this problem as a deterministic equivalent MILP model that was constructed using a commercial MILP solver for business use (e.g. CPLEX). However, Rossi et al. (2010b) approached this stochastic model with a deterministic equivalent constraint programming (CP) model with a suggestion on extension of positive lead time.

Solving the (mixed integer) linear optimisation problem is a complex task due to the multidimensional and hierarchical structure. Choosing the right solver to model the problems can be a time-efficient alternative to implementing original code. Ison and Caire (2008) gave a review of optimisation solvers such as CPLEX and MATLAB along with their algorithms and main advantages.

Furthermore, Meindl and Templ (2012) described and compared software tools from both open-source and commercial solvers that come with different licenses, costs and features in terms of how problems can be specified and the algorithms that are incorporated to solve problems, for instance.

Popular and well-known free and open source solvers including GLPK, LP_SOLVE, CLP, SCIP and SoPlex can be used without any restrictions in any software since the source code is released in the public domain and usually very well documented. These solvers can be compiled on different platforms and architectures. The commonly and widely used commercial LP-Solvers include Xpress, Gurobi, CPLEX and MATLAB. The IBM ILOG CPLEX Optimization Studio simply referred to as CPLEX is actively developed and designed by IBM to tackle (among others) large scale (mixed integer) linear problems. CPLEX is unique in having additional algorithms to solve highly degenerate, sparse problems and problems with more variables than equations (Ison and Caire, 2008). MATLAB is a computing language developed by The MathWorks®. The Optimization Toolbox is an extension of MATLAB that contains algorithms written in open source code for solving standard and large-scale problems. Although in tests CPLEX has been shown to be the faster solver, the ubiquity of MATLAB makes it highly accessible to many users (Ison and Caire, 2008). It can be noted from Meindl and Templ's (2012) research that using only open source solvers will likely not lead to a fast solution of the problem if any. Commercial solvers do a much better job as was, for example, shown by Mittelmann (2010) for mixed linear integer test cases.

CP is a declarative programming paradigm in which relations between decision variables are stated in the form of constraints which has proved to be a very effective technique for decision making under uncertainty (Rossi et al., 2012b). In papers by Pauls-Worm et al. (2010, 2014) and Rossi et al. (2010b), the chance-constrained model originally proposed by Bookbinder and Tan (1998) were extended with the following modified formulations.

To handle a product with a fixed lifetime, the age of the inventory is tracked as time passed. $I_{b,t}$ is introduced denoting the inventory level at time t with age $b = 1, \dots, Q$. Items of age Q cannot be used in the next period so period t starts with the inventory level at the end of period $t - 1$ at ages $b = 1, \dots Q - 1$.

$$E\{TC\} = \int_{d_1}\int_{d_2}\cdots\int_{d_N}\sum_{t=1}^{N}\left(a\delta_t + h\sum_{b=1}^{Q-1} I_{b,t} + vX_t\right) \times g_1(d_1)g_2(d_2)\ldots g_N(d_N)d(d_1)d(d_2)\ldots d(d_N) \quad (4.30)$$

$$X_t = R_t - \sum_{b=1}^{Q-1} I_{b,t-1} \quad (4.31)$$

$$\sum_{b=1}^{Q} I_{b,t} = R_t - d_t \quad (4.32)$$

Rossi (2013) discussed a number of production/inventory control policies that may be adopted in this periodic-review, single-location, single-product inventory system under non-stationary demand and service level constraints. The policies included a deterministic equivalent scenario based MILP model as well as Rossi et al.'s (2010b) CP model, for instance. A similar problem was considered in Minner and Transchel's (2010) dynamic inventory control method for food retailing in which the simplifying assumption that fixed ordering costs are negligible was adopted.

4.2.3 Replenishment policy

Researchers make different assumptions regarding policies on shortages when considering the product and market characteristics (Ghiami et al., 2013). An assumption that shortages are not allowed is critical when developing a blood bank model or optimising a distribution system for a group of pharmaceuticals as these products are related to health issues. Service level is normally adopted as an objective function. However, when there are similar products in the market and differences are negligible, it can be assumed that the shortages are lost. Sometimes customers wait for the orders if the products offered have a specific characteristic or outstanding quality. In the inventory control, different replenishment policy can be adopted under either periodic or continuous reviews.

Periodic (discrete) review

Under the periodic review policy, papers have considered the optimal control policy, the base stock policy that keeps a constant order-up-to-level for total items in system, other heuristics, and, when fixed ordering costs are present, the *(s*, *S*) and *(R, S*) policies, for instance.

Most of the research in replenishment policy for deteriorating inventory is dedicated to stock-level dependent policies including order-up-to *S* and *(s*, *S*) policies. Order-up-to policies are suggested as good approximations of optimal policies (Duan and Liao, 2013). With these operating policies, the facility replenishes its inventory according to its target order-up-to level. In an order-up-to without age consideration *(s*, *S*) policy, whenever the inventory level drops to *s*, an order for *Q* (=*S*-*s*) items is placed (Sivakumar, 2009). The order-up-to level can vary from day to day. However, these policies do not acknowledge the perishable nature of the product and are therefore generally suboptimal. Considering perishables with a fixed maximum shelf life, Haijema (2013) proposed a new class of stock-level dependent policy, the *(s*, *S, q, Q*) policy, which is a periodic review (*s*, *S*) policy with the order quantity restricted by a minimum (*q*) and maximum (*Q*). This simple policy is preferred for practical use given that only the total stock level is required as an input. This approach is developed in avoidance of the computational complexities by using some statistics from the optimal ordering policy computed by formulating and solving the underlying Markov decision problem as a benchmark.

For the management of inventory when products have reached end of life status, it can be considered that the deteriorated units are not repaired or replaced during the planning horizon (Wang, 2002, Balkhi and Benkherouf, 2004, Hsu et al., 2007, He et al., 2010, Cheng et al., 2011). However, due to new information technologies such as RFID, it is now economically feasible to track the age of the products. This leads to the development of inventory replenishment policies with age consideration.

The replenishment policy where an order size must be adjusted upwards to account for the deteriorated items has received attention by many researchers (Gürler and Özkaya, 2003, Zhou and Yang, 2003, Broekmeulen and van Donselaar, 2009, Rossi et al., 2010b, Rossi, 2013, Pauls-Worm et al., 2014). In this policy, the order quantity will be the difference between the current inventory level/position and the order-up-to-level, after disposing of the outdated items. Broekmeulen and van Donselaar (2009) named this method the EWA. This policy works similarly to the base order-up-to policy except that the inventory position (including outstanding orders in addition to the physical inventory) is corrected for the estimated amount of outdating and an order is placed if this revised inventory position drops below the target order-up-to level. With the known inventory state at the current period, the possible number of outdated items is determined. In the non-stationary (R^n, S^n) policy considered by Pauls-Worm et al. (2010, 2014), Rossi et al. (2010b) and Rossi (2013), the order-up-to level S^n for each period is corrected for the expected waste by explicitly considering for every period the expected age-distribution of the products in stock. Pauls-Worm et al. (2010, 2014) addressed this policy as a “waste-compensating” replenishment cycle policy.

Duan and Liao (2013) proposed an age-based replenishment policy called the old inventory ratio policy (OIR). This policy operates under the base order-up-to policy that takes an old inventory ratio (the proportion of “old” items to the total items on hand) into account. The definition of an old item is defined as an item with residual lifetime of a certain number of days that could also vary subject to optimisation with respect to the length of its lifetime. If the ratio exceeds a certain threshold level, an additional replenishment with the size of the total number of “old” items is triggered to account for the possible outdating.

Continuous review

Under continuous review policy, papers have considered the base stock policy, the *(s*, *S*) policy or the *(r*, *Q*) policy when batch sizes are fixed and the *(Q*, *r, T*) policy that orders when inventory is depleted below *r* or when items exceed *T* units of age, for instance.

A more realistic base stock policy with variable ordering quantity and arbitrary replenishment times has been considered in a continuous review perishable system (Kalpakam and Shanthi, 2001). At every demand period, an order for items is placed to restore the inventory position back to the maximum stock level *S*. There is no order initiated by deteriorated items for practical and economical purposes such that the continuous monitoring of items can be avoided.

Tekin et al. (2001) considered the modified lot-size *(Q*, *r, T*) replenishment control policy that involves both the inventory level and the remaining shelf life of the items in stock. A replenishment order of size *Q* is placed either when the inventory drops to *r*, or when *T* units of time have elapsed since the last instance at which the inventory level hit *Q*, whichever occurs first. Concerning the specified aging process, *T* corresponds directly to an age threshold for reorder, whereas, *r* is an inventory level threshold for reorder in the classical sense.

The perishable inventory is controlled with an *(r*, *Q*) review system in the inventory model proposed by Kouki et al. (2013). At each unit of time the inventory position is monitored. If it falls to or below the replenishment level *r*, an order of size *Q* is placed. The expected outdating quantity associated with an order is calculated following the replenishment policy. It is assumed that items arrive fresh in stock and there is no decrease in the value of products during their fixed usable lifetime. Additionally, the benefit of using time temperature integrator technology (TTI) on inventory management is investigated in this research. The TTI makes it possible to monitor product freshness and provides information on the products' remaining shelf lives. The probability of products having a certain lifetime, which affects the expected outdated quantity, is integrated into the model.

4.2.4 The multi-echelon supply chain

Multi-echelon SC involves multiple stages of firms in a SC. Multi-echelon inventory control is gaining importance due to the need for SC integration. However, only a few deteriorating inventory related works do exist (Lystad et al., 2006). This is mainly due to the added complexity in replenishment and allocation decisions involving age-composition of inventory, logistics-related decisions relating different remaining product lifetimes, and centralised vs. decentralised planning concerning consequences from different, conflicting operating rules (i.e. retailers require LIFO but a supplier prefers FIFO) (Karaesmen et al., 2011).

Deterioration complicates the replenishment and allocation processes. In determining the replenishment decisions for deteriorating products, the manager should account for not only the total inventory level but also the age distribution (freshness) of the stock and its position in the SC in cooperation with their SC partners up- and downstream such that the items are processed within strict time limits avoiding the loss in value of items that may resulted in additional costs, loss of resources, increased energy consumption, related CO_2 emissions and unsatisfied customers waiting for products (Pahl et al., 2007, Duan and Liao, 2013). The information required in the characterisation of the inventory level process involving the tracing of the age/quality of the deteriorating items includes the stock level of each possible age category which is a massive set of possible inventory states that simply becomes too large for computation. Furthermore, item dispatching decisions to fulfil orders when items of several different ages coexist also requires consideration of the age distribution of the on-hand inventory since the value of older items in stock is lower than that of the newer ones for deteriorating products in general.

Deterioration adds an extra dimension to the logistics-related problem. Logistics is all about managing the flow of materials and information from source to customer that involves various decisions and their effect on items' shelf life. For the distribution planning tasks, a supplier may need to increase the frequency of deliveries in order to achieve better customer service regarding product freshness, which, in turn, may influence fleet dimensioning (Amorim et al. 2013). For the transport planning, some constraints may be forced on the travel duration or cooling costs may be included when determining decisions about the distribution quantities between echelons of the SC and outbound vehicle routings seeing that the temperature/time of the distribution can have an impact on the lifetime of the deteriorating items. Attaining high logistical performance of the inventory process by means of low delivery delay and/or high service level is often accompanied by a high inventory level that allows a safer buffering of volatile demands (Lutz et al., 2003). Therefore, managerial effort is required to ensure that short-expiry units are distributed and do not expired before reaching their buyers.

The different types of decision making can be characterised according to whether SC decisions are carried out in a centralised or decentralised way. The practice of decentralising decisions right to the person who is just at the decision spot and has specialised knowledge of his or her surroundings is commonly exercised in a SC that constantly faces the challenge of making timely decisions (Lee and Whang, 1999, Yu et al., 2001). In a decentralised SC, the members belong to different companies and each act as a single decision maker to optimise its own performance (Yu et al., 2001, Baboli et al., 2011). The inventories are controlled independently and provided with local information in the form of orders that arrive from the locations it directly supplies (Yu et al., 2001, Kalchschmidt et al., 2003). Uncertainty arises in the SC due to a lack of information and visibility of inventory status and cost structure about other members and the system. There is also a potential for incentive misalignment among members of the SC under this decentralised control (Lee and Whang, 1999). The inventory pressure of holding a substantial stock is often put on the upstream SC participants (or suppliers) such that the customer service level is maintained even when one member decides to reduce its inventories.

The negative impact of the bullwhip effect caused by the presence of uncertainty in a decentralised SC can be reduced or eliminated through increased information sharing with strategic partnership relations among SC members and coordination mechanisms (Yu et al., 2001). Coordination-based SCs have been advocated in past decades to respond quickly to customer needs and reduce the cost of carrying inventory for a multi-echelon SC (Wang et al., 2011). Furthermore, a set of corporate rules including how sites are to pay each other for transfer of goods, what performance metric should be applied to each individual manager, what operational constraints he or she should abide by, what fill-rate target should be achieved by the upstream manager so that the downstream manager may be guaranteed on-time deliveries for a percentage of its orders, and what penalty should be imposed on each stock-out can be put in place to mitigate the problem of incentive misalignment (Lee and Whang, 1999).

In multi-echelon inventory systems, one way of decreasing the inventory cost for suppliers is to obtain information about the buyers' demand and to centralise the replenishment decisions for all members of the SC (Baboli et al., 2011). Under the centralised control situation, a SC can be considered as a single firm (i.e. all members belong to the same company) striving for an optimum performance of the whole system (Yu et al., 2001). A centralised decision maker places replenishment orders based on knowledge of the entire SC inventory and the customers' demand information by having an access to global information that can be retrieved in a synchronised manner through electronic data interchange (EDI) (Lystad et al., 2006).

Few integrated inventory approaches for deteriorating items have been developed to date following the notion of cooperation between suppliers and buyers. Most multi-echelon deteriorating inventory models are restricted to two echelons except in the EOQ-based work (e.g. Wang et al. (2011)), the simulation-based work (e.g. van der Vorst et al. (2000)) and the network-based model (e.g. Yu and Nagurney (2013)). Motivated by food SCs, the upstream location(s) in the two-echelon models typically involve the supplier(s) or the distribution centre(s), and the downstream location(s) involve the retailer(s), or the warehouse(s). Some models include a third echelon or a return facility. A paper by Soysal et al. (2014) analyses a situation with more than three echelons in the MOLP model for logistics network problem. Analytical research in multi-echelon and multi-location systems has mainly focused on particular applications and heuristic methods owing to the complexity in obtaining or characterising optimal decision structures (Karaesmen et al., 2011). There is currently no work that investigates replenishment policies in continuous review with perishables for multi-echelons or multi-locations, although this is a well-studied problem for single-location models with perishables and for non-perishables in multi-echelon SCs.

4.3 Relationship between food producers and their buyers, supermarkets

Food and drink processing is the largest industrial sector in South West England (SouthWestFood&Drink, 2005). However, the region’s producers and processors face many competitive challenges within the industry and pressure from the big supermarket chains. The UK food, grocery and drink retail market was worth £174.5bn in the year to April 2014 (IGD, 2014) and is dominated by supermarket, convenience and discounter retail chains (e.g. Tesco, Sainsbury’s, SPAR, Londis, Aldi and Lidl). In the supply of products to consumers, supermarkets respond to consumer demand for lower prices and the convenience of buying all one’s grocery needs under one roof along with shareholder demand for better returns.

The SC journey starts from field or factory to finished products on supermarket shelves. Suppliers large or small have limited access to end consumers through only a small number of supermarkets which leads to considerably less bargaining power as Figure 4.3 below shows (Nicholson, 2012). This allows supermarkets the opportunity to squeeze and dictate the terms of business after economies of scale and also transfer costs and risks on to their suppliers

(FarmersGuardian, 2007). The ability that allocates more favourable buying terms to supermarkets is called buyer power (Nicholson, 2012). This buyer power arises from the retailer power of the supermarkets themselves. The increase in retail market share facilitates supermarkets to secure better deals from their suppliers in order that lower retail prices are offered to consumers and even more market share is gained afterwards. Small and medium enterprises in the food and agricultural sector are especially vulnerable owing to the fragmentation on the supply side that reinforces the bargaining power of supermarkets, the labour intensive nature of production that involves variable cost and can be squeezed, and the perishable nature of products that allows the supplier only a short period of time and can be exploited by supermarkets. The abusive buying practices of UK supermarkets affect not only producers of food for supermarkets but farmers, their workers, the environment and wider rural livelihoods (Tallontire and Vorley, 2005). At the root of the problem is an extremely unbalanced trading environment that is characterised by both a proliferation of standards for ethics and sustainability and the abuse of buyer power (Tallontire and Vorley, 2005, TradcraftSchools, 2007).

Figure 4.2 UK- suppliers, supermarkets and consumers taken from Nicholson (2012)

The abuse of buyer power is financial in nature and/or creates uncertainty for suppliers (Nicholson, 2012). Supermarkets determine what will and will not be stocked and on what terms including sources, quantity, quality, shelf life, delivery schedules, packaging, returns policy, price and retrospective payments.

They demand the flexibility to change supply agreements at the very last minute to meet their latest demand forecasts, and request a certain service level from suppliers when promotions are continually employed to catch the attention of consumers (Nicholson, 2012, FarmersGuardian, 2007). Supermarkets normally practice sudden promotions that are not agreed upon in advance such that producers are forced to bear the costs and risks. In addition, supermarkets often do not provide sufficient information and long-term commitments to farmers that leave them with no choice but to take the risk of planting too little or too much and to accept whatever price they are offered at harvest time. This widely practiced abuse of buyer power drives the need for suppliers to raise quality standards and develop new products, processes and services with unique selling points.

In response to this abuse, some suppliers are supplying a smaller range of products in larger volumes to more than one supermarket using different packaging to cut their costs (TradcraftSchools, 2007). Furthermore, they are attempting to reduce the damage to the environment and animal welfare of food production and transportation (Tallontire and Vorley, 2005). Farmers have also tried to diversify by creating new, value-added products or selling through farmers' markets. It is hoped that collaboration among producers will lead to farmers becoming "price makers" not "price takers" (Arnold, 2004).

Following the growing demand for ethically-sourced products, consumer choice is without doubt best served not only through supermarkets. As the consumers and their suppliers are mutually connected, the abuse of buyer power also has implications for consumers. Effective measures to prevent unfair trading practices and the resulting disadvantages to both producers and consumers are urgently required (Nicholson, 2012). Government regulations to deal with the consequences of supermarket power and the business environment they operate within are necessary such that no exploitation is witnessed (TradcraftSchools, 2007). Raising consumer awareness of supermarkets misuse of market power is needed to assure that consumer purchases have not contributed to the exploitation and economic marginalisation of producers (Tallontire and Vorley, 2005).

4.4 Literature discussion

Despite the intense, unbalanced relationship between food industry and supermarkets, there are only a limited number of contributions on production/inventory planning and control for upstream members of perishable food SC. It is worth noticing that, so far, the focus of the deteriorating inventory literature has been mainly on retailers with marketing issues (e.g. pricing, discount, inflation, time value of money and permissible delay in payment), two-warehouse problems or limited shelf space, for instance, leaving the inventory challenges for food producers behind.

It is a normal practice for supermarkets to change their orders last minute and request a certain service level from suppliers with no information sharing. This abuse in buyer power together with the aspects distinctively held in the food industry such as seasonality and weather conditions lead to the non-stationary stochastic demand the food producer has to face. Non-stationary stochastic demand has also seen only limited (and recent) attention in the reviewed work. Furthermore, Bakker et al. (2012) suggested that a stronger focus on stochastic modelling of perishable inventory is needed to facilitate better representation of inventory control practice. The non-stationary (R^n, S^n) policy seems to be the promising inventory control policy for companies facing non-stationary demand of deteriorating products. Deterministic equivalent -MILP and -CP were introduced as representatives in finding the approximate solutions to this stochastic problem (Pauls-Worm et al., 2010, Rossi et al., 2010b, Rossi, 2013, Pauls-Worm et al., 2014). When taking the previous related works, the familiarity of technique and the compatibility between the analysis and solution technique into account, the choice of using deterministic equivalent –MILP is promising. Various solvers for MILP problems were discussed. However, there is a trend to use CPLEX to describe production/inventory problems that show promising results to find optimal solutions in acceptable time.

Modelling deterioration in a proper way would be of significant benefit. Based on the contributions discussed, it is clear that there is a selection of ways to formulate deterioration in inventory modelling. Implicit modelling approaches consider a limitation on product storage time, an assumption that the planning horizon is shorter than or equal to the lifetime of the products or an assumption that a fraction of inventory on hand deteriorates every time period, for instance. Deterioration can be modelled explicitly as a decrease in product value over time such that its quality is tracked throughout the system. This can lead to the issue of computational tractability when highly perishable product is considered. Furthermore, the initial quality level of product that is required in the formulation might not be easily detectable. The inclusion of temperature effects on food quality degradation during storage and transportation and its trade-off with a change in costs can be seen in some work. Frequently, a product will be considered completely perished at a certain quality level. This could be a case for a company facing a certain quality requirement for their products. The product is considered perished when it can no longer be used for sales. Supermarkets normally specify certain quality requirements in their demand in terms of a remaining shelf life of the product. In order to guarantee the remaining shelf life, the maximum time an item can stay with the company is limited. Consider an item with a 20-day shelf life at production and a 17-day shelf life requirement from supermarket. A company then has three days as a maximum time limit before the product is considered perished. The product is then regarded as having a fixed lifetime. This deterioration can be modelled explicitly as an increase in product age every time period. This introduces the age-distribution of products into the system.

Seeing that the analysis of multi-echelon SCs for deteriorating products is challenging, it deserves further research. However, no contribution addresses a multi-echelon deteriorating inventory system under non-stationary stochastic demand. Furthermore, the concepts of partnerships and JIT seem to have gotten attention in multi-echelon inventory problems. Therefore, it is interesting to study the effect of adopting centralised and decentralised control when JIT philosophy is practiced.

Environmental sustainability considerations are thus far not explicitly addressed in deteriorating inventory management research. Inventory decisions, for instance affect how many productions/deliveries are involved, how long the product is kept in stock, how fast the product gets to the customer and how deterioration is treated. All of these will then exert an influence on environmental sustainability and food security. Some of the studies do include cost elements relating to the temperature control factors that affect the energy consumption for refrigeration and/or waste disposal to convey an increasing awareness of the environment. Considering the importance and relevance of sustainability in the food sector, there is room for researchers to integrate the issue explicitly. Chapter 3 in this thesis show that waste and carbon emission are worth addressing as SC performance measures. The identification of potential waste could be based on some recent approaches that formulate deterioration of products having a fixed lifetime. By observing the age-distribution of items in stock, the production/inventory plan can be determined such that waste is avoided. Carbon emissions can be interpreted as potential energy use for refrigeration in production, warehousing and transportation activities. Therefore, it seems logical to extend the cost-minimising inventory problem into the multi-objective optimisation problem. This environmentally integrated production inventory model would improve the possibilities for a proactive approach to sustainability, something which is currently lacking in the quantitative sustainable SCM literature.

In this thesis, to obtain robust and general results, the author extends the constant demand to a non-stationary stochastic demand which can represent a situation faced by food industry. The general questions that the author pursued are how losses due to perishability of items can be prevented and how carbon emissions owing to energy/fuel consumption in SC activities can be reduced. The author seeks to identify the best possible quantities and periods of production/replenishment of items for a joint optimisation of costs, wastes and emissions. Then, a deterministic equivalent multi-objective mixed-integer linear programming (mo-MILP) model is formulated as the building block of the modelling analysis for perishable production/inventory systems. The author aims to compare the total system performance in decentralised and centralised replenishment contexts under the two-echelon SC comprising multiple suppliers (e.g. farmers) and one producer (e.g. manufacturing industry).

4.5 Summary

Some products may experience deterioration which then ends their value. The deteriorating item either loses its functionality/physical fitness or its customers' perceived utility over time. The deteriorating item can be managed to obtain optimal returns during its useful lifetime via decisions regarding inventory issuance, inventory replenishment, and inventory allocation.

Products deteriorate in different manners in terms of the initial point and rate. The deterioration rate is assumed to be fixed, time-dependent, inventory dependent or age-dependent. The decrease in quantity and the degradation in quality can be used to measure the loss of products by deterioration. Considering the model type (deterministic or stochastic) and the considered time horizon (infinite or finite), deterioration can be integrated into mathematical models implicitly using the rate of deterioration for on-hand inventory or explicitly as a decrease in product value over time, for instance.

In the modelling of deteriorating inventory, a deterministic demand distribution is assumed known with certainty and can be categorised into uniform demand, time-varying demand, stock-dependent demand and price-dependent demand. The stochastic demand process incorporates randomness and unpredictability that can be described with probability distribution. Stochastic modelling of deteriorating inventory is suggested in order to better represent inventory control in practice since customer demand is variable in time and uncertain in amount. Deterministic equivalent MILP and CP can be used to formulate the stochastic dynamic lot-size inventory problem with non-stationary demand to produce more implementable near optimal solutions to the problem. Commercial solvers commonly used in solving MILP problems like CPLEX and MATLAB have been found promising.

Different assumptions regarding policies on shortages (e.g. shortages are not allowed, shortages are lost or shortages are backlogged) made in the inventory modelling depends on the product and market characteristics. Different replenishment policies can be adopted in controlling the deteriorating inventory under either periodic or continuous reviews with stock-level dependent policies receiving the most attention.

Multi-echelon inventory control is gaining importance due to the need for SC integration but few deteriorating inventory related works exist due to the added complexity in replenishment and allocation decisions involving age-composition of inventory, logistics-related decisions relating different remaining product lifetimes and centralised vs. decentralised planning.

Following the domination of supermarket, convenience and discounter retail chains in the UK food, grocery and drink retail market, suppliers large or small have limited access to end consumers which leads to considerably less bargaining power. This allows supermarkets the opportunity to squeeze and dictate the terms of business and also transfer costs and risks on to their suppliers. The abuse of buyer power is financial in nature and/or creates uncertainty for suppliers. Effective measures to prevent unfair trading practices and the resulting disadvantages to both producers and consumers are urgently required. Last but not least, a change in consumer tastes together with market forces and voluntary action by supermarket themselves can help to reasonably balance the bargaining power in the SC.

Chapter 5 Research Methodology

5.1 Introduction

This chapter describes the procedure of the research in this thesis. The author seeks to demonstrate a valid contribution to knowledge and to show relevant implications to both academics and industry.

5.2 Literature review

The SC with deteriorating inventory was selected for this study. A literature review of SCM and sustainable SCM was carried out including literature specific to SCM in the perishable food industry. First, the classic SCM literature such as Simchi-Levi et al. (2007), Chopra and Meindl (2013) etc. was studied to see the overall SC structure and the potential operations affecting its performance. Next, the sustainable SCM was investigated. It was found that only few studies explicitly addressed inventory management within a sustainable SC despite it being a major SC performance driver (Hassini et al., 2012, Brandenburg et al., 2014). The generation of carbon emissions in the SC and its relation to production and inventory processes were identified and studied. Perishable food SC was shown to be relevant in the sustainability study. This is due to the specific characteristics of food products including perishability, seasonality and requirement for conditioned storage and transportation means that affect the environment. Inventory systems with deterioration was the last part of literature review. The existing SC models and their limitations for solving production and inventory problems were investigated in search for models that represent perishable food SC that are being studied for this research. The aim of the literature review was to find the existing research gaps in order to construct the algorithms capable of integrating environmental issues into production and inventory systems with deterioration.

5.3 Research methodology

Mathematical modelling is often adopted with the aim of answering research questions such as the ones that have been proposed in this research. This is because of an increased recognition that sustainable SCM requires industry to address a multitude of decisions. By providing tangible outputs (e.g. formal models) that serve as decision support tools for managers, it attempts to ensure that the outcomes of sustainable SCM research are relevant and useful to practitioners such as operations managers. Production planning and inventory replenishment are operational level management decisions. As operational decisions, it is essential that the decision process should quickly find a unique and optimal solution in a reasonable time.

5.3.1 The need of mathematical modelling

During the past two decades, the sustainable SCM discipline has witnessed employment of formal mathematical models for practice and theory-driven research (Seuring and Müller, 2008*,* Hassini et al., 2012). This is because research using quantitative models to develop and test theories in sustainable SCM is of significant usefulness in explaining (part of) the behaviour of SC processes. They also capture many of the decision-making problems that are faced by managers such as vehicle routing problems, SC network design, production planning etc. (Akkerman et al., 2010). It is believed that with increasing acknowledgment of the sustainable SCM field, the use of mathematical modelling approaches in improving organisational, industrial, and commercial sustainability are key in linking management theory with practice (Brandenburg et al., 2014). This enhances the relevance of sustainable SCM research to its industrial applications.

In order to ensure that this research is relevant to those who will use it, it was decided that mathematical programming accommodating large quantities of numerical data describing the SCs should be used. Descriptions of the SCs such as MOP, MILP will be used in order to understand and solve multi-objective stochastic problems in deterministic context.

5.3.2 Taking action

Following the rise in scientific recognition of model-based quantitative research in sustainable SCM research, mathematical programming (with LP in particular) is a common model type used for problem formulation of emissions and pollution control in SC operations (Srivastava, 2007, Tang and Zhou, 2012). Since companies that practice sustainable SCM strive to satisfy multiple, possibly conflicting objectives, optimisation concepts are utilised by some researchers. Multi-objective optimisation is a frequent technique applied to identify the synergies between cost and environmental objectives (Dekker et al., 2012, Brandenburg et al., 2014).

Since this research aims to provide practical tools to industry, it was thought that mathematical programming research would be an appropriate method. Mathematical programming generates optimal solution. The quantitative analysis of the method alerts industrial managers of the consequences of alternative courses of action. It was decided to adopt mathematical programming as the research methodology.

5.4 Ensuring rigour in research

A systematic working process for mathematical modelling in OR (Hillier and Lieberman, 2001) was followed in order to ensure the research was sufficiently rigorous. The process includes six major phases as follows:

1. Define the problem of interest and gather relevant data
2. Formulate a mathematical model to represent the problem
3. Develop a computer-based procedure for deriving solutions to the problem from the model
4. Test the model and refine it as needed
5. Prepare for on-going application of the model as prescribed by management
6. Implement

This section details actions that were taken under each of the phases. However, phases 5 and 6 were not possible as part of this project due to the lack of access to industry and the short time frame of the project.

5.4.1 Statement of the problem and data collection

The identification of the problem of interest was carried out during the literature survey stage of the research project. An investigation into the potential for optimising operational level decisions with environmental sustainability concerns was carried out to answer the research problem defined. The literature was used to form the following specifications of the proposed models and as summarised in Figure 5.1.

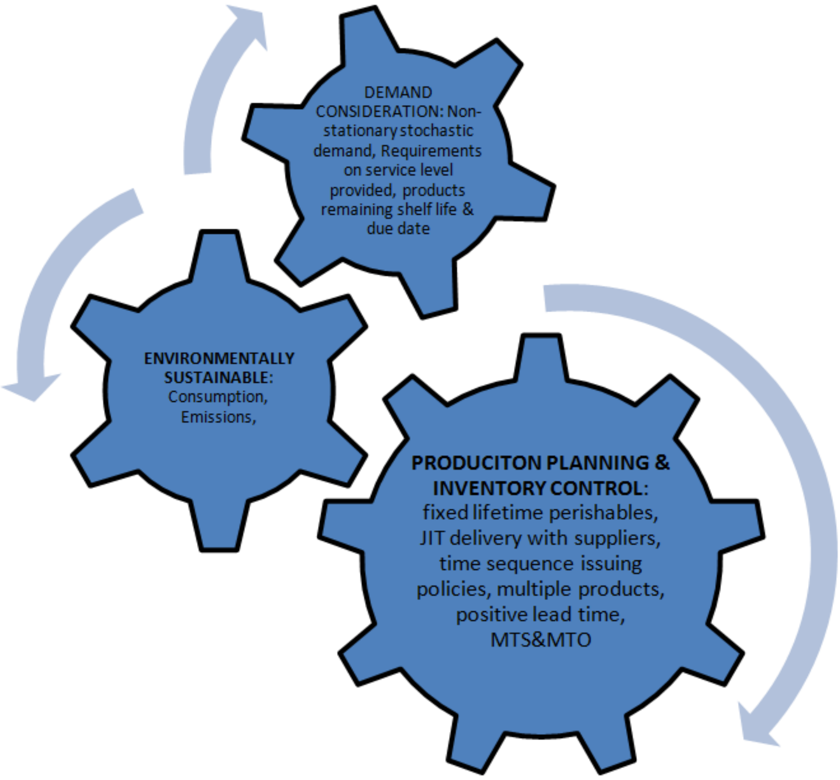


Figure 5.1 Considerations for production planning and inventory control problem

The desired results of the model relate directly to the performance measures proposed for SC targeting or benchmarking (Min and Zhou, 2002). The development of these performance measures is facilitated by the establishment of specific goals (or visions). In setting up these goals, an acknowledgment of the essential components of the SC which must be managed is required. Therefore, it is vital to identify these key components and include them in the model under study.

Customer requirements regarding products and services received are the ultimate drivers of a SC. Adding these requirements and reflecting service performance measures in the model is therefore essential (Min and Zhou, 2002, Minner and Transchel, 2010, Pauls-Worm et al., 2010). For the monetary value of a SC, traditional cost measurement of costs related to production and inventory decisions is used in the model as one of the objectives (Bonney and Jaber, 2011). The model should also be able to deal with uncertainty which, in this case, is from the demand side of the SC (Villegas and Smith, 2006, Gumus et al., 2010). The model deals with forecasted customer demand characteristics. In addition, specific process and product characteristics of a perishable food SC should be addressed. The perishable nature of materials and products is captured while progressing through the SC (van der Vorst et al., 2009, Yu and Nagurney, 2013). The model captures the discarding of spoiled materials and products associated with all the post-production SC activities as food waste. The quality and environmental requirements as well as product responsibility create the necessity for traceability of materials and products throughout the SC. This is considered in the model via age distribution of inventory (van der Vorst et al., 2009, Pauls-Worm et al., 2010, Duan and Liao, 2013). This is supported by Frank et al. (2009) who state that the optimal inventory policy depends on the shelf life of the final product and its inventory holding cost. This is particularly relevant in the make-to-stock environment. Consequently, the stock level of each possible age category is considered and included in the model. In order to optimise sustainability, SC processes are also evaluated on resource usage, energy use and environmental load (van der Vorst et al., 2009, Bonney and Jaber, 2011, Soysal et al., 2014). Overall, the model assesses the food SC and helps to produce both economically and environmentally sound judgments. Firstly that the system is providing the services required and that the environmental consequences are acceptable (Bonney and Jaber, 2011).

This model is built with the intention of providing managers with a decision support tool with the aim of optimising SC performance. The model identifies and measures performance including the environmental effects of activities and how far these activities satisfy the needs of the players in the SC (Bonney and Jaber, 2011).

A manager can then use the model to make production and/or inventory decisions of whether a production run has to be operated, a replenishment order has to be made and/or a specific issuing policy is to be applied. If the decision is ‘yes’, then the model will assist them to determine the quantity and/or which issuance policy to use. These decisions are to be determined optimally throughout the SC (Yu and Nagurney, 2013). Additionally, the model helps users to understand the effects of holding stock and contributes to decision making designed to improve environmental conditions. Production and inventory actions need to be defined which should be based on the beneficial and adverse effects that these actions would have (Bonney and Jaber, 2011).

All the specifications mentioned above are set for the proposed models to ensure they reflect reality as closely as possible.

Data collection

Data from the literature was used to test the proposed models.

5.4.2 Development of the models

Multi-objective mixed-integer linear programming (mo-MILP) models were formulated to represent the problem. The model can be solved using the ε-constraint method in search for the appropriate trade-off among multiple objectives proposed by the author. When the preference in the SC performances does exist, weighted goal programming method can be adopted. The multi-objective optimisation results are used to highlight some insights about the effectiveness of operational adjustments in improving the sustainability of the SC. The deterministic MILP approximation deals with the aspects of fixed lifetime perishables, non-stationary stochastic demand and a service level approach.

In the make-to-stock (MTS) operating system where the producer produces products in anticipation of customer demand, the SC performances (including costs, wastes and emissions) under centralised and decentralised controls are explored. Under decentralised control, models are formulated for the optimisation of each SC member separately. The planning results from the producer are used as the data for optimisation for the upstream SC members. The planning is optimised simultaneously for the SC under centralised control. This is carried out to investigate the consequence of information sharing between SC members. The effect of a given production and/or replenishment plan (i.e. when to produce/order and how much to produce/order) and issuing policy on the SC performances for a finite planning horizon are considered. The model is formulated under no predetermined issuing policy and is relevant for the FIFO issuing policy and LIFO issuing policy.

Given that the products lifetime limits the possibility of use of built-up finished product inventories to fultil customer orders, an increasing number of products with customer-specific features as well as an expectation of small deliveries within short and dependable time window from customers with erratic behaviour (e.g. supermarkets' last minute change in orders), food industries can be caterred to shift their production system from MTS to MTO (Soman et al., 2004). In the make-to-order (MTO) operating system where the producer produces products in response to customer demand, the effects of customer orders selection on SC performances (include profit, wastes and emissions) are studied. The MTS model is formulated for the planning of raw material inventory at the suppliers. However, the raw material plans can be changed following the request of additional raw materials for accepted orders. The MTO model formulated takes account of this aspect and cost incurred from this adjustment in the plan.

5.4.3 Development of a computer-based procedure

Options of LP solvers for constructing practical solutions to the problems from the models were explored. Based on the preliminary investigation of different LP solvers supported by relevant academic works, further research into the programming codes that different solvers used was carried out. CPLEX is chosen as a computer-based procedure for the proposed models. For learning purposes, various MILP models from related literature (e.g. Rossi et. al, 2010a, Kouki et al., 2013, Pausl-worm et al., 2010) were developed using CPLEX. Models published in the literaure were used as a starting point. These were then added to in order to give them the additional functionality required for the research.

5.4.4 Validation

The multiple objectives of the model give a clear definition of what is going to be measured. Due to the quantitative procedure and the results being numerical measurements, little space is left for measuring errors. To test the models and verify the proposed solutions, comparisons with published research work and the single objective optima cases were carried out. This is described in Chapter 7. In the first numerical example, the MTS model is compared with the stationary stochastic demand case shown in Kouki et al.'s (2013) paper. This was done in order to demonstrate the validity of the proposed model. The single objective optima cases (with minimum cost, minimum waste or minimum emissions) are solved and the results are compared to the results shown in the paper. The affect of production/inventory decisions on SC performances can be seen. This validation showed that the operational adjustments improve the sustainability of the SC in the proposed models. The proposed models are then tested against a problem under either MTS or MTO inventory system with data collected from literature. It was thought to be important to study different scenarios of non-stationary stochastic demand as representatives of a number of important practical situations. Various test cases are carried out for sensitivity analysis.

5.5 Summary

As a model-based quantitative research, mathematical programming was found to be an appropriate method for the normative research in immature research area studied in this research. It was decided that multi-objective mixed-integer linear programming would be used as the technique in solving the production/inventory problems for improved sustainability in perishable food SC.

Chapter 6 Mathematical Modelling of Inventory Systems in a Perishable Food Supply Chain

6.1 Introduction

In this chapter, mathematical models for production and inventory planning in a perishable food supply chain are derived. In Section 6.2, a description of the system studied is provided. The mathematical models of the make-to-stock and make-to-order systems are developed and described in Section 6.3 and Section 6.4, respectively. Section 6.5 summarises the chapter.

6.2 A Perishable Food Supply Chain System

A food SC in general is a global and complex network linking farms to customers. The SC of fresh and perishable foods is characterised by short product lives and fast transportation (Govindan et al., 2014). Supermarkets in developed economies around the world have acquired an increasing share of retail markets, and in doing so have increased their influence over suppliers. They often have long term contracts with food processors and manufacturers. This research explores the implication for food producer and its suppliers in response to retailers' requirements. Figure 6.1 provides diagram of the perishable food SC network within the scope of this research. The products are make-to-stock. Whereas, the producer practises make-to-order production in the perishable food SC network is presented in Figure 6.2. Each supplier supplies one type of raw materials to the producer who will use the materials to process into products that are shipped to retailers. An important feature of this type of SC is that materials and products are subject to notable quality changes over time. Although this two-echelon model differs from real-world problems, it requires complex mathematical calculations with a trade-off between the accuracy of the decision variables and the solution time.

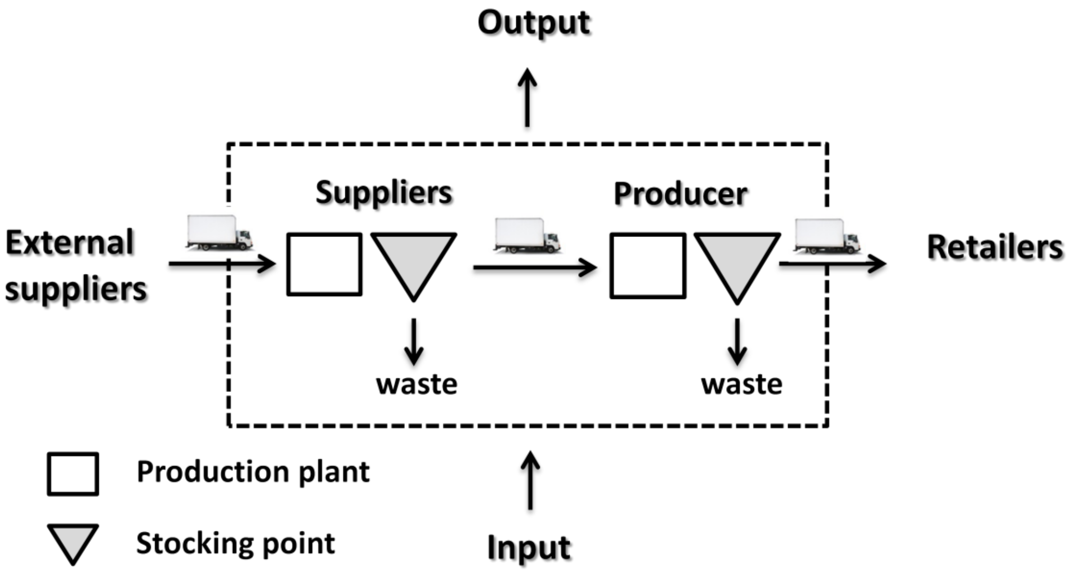


Figure 6.1 A schematic diagram representing a MTS two-level SC with multiple suppliers, a single producer, and retailers

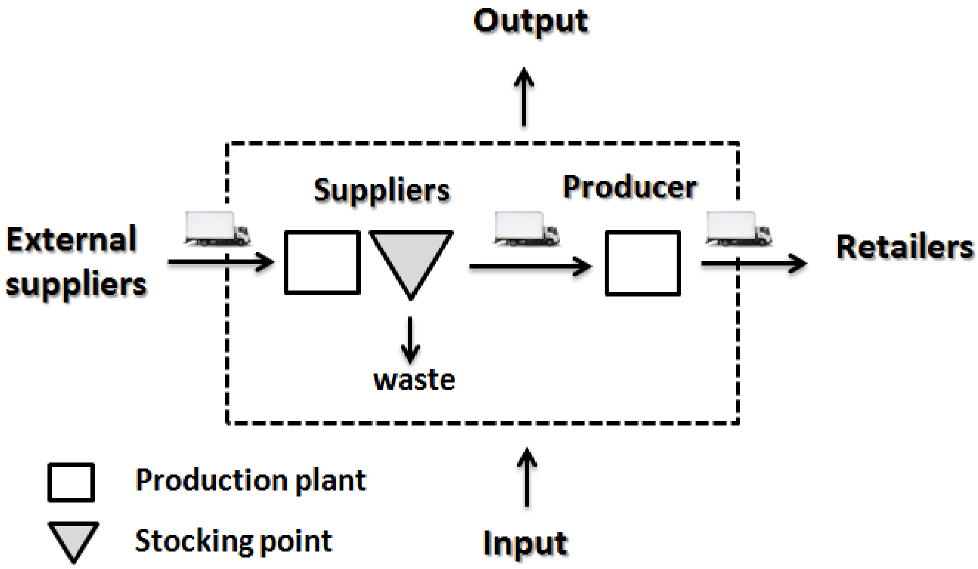


Figure 6.2 A schematic diagram representing a MTO two-level SC with multiple suppliers, a single producer, and retailers

6.3 Mathematical Modelling of the Make-to-Stock Operating System

Growing world population challenges food industries in producing and appropriately distributing enough food while considering higher GHG emissions from SC operations as well as food waste problem that can be caused by perishability characteristics of food products, irregular customer demand and contracts with customers especially the big supermarket chains regarding delivery performance of promised availability and a guaranteed remaining shelf life. This has necessitated the development of a production and inventory model addressing both economic and environmental aspects which can be applied to quantitatively investigate the optimisation problem in perishable food SCs given non-stationary demand. These subjects lead to the design of the proposed model that is discussed in the next section.

6.3.1 Assumptions and limitations

Before building the mathematical model of the system, all assumptions, limitations and concepts used were explained and summarised. The production-inventory control problem of perishable products under random demand and periodic review policy was considered. The SC model consists of two stages, namely supply and production. It is assumed that decision makers exist in every stage and has the responsibility of managing inventory at that stage.

The raw materials necessary for producing the product are obtained from one or more external suppliers via single sourcing for each item which is in consistent with JIT practice. The inventory of products is produced according to the production plan under a JIT schedule with suppliers. For that reason, suppliers have agreed to carry all of the material inventories and to instantly deliver those following requests as shown in Figure 6.1. This instantaneous delivery just in time for the production is possible when a strategic partnership is developed among them. The production operates on a day-to-day basis as cleaning is required at the end of the production day for hygiene reasons. Energy is consumed as input in the production and warehousing activities to condition and preserve perishable food which gives CO_2 emissions as the output from the process as shown in Figure 6.1.

Multiple products are produced here in the production plant. It is possible that different products may require the same type of raw materials. In a situation where products scheduled to produce in a period can be used instantaneously to satisfy demand in the same period (i.e. zero production lead time), it was assumed no restrictions on manpower and machine, and each product is manufactured by a dedicated production facility/line because the problem of product scheduling can be disregarded. Only the data taken from bill of materials of the products is needed. Otherwise, a production at the producer is assumed the planned production lead time. This planned lead time is interpreted as a time, determined by experience, in which it may be expected that any reasonable work order can be produced. The production lead time is regarded in the major setup cost and the average environmental impacts for setting up the production run (i.e. the major set up cost reflects the total cost incurred in setting up the productions for a number of lead time periods and the same applies to environmental impacts). By adopting planned lead time, the reliability between SC operations planning and scheduling as regards the feasibility of the planning is increased (Spitter et al., 2005). It also reduces system nervousness. Demand variability during this planned production lead time can be taken care of with safety stock.

Materials and products are assumed to have a fixed lifetime. After the end of the lifetime, if they are not consumed by demand, units are spoiled and have to be discarded as food waste as shown in Figure 6.1. It was assumed that the ageing of the materials and products begins just at the time replenishment order is delivered to supplier and production run at producer is completed and there is no decrease in the value during their usable lifetime which they are of satisfactory quality and functionality for both suppliers and producer. An implication of fixed lifetime of raw materials is that the supplier supplies fresh items upon their delivery. An implication of fixed lifetime of products is that the producer satisfies customers' requirement regarding remaining shelf life of products. It is assumed that there is known material replenishment transportation lead time for every raw material a to each supplier similar to the planned lead time by Spitter et al. (2005). The author introduces the maximum planned transport lead time $LT_{a,max}$ at the supply stage. For that reason, the planning interval begins in period $1 - LT_{a,max}$. There is assumed to be quick sorting and packaging activities going on in the supply stage which can be done on the same day materials are delivered to the supplier and then the delivery is continued to the producer just in time for the production run.

The inventory of products can be depleted randomly or according to a FIFO issuing policy or a LIFO issuing policy and all unmet demands are backlogged. The demand for product i per unit time t, $\sum_{r=1}^{n(r)} d_{r,i,t}^{v}$ facing the producer is a nonnegative random variable following a distribution with probability density function $g_t^i(\cdot)$ and cumulative distribution function $G_t^i(\cdot)$. In order to account for the different remaining shelf life requirements from retailers, $d_{r,i,t}^{v}$ is introduced. The demand for product i from retailer r per unit time t, $d_{r,i,t}^{v}$ represents a fraction of forecast demand that may request products with different remaining shelf life (i.e. may require longer remaining shelf life). Producer might get this data from his forecast or as an assumption that a certain percentage of forecast demand will have different requirements. The demand considered here is non-stationary, meaning that it can vary from period to period, and it is also assumed that demands in different periods are independent. Therefore, it is appealing to investigate the use of order policy with time-dependent order-up-to levels and replenishment cycle lengths (R^n, S^n) in this case.

In this particular setting, the problem considered in this study is to determine production and inventory decisions with the aim of finding trade-off among total associated costs, total spoiled food wastes and total emissions in the SC. This problem can be categorised as deterministic (deterministic equivalent modelling approach employed for stochastic demand), constrained (required service level), mix-integer (order-up-to levels) and with multiple performance measures (economic and environmental objectives).

In this section, a quantitative model that can manage economic issues along with sustainability concerns is developed in response to the need in practice. The model of the cost function per unit time for producer, suppliers and the SC which is the sum of all companies' cost function is built. In addition to this economic assessment, waste and emissions estimations are modelled for environmental judgment. Especially, the author extends and develops other studies that have been carried out by Rau et al. (2003), Tarim and Kingsman (2004), Jaber and Goyal (2008), Pauls-Worm et al. (2010), Rossi et al. (2010a), Rossi et al. (2010b), Rong et al. (2011), Abdallah et al. (2012), Bouchery et al. (2012), Chaabane et al. (2012), Zanoni and Zavanella (2012), Absi et al. (2013), Chen et al. (2013), Kouki et al. (2013), Pauls-Worm et al. (2014), Soysal et al. (2014), Bozorgi et al. (2014) and Govindan et al. (2014). The mathematical model will be developed using notations listed comprehensively below to capture the above described operations.

6.3.2 Notations

The input parameters and decision variables for retailers, producer, and suppliers are denoted by the subscripts r, v, and s, respectively.

Common Parameters

$E(\cdot)$	The expectation operator representing probability-weighted average of all possible values
$\boldsymbol{M}$	A large positive value
t	Index for time referring to a period,$t = 1 - LT_{a,max}, \ldots, T$ where $LT_{a,max}$ is the maximum planned material transportation lead time of suppliers and T is the planning horizon
w_1, w_2, w_3	Relative importance of objective function 1, 2 and 3 respectively
$G1, G2, G3$	Gap between the performance of a SC and its requirement for objective function 1, 2 and 3 respectively

Retailers:

Parameters

r	Index for retailers, $r = 1,2, \ldots, n^{(r)}$, where $n^{(r)}$ is the total number of retailers (Different retailers represent different remaining shelf life requirements for products)
α_i	Service level for product i
$M_{r,i}$	Remaining shelf life for product i as required by retailer r (Modelled as a maximum internal shelf life for product i used to fulfil demand from retailer r)

Producer:

Parameters

i	Index for product, $i = 1,2, \ldots, n^{(i)}$ where $n^{(i)}$ is the number of product
b	Index for product ages, $b = 0, \ldots, M_{r,i}$ where $M_{r,i}$ is the shelf life requirement of retailer r for product i and M_i is the maximum

	internal shelf life of the producer as required by all retailers for product i, $M_i = max\{M_{r,i}\}; r = 1,2,\dots,n^{(r)}$
M_i	Remaining shelf life for product i (Modelled as a maximum internal shelf life for product i)
$E(d^v_{r,i,t})$	Expected demand on the producer from retailer r for product i in period t (i.e. one realisation of demand)
LT_i	Production lead time of product i for the producer
k^v	Fixed setup cost of the producer for all finished products
${k^v}_i$	Setup cost for producing product i per production run of the producer
h^v_i	Holding cost based on inventory level of the producer for product i
hp^v_i	Holding cost based on inventory position (inventory on-hand plus outstanding orders) of the producer for product i
p^v_a	Cost of placing a purchase order for raw material a
c^v_i	Cost for producing one unit of product i in period t
q^v_a	Fixed cost of transporting from supplier a to a producer
VC^v_a	Variable cost for transporting each unit of material a to a producer
w^v_i	Cost for disposing of one unit of spoiled product i
$mlot^v_i$	Minimum production lot size of product i
Ek^v	Average environmental impacts for setting up the production run for the period
${Ek^v}_i$	Environmental impacts for setting up the production run of product i

EP_i	Environmental impacts for producing each unit of product i
ES_i	Environmental impacts for storing each unit of product i
ET_a^v	Average environmental impacts of transporting from supplier a to a producer
VT_a^v	Environmental impacts for transporting each unit of material a to a producer

Decision variables

$E(d_{r,i,b,t}^v)$	Target purchasing volume of retailer r that is satisfied with product i with the age of $b = 0, \dots, M_{r,i} - 1$ in period t where $\sum_{b=0}^{M_{r,i}-1} E(d_{r,i,b,t}^v)$ equals the forecast demand from retailer r for product i in period t
$E(I_{i,b,t}^v)$	Target inventory level of product i with the age of $b = 1, \dots, M_i$ at the end of period t
$E(S_{i,t}^v)$	Target order-up-to position of product i in period t
$E(Q_{i,t}^v)$	Target quantity of product i produced by the producer in period t
$E(X_{i,b,t}^v)$	Target residual demand of product i used in demand fulfilment in period t (auxiliary variable used in tracking the age-distribution of inventory)
Y_t^v	Binary variable that equals 1 if there is a production run in period t
$Y_{i,t}^v$	Binary variable that equals 1 if there is a production run of product i in period t
$F_{a,t}^v$	Binary variable that equals 1 if there is a purchase order for raw material a in period t

$z_{i,t,j}^{v}$	Binary variable that equals 1 if the most recent order of product i prior to period t was in period $t-j+1-LT_i$ for the producer
$BX_{i,b,t}^{v}$	Auxiliary binary variable for FIFO and LIFO issuance policies of product i with the age of b in period t

Suppliers:

Parameters

a	Index for material types, $a = 1,2,\dots,n^{(a)}$ where $n^{(a)}$ is the number of material types
e	Index for material ages, $e = 1,\dots,M_a$ where M_a is the maximum internal shelf life of material a for the supplier
M_a	Maximum internal shelf life for raw material a
k_a^s	Ordering cost of placing an order for material a
h_a^s	Holding cost based on inventory level for material a
hp_a^s	Holding cost based on inventory position for material a
s_a^s	Cost for purchasing one unit of material a
q_a^s	Average cost of transporting material a to a supplier
VC_a^s	Variable cost for handling each unit of material a in transport to a supplier
w_a^s	Cost for disposing of one unit of spoiled material a
LT_a	Planned transportation lead time for material a where $LT_{a,max}$ is the maximum planned material replenishment lead time, $LT_{a,max} = max\{LT_a\}$
$mlot_a^s$	Minimum replenishment order lot size of material a
$Usage_{a,i}$	The usage rate of raw material a per unit product i

EP_a	Environmental impacts for purchasing each unit of material a
ES_a	Environmental impacts for storing each unit of material a
ET_a^s	Average environmental impacts of transporting material a to a supplier
VT_a^s	Environmental impacts for transporting each unit of material a to a supplier

Decision variables

$E(I_{a,e,t}^s)$	Target inventory level of material a with the age of $e = 1, \dots, M_a$ at the end of period t
$E(S_{a,t}^s)$	Target order-up-to position of material a in period t where $t = 1 - LT_a, \dots, T$
$E(d_{a,t}^s)$	Target demand on the supplier of material a from the producer in period t where $t = 1, \dots, T$
$E(Q_{a,t}^s)$	Target quantity of material a ordered by the supplier in period t where $t = 1 - LT_a, \dots, T$
$Y_{a,t}^s$	Binary variable that equals 1 if there is a replenishment order of material a in period t
$z_{a,t,j}^s$	Binary variable that equals 1 if the most recent order prior to period t was in period $t - j + 1 - LT_a$ for the supplier

6.3.3 Deterministic Multi Objective Mixed Integer Linear Programming Approximation

The choice of mo-MILP as a deterministic approximation to investigate the stochastic inventory problem with environmental sustainability concerns is basically because it helps to find different production and inventory decisions of linear objective functions that guarantee a trade-off with respect to some linear constraints. This mathematical model represents production/inventory system in two-level perishable food SC with time-dependent order-up-to levels and replenishment cycle lengths (R^n, S^n) and the optimal solution will specify how much and how often the members of this SC should produce/order. The author of this thesis seeks to identify the best possible quantities and periods of production/replenishment for a joint optimisation among costs, wastes and emissions.

According to Tarim and Kingsman (2004), solving the stochastic optimisation problem requires the timing of replenishments to be decided once and for all before any of the demands become known. Following that, the deterministic equivalent model for the multi objective mixed integer linear programming (mo-MILP) model may be obtained by taking expectations.

6.3.3.1 Replenishment policy

The replenishment policy studied works similar to the base order-up-to policy except that the order-up-to position in this model is corrected for the estimated amount of outdating. That is the perished items are replaced in the next replenishment. Each partner in the SC follows the policy to determine the amount to order and/or the amount to produce each day. The formulations are derived based on standard order-up-to policy and works that have been carried out by Pauls-Worm et al. (2010, 2014) and Rossi et al. (2010b).

The transition of inventory states from one period to the next is determined jointly by demand, production/ordering quantity, and production/replenishment policy. For each period, the order of events affecting the inventory state has the following sequence:

(1) An order arrives;
(2) Perished products are discarded;
(3) Demand is observed;
(4) Inventory Position is reviewed;
(5) An order is triggered.

The author shows how a deterministic mo-MILP model can generate a waste-compensating replenishment cycle policy as an approximate solution of the SP model for perishable products.

6.3.3.2 Economic objective (OF_1)

The sustainable food SC production and inventory planning described before has the objective to find a trade-off solution between the economic and environmental performances. The economic objective is evaluated by the total cost. The environmental performance is evaluated by the total spoiled waste and emissions resulting from operation strategies and manufacturing activities. The economic dimension includes different costs.

The producer's cost function

In Rossi et al. (2010a), an inventory holding cost at the end of each period is charged based on the current inventory position rather than the current inventory level. This reflects the fact that interest is charged not only on the actual amount of items in stock but also on outstanding orders. This way of representing the inventory cost is adopted in the proposed model, a decision maker can choose either to charge an inventory holding cost based on the inventory level or the inventory position. The order-up-to position calculated in the model is aimed to be used in the inventory position based holding cost estimate.

The customer service level α is typically set as a large number. Consequently, the occurrence and amount of stock-outs is assumed to be small enough such that the calculation of the holding cost is negligible (Bookbinder and Tan, 1988). The producer orders materials from suppliers to manufacture into finished products. Raw materials ordered are delivered immediately just in time for the production run. The producer incurs a cost of placing a purchase order and receiving materials a, ordering cost. The author develops work that has been carried out in Jaber and Goyal (2008) for this cost.

Since orders from a producer are processed and delivered depending on the optimal production plan of a producer, the author needs a fixed transportation cost which is separated from the producer's ordering cost. The author develops works that have been carried out in Rau et al. (2003), Chaabane et al. (2012) and Govindan et al. (2014) for this cost. Apart from this, variable supplying cost related to shipping one unit of a material to a producer that has been considered in Abdallah et al. (2012), Chaabane et al. (2012), Absi et al. (2013)

and Govindan et al. (2014) is developed here. Disposal cost that considered in Rossi et al. (2010b), Rong et al. (2011), Kouki et al. (2013) and Pauls-Worm et al. (2010, 2014) for each unit of food product that perishes in stock after its fixed lifetime is used in the present model. This gives the following objective function:

$$E(TC_v) = \sum_{t=1}^{T}\{k^v Y_t^v + \sum_{i=1}^{n(i)} k^v{}_i Y_{i,t}^v + \sum_{a=1}^{n(a)} p_a^v F_{a,t}^v + \sum_{a=1}^{n(a)}(q_a^v F_{a,t}^v + E(d_{a,t}^s) \cdot VC_a^v) + \sum_{i=1}^{n(i)} \sum_{b=1}^{M_i-1} h_i^v E(I_{i,b,t}^v)) + \sum_{i=1}^{n(i)} hp_i^v \left(E(S_{i,t}^v) - \sum_{r=1}^{n(r)} E(d_{r,i,t}^v)\right) + \sum_{i=1}^{n(i)} c_i^v E(Q_{i,t}^v) + \sum_{i=1}^{n(i)} w_i^v E(I_{i,M_i,t}^v)\} \tag{6.1}$$

This expected total cost for the producer comprises fixed setup costs for every production run, minor setup costs for different products, ordering costs for raw materials, fixed and variable delivery costs of raw materials from suppliers, holding costs for every product in stock, holding costs for products in stock plus outstanding orders, unit production costs and costs of wasted spoil products.

The suppliers' cost function

The planning horizon for each supplier begins LT_a periods before the production at the producer starts due to the known materials replenishment transportation lead time. $LT_{a,max}$ is introduced in the calculation of the expected total cost for suppliers. An ordering cost is charged for each replenishment order made from a supplier at time t. This gives the following objective function:

$$E(TC_s) = \sum_{t=1-LT_{a,max}}^{T}\{\sum_{a=1}^{n(a)} k_a^s Y_{a,t}^s + \sum_{a=1}^{n(a)}(q_a^s Y_{a,t}^s + E(Q_{a,t}^s) \cdot VC_a^s) + \sum_{a=1}^{n(a)} \sum_{e=1}^{M_a-1} h_a^s E(I_{a,e,t}^s) + \sum_{a=1}^{n(a)} hp_a^s\left(E(S_{a,t}^s) - E(d_{a,t}^s)\right) + \sum_{a=1}^{n(a)} s_a^s E(Q_{a,t}^s) + \sum_{a=1}^{n(a)} w_a^s E(I_{a,M_a,t}^s)\} \tag{6.2}$$

This expected total cost for suppliers comprised of ordering costs for all replenishments made, fixed and variable delivery costs of raw materials, holding costs over every material in stock, holding costs over materials in stock and outstanding orders, unit procurement costs and costs of wasted spoil materials.

The supply chain's cost function

The supply chain cost is determined by summing (1) and (2) to obtain

$$OF_1 = E(TC) = E(TC_v) + E(TC_s) \tag{6.3}$$

6.3.3.3 Environmental objectives (OF_2 and OF_3)

The second key objective is to achieve a sustainable SC by means of the evaluation and the optimisation of the environmental impacts in the form of spoiled wastage, energy use and CO_2 emissions. The determination of the environmental performance of an SC is not easy and might be different from one industry section to another. In this model, spoiled wastage consideration is introduced as a separate performance measure from the total cost objective function. Energy efforts required to condition perishables and to preserve those items in a cold storage over time as addressed in Zanoni and Zavanella's (2012) model are adopted here. This energy consumption is then expressed in terms of carbon emissions as introduced by Bouchery et al. (2012), Chaabane et al. (2012), Chen et al. (2013) and Bozorgi et al. (2014). Environmental impact related to shipping materials to each supplier and then distributing them to a producer that has been considered in Abdallah et al., (2012), Absi et al. (2013), Soysal et al. (2014) and Govindan et al. (2014) is developed here.

Objective function (6.4)-(6.5) represent the waste consideration from both the supply and production stages.

$$E(TW) = E(TW_v) + E(TW_s) \tag{6.4}$$

$$OF_2 = E(TW) = \sum_{t=1}^{T} \sum_{i=1}^{n(i)} w_i^v E(I_{i,M_i,t}^v) + \sum_{t=1-LT_{a,max}}^{T} \sum_{a=1}^{n(a)} w_a^s E(I_{a,M_a,t}^s) \tag{6.5}$$

Objective functions (6.6)-(6.7) express the CO_2 emissions estimation. Emissions are associated with production/purchasing, inventory holding and transportation. For food industry, machine setup process may require various procedures and consume energy and resources owing to the safety and hygiene reasons. In that case, this operational activity and production run share an impact on the environment. The refrigerated storage of perishables also has an environmental impact. Energy is consumed to keep products and materials at the storing temperature. In this case, each item has its own inventory holding environmental impact. The environmental impacts from energy consumption in various operational activities are then aggregated in terms of emissions. The total emission from transportation is related to the load weight of each vehicle and travelled distance. The variable carbon emission of each delivery is modelled using a linear function of a quantity delivered and the fixed emission depends on the number of required shipments.

$$E(TE) = E(TE_v) + E(TE_s) \tag{6.6}$$

$$OF_3 = E(TE) =$$

$$\sum_{t=1}^{T}\{\sum_{i=1}^{n^{(i)}}(Ek^v Y_t^v + \sum_{i=1}^{n^{(i)}} Ek^v{}_i Y_{i,t}^v + \sum_{b=1}^{M_i} E(I_{i,b,t}^v) \cdot ES_i + E(Q_{i,t}^v) \cdot EP_i) +$$

$$\sum_{a=1}^{n^{(a)}}(F_{a,t}^v\, ET_a^v + E(d_{a,t}^s) \cdot VT_a^v)\} +$$

$$\sum_{t=1-LT_{a,max}}^{T}\{\sum_{a=1}^{n^{(a)}}\big(\sum_{e=1}^{M_a} E(I_{a,e,t}^s) \cdot ES_a + E(Q_{a,t}^s) \cdot EP_a\big) +$$

$$\sum_{a=1}^{n^{(a)}}(\,Y_{a,t}^s \cdot ET_a^s + E(Q_{a,t}^s) \cdot VT_a^s)\} \tag{6.7}$$

6.3.3.4 Constraints

The model constraints include the following: inventory and product flow balance, demand satisfaction, flow structure and decision variable constraints.

Inventory and product flow balance constraints

Constraints (6.8) and (6.9) enforce the desired order-up-to positions for the starting periods up to the production lead time extent where no demand has been physically fulfilled. Constraint (6.10) and (6.11) represent the same enforcement for the suppliers. The difference is that the suppliers place their material orders in advance of LT_a periods such that the order arrives just in time for the production schedule of the producer.

$$E(Q_{i,1}^v) = E(S_{i,1}^v),\ i = 1, \dots, n^{(i)} \tag{6.8}$$

$$E(S_{i,t-1}^v) - \sum_{r=1}^{n^{(r)}} E(d_{r,i,t-1}^v) + E(Q_{i,t}^v) = E(S_{i,t}^v),\ 1 < t \le LT_i + 1; i = 1, \dots, n^{(i)} \tag{6.9}$$

$$E(Q_{a,t-LT_a}^s) = E(S_{a,t-LT_a}^s),\ t = 1; a = 1, \dots, n^{(a)} \tag{6.10}$$

$$E(S_{a,t-LT_a-1}^s) + E(Q_{a,t-LT_a}^s) = E(S_{a,t-LT_a}^s),\ 1 < t < LT_a + 1; a = 1, \dots, n^{(a)} \tag{6.11}$$

For the rest of the planning period, constraints (6.12) and (6.13) ensure balanced product inventories at the producer and balanced material inventories at the suppliers respectively. The inventory at the end of period t equals the order-up-to position at the beginning of period t decreased by the product or material amounts that are scheduled to be produced or ordered from the lead time plus one period prior until period t minus the demand in period t. The order-up-to position can be interpreted as the total amount of stock on hand plus outstanding orders plus fulfilled demand in that period. The author develops these constraints based on Rossi et al.'s (2010a) inventory position and Pauls-Worm et al.'s (2010, 2014) order-up-to level formulated constraints.

$$\sum_{b=1}^{M_i} E(I_{i,b,t}^{v}) + \sum_{n=t-LT_i+1}^{t} E(Q_{i,n}^{v}) = E(S_{i,t}^{v}) - \sum_{r=1}^{n^{(r)}} E(d_{r,i,t}^{v}),\ t = LT_i + 1, \dots, T; i = 1, \dots, n^{(i)} \tag{6.12}$$

$$\sum_{e=1}^{M_a} E(I_{a,e,t}^{s}) + \sum_{n=t-LT_a+1}^{t} E(Q_{a,n}^{s}) = E(S_{a,t}^{s}) - E(d_{a,t}^{s}),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \tag{6.13}$$

Constraints (6.14) and (6.15) ensure that setup cost is incurred when there is a production run. The production quantities are all equal to zero except in the production periods. The same logic applies to suppliers in constraints (6.16) and (6.17). In the replenishment periods, an order quantity results in an ordering cost. There is no replenishment for producer and suppliers from $LT_i - 1$ and $LT_a - 1$ periods prior to the end of the planning horizon, respectively. Constraints (6.18) and (6.19) guarantee this aspect.

$$E(Q_{i,t}^{v}) \leq \boldsymbol{M} \cdot Y_{i,t}^{v},\ t = 1, \dots, T; i = 1, \dots, n^{(i)} \tag{6.14}$$

$$E(Q_{i,t}^{v}) \geq Y_{i,t}^{v},\ t = 1, \dots, T; i = 1, \dots, n^{(i)} \tag{6.15}$$

$$E(Q_{a,t}^{s}) \leq \boldsymbol{M} \cdot Y_{a,t}^{s},\ t = 1 - LT_a, \dots, T; a = 1, \dots, n^{(a)} \tag{6.16}$$

$$E(Q_{a,t}^{s}) \geq Y_{a,t}^{s},\ t = 1 - LT_a, \dots, T; a = 1, \dots, n^{(a)} \tag{6.17}$$

$$E(Q_{i,t}^{v}) = 0,\ t = T - LT_i + 1, \dots, T; i = 1, \dots, n^{(i)} \tag{6.18}$$

$$E(Q_{a,t}^{s}) = 0,\ t = T - LT_a + 1, \dots, T; a = 1, \dots, n^{(a)} \tag{6.19}$$

Demand satisfaction constraints

Customers may request different product specifications. For instance, it is possible that the remaining shelf life requirements will vary. The producer therefore assumes certain amount/fraction of the forecast demand to have different shelf life requirements and regarded as demand from different retailers. This aspect of real life is adopted into the proposed model. Target demand on the producer from retailer r for product i, $E(d^{v}_{r,i,t})$, corresponds to a fraction of the forecast demand with a certain remaining shelf life requirement. Therefore, $\sum_{r=1}^{n^{(r)}} E(d^{v}_{r,i,t})$ equals to the forecast demand. Constraints (6.20), (6.21) and (6.22) guarantee the retailers' conditions are satisfied. The age-distribution of units of product used in fulfilling the demand is considered. Constraint (6.23) relates the net requirements of material a to the planned production schedule of products of which a is a component. The data can be taken from the BOM for the products.

$$E(d^{v}_{r,i,t}) = \sum_{b=0}^{M_{r,i}-1} E(d^{v}_{r,i,b,t}),\ t = 1,\dots,T; i = 1,\dots,n^{(i)}; r = 1,\dots,n^{(r)} \tag{6.20}$$

$$E(Q^{v}_{i,t}) - \sum_{r=1}^{n^{(r)}} E(d^{v}_{r,i,0,t+LT_i}) = E\left(I^{v}_{i,1,t+LT_i}\right),\ t = 1 + LT_i,\dots,T - LT_i; i = 1,\dots,n^{(i)} \tag{6.21}$$

$$E\left(I^{v}_{i,b,t-1}\right) - \sum_{r=1}^{n^{(r)}} E(d^{v}_{r,i,b,t}) = E\left(I^{v}_{i,b+1,t}\right),\ t = 1,\dots,T; i = 1,\dots,n^{(i)}; b = 1,\dots,M_{r,i} - 1 \tag{6.22}$$

$$E(d^{s}_{a,t}) = \sum_{i=1}^{n^{(i)}} (E(Q^{v}_{i,t}) \cdot Usage_{a,i}),\ t = 1,\dots,T; a = 1,\dots,n^{(a)} \tag{6.23}$$

The safety stock is added at the last stage (for the producer) to cope with customer demand uncertainty (Giannoccaro and Pontrandolfo, 2002, Seliaman and Ahmad, 2008, Ertogral, 2011). Safety stock at the producer has to be adjusted when there is a positive production lead time. The adjusted safety stock is developed based on Rossi et al.'s (2010a) model. The total amount of safety stock for each product can be calculated or possibly read from a table, once the form of $g^{i}_{t}(\cdot)$ is selected. Let $z^{v}_{i,t,j}$ be a binary variable that is equal to 1 if the most recent production schedule prior to period t was in period $t - j + 1 - LT_i$. Constraints (6.24) and (6.25) stipulate that the order-up-to position is at least equal to the safety stock plus the target demand in the current replenishment period until the next review takes place in which this concept is based on Tarim and Kingsman (2004)'s model. Constraint (6.26) is developed to ensure that the minimum of the total amount of inventory on hand is equal to the safety stock.

$$E(S^{v}_{i,t-j+1-LT_i}) \geq \left(\sum_{n=t-j+1-LT_i}^{t}\sum_{r=1}^{n^{(r)}} E(d^{v}_{r,i,n}) + \left(G^{-1}_{t-j+1-LT_i,t}(\alpha_i) - \sum_{n=t-j+1-LT_i}^{t}\sum_{r=1}^{n^{(r)}} E(d^{v}_{r,i,n})\right)\right)\cdot z^{v}_{i,t,j},\ 1 \leq t < M_i + LT_i; j = 1,\dots,t-LT_i; i = 1,\dots,n^{(i)} \quad (6.24)$$

$$E(S^{v}_{i,t-j+1-LT_i}) \geq \left(\sum_{n=t-j+1-LT_i}^{t}\sum_{r=1}^{n^{(r)}} E(d^{v}_{r,i,n}) + \left(G^{-1}_{t-j+1-LT_i,t}(\alpha_i) - \sum_{n=t-j+1-LT_i}^{t}\sum_{r=1}^{n^{(r)}} E(d^{v}_{r,i,n})\right)\right)\cdot z^{v}_{i,t,j},\ t \geq M_i + LT_i; j = 1,\dots,M_i; i = 1,\dots,n^{(i)} \quad (6.25)$$

$$\sum_{b=1}^{M_i} E(I^{v}_{i,b,t}) \geq \sum_{j=1}^{M_i}\left(G^{-1}_{t-j+1-LT_i,t}(\alpha_i) - \sum_{n=t-j+1-LT_i}^{t}\sum_{r=1}^{n^{(r)}} E(d^{v}_{r,i,n})\right)\cdot z^{v}_{i,t,j},\ t = 1,\dots,T; i = 1,\dots,n^{(i)} \quad (6.26)$$

Constraints (6.27) and (6.28) ensure that there can only be one most recent order release period prior to period t. These constraints are adopted from Tarim and Kingsman (2004)'s model.

$$\sum_{j=1}^{M_i} z^{v}_{i,t,j} = 1,\ t = 1 + LT_i,\dots,T; i = 1,\dots,n^{(i)} \quad (6.27)$$

$$z^{v}_{i,t,j} \geq Y^{v}_{i,t-j+1-LT_i} - \sum_{n=t-j+2-LT_i}^{t-LT_i} Y^{v}_{i,n},\ t = 1,\dots,T; i = 1,\dots,n^{(i)}; j = 1,\dots,M_i \quad (6.28)$$

Forcing constraints

Constraint (6.29)-(6.30) relates the major setup cost to the minor product specific setup costs. Constraints (6.31)-(6.32) ensure that the ordering cost is incurred when a producer placing a raw material purchase order. In every production run, raw materials are ordered following the product's bill of materials.

$$\sum_{i=1}^{n^{(i)}} Y^{v}_{i,t} \leq \boldsymbol{M}\cdot Y^{v}_{t},\ t = 1,\dots,T \quad (6.29)$$

$$\sum_{i=1}^{n^{(i)}} Y^{v}_{i,t} \geq Y^{v}_{t},\ t = 1,\dots,T \quad (6.30)$$

$$\boldsymbol{M}\cdot F^{v}_{a,t} \geq Y^{v}_{i,t},\ t = 1,\dots,T; i = 1,\dots,n^{(i)}; a = 1,\dots,n^{(a)} \quad (6.31)$$

$$Usage_{a,i}\cdot Y^{v}_{i,t} \geq F^{v}_{a,t},\ t = 1,\dots,T; i = 1,\dots,n^{(i)}; a = 1,\dots,n^{(a)} \quad (6.32)$$

Constraints (6.33) and (6.34) ensure that the production and the replenishment quantities follow the minimum lot size requirements respectively.

$$E(Q_{i,t}^{v}) \geq mlot_i^v \cdot Y_{i,t}^v,\ t = 1, \dots, T; i = 1, \dots, n^{(i)} \tag{6.33}$$

$$E(Q_{a,t}^{s}) \geq mlot_a^s \cdot Y_{a,t}^s,\ t = 1 - LT_a, \dots, T; a = 1, \dots, n^{(a)} \tag{6.34}$$

FIFO issuing policy constraints

When the producer operates with the FIFO issuing policy, the following constraints apply. Constraint (6.35) requires that the oldest item in stock is to be used first to fulfil demand. This is to eliminate or reduce the number of leftover items that become spoiled waste due to their possession of a maximum shelf life. In a case in which the oldest items are not enough to satisfy all the demand, there is a resulting residual demand for the next oldest items. Constraint (6.36) guarantees the fulfilment of demand by products of intermediate ages first until the demand is fulfilled by the freshest products that are currently produced according to constraint (6.37). Constraints (6.38) and (6.39) ensure that either residual demand or stock on hand of items with a certain age can have a positive value. Constraints (6.40) and (6.41) are definition constraints purposely for FIFO. These constraints are adopted from Pauls-Worm et al.'s (2010, 2014)'s models.

$$E(I_{i,M_i-1,t-1}^{v}) - \sum_{r=1}^{n^{(r)}} E(d_{r,i,t}^{v}) = E(I_{i,M_i,t}^{v}) - E(X_{i,M_i-1,t}^{v}),\ t = 1, \dots, T; i = 1, \dots, n^{(i)} \tag{6.35}$$

$$E(I_{i,b,t-1}^{v}) - E(X_{i,b+1,t}^{v}) = E(I_{i,b+1,t}^{v}) - E(X_{i,b,t}^{v}),\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 2 \tag{6.36}$$

$$E(Q_{i,t-LT_i}^{v}) - E(X_{i,1,t}^{v}) = E(I_{i,1,t}^{v}),\ t = 2 + LT_i, \dots, T; i = 1, \dots, n^{(i)} \tag{6.37}$$

$$\boldsymbol{M} \cdot (1 - BX_{i,b,t}^{v}) \geq E(X_{i,b,t}^{v}),\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 1 \tag{6.38}$$

$$\boldsymbol{M} \cdot BX_{i,b,t}^{v} \geq E(I_{i,b+1,t}^{v}),\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 1 \tag{6.39}$$

$$E(X_{i,b,t}^{v}) \geq 0,\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 1 \tag{6.40}$$

$$BX_{i,b,t}^{v} \in \{0,1\},\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 1 \tag{6.41}$$

No predetermined issuing policy constraints

In regards to the practical decision problem, a FIFO issuing policy is used following common sense for spoiled waste minimisation. A different approach to determine production and replenishment plans is not to use a predetermined issuing policy. This is a relaxation of the FIFO issuing policy. The following constraints apply instead of the inventory balanced constraints (6.35)-(6.41) discussed above. Constraint (6.42) imposes the flow structure of products at the producer in each time period. Constraint (6.43) shows that freshly produced products in period t that are not used to fulfil the demand in that period will have an age of 1 at the end of the period. Constraint (6.44) keeps track of the age-distribution of inventory on hand. Constraints (6.45), (6.46) and (6.47) illustrate the same concepts for the suppliers respectively. These constraints are adopted from Pauls-Worm et al.'s (2010, 2014)'s models.

$$\sum_{b=1}^{M_i-1} E(I_{i,b,t-1}^{v}) - \sum_{r=1}^{n^{(r)}} E(d_{r,i,t}^{v}) + E(Q_{i,t-LT_i}^{v}) = \sum_{b=1}^{M_i} E(I_{i,b,t}^{v}),\ t = LT_i + 2, \dots, T; i = 1, \dots, n^{(i)} \qquad (6.42)$$

$$E(Q_{i,t}^{v}) \geq E\left(I_{i,1,t+LT_i}^{v}\right),\ t = 1, \dots, T - LT_i; i = 1, \dots, n^{(i)} \qquad (6.43)$$

$$E\left(I_{i,b,t-1}^{v}\right) \geq E\left(I_{i,b+1,t}^{v}\right),\ t = LT_i, \dots, T; b = 1, \dots, M_i - 1; i = 1, \dots, n^{(i)} \qquad (6.44)$$

$$\sum_{e=1}^{M_a-1} E(I_{a,e,t-1}^{s}) - E(d_{a,t}^{s}) + E(Q_{a,t-LT_a}^{s}) = \sum_{e=1}^{M_a} E(I_{a,e,t}^{s}),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \qquad (6.45)$$

$$E(I_{a,e,t-1}^{s}) \geq E(I_{a,e+1,t}^{s}),\ t = 1, \dots, T; e = 1, \dots, M_a - 1; a = 1, \dots, n^{(a)} \qquad (6.46)$$

$$E(Q_{a,t-LT_a}^{s}) \geq E(I_{a,1,t}^{s}),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \qquad (6.47)$$

LIFO issuing policy constraints

When the producer operates with the LIFO issuing policy, the following constraints apply instead of the FIFO constraints (6.35)-(6.41) and the inventory balanced constraints (6.42)-(6.47) discussed above. Constraint (6.48) requires that the freshest item in stock of the currently produced product is to be used in fulfilling demand first. In a case in which the freshest items are not enough to satisfy all the demand, there is a resulting residual demand for the next freshest items. Constraint (6.49) guarantees the fulfilment of demand by products of intermediate ages first until the demand is fulfilled by the oldest products according to constraint (6.50).The leftover items will become spoiled waste owing to their possession of a maximum shelf life. Constraints (6.51), (6.52) and (6.53) ensure that either residual demand or stock on hand of items with a certain age can have a positive value. Constraints (6.54) and (6.55) are definition constraints for LIFO.

$$E(Q^v_{i,t-LT_i}) - \sum_{r=1}^{n^{(r)}} E(d^v_{r,i,t}) = E(I^v_{i,1,t}) - E(X^v_{i,2,t}),\ t = 2 + LT_i, \dots, T; i = 1, \dots, n^{(i)} \tag{6.48}$$

$$E(I^v_{i,b,t-1}) - E(X^v_{i,b+1,t}) = E(I^v_{i,b+1,t}) - E(X^v_{i,b+2,t}),$$

$$t = 1 + LT_i, \dots, T; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 2 \tag{6.49}$$

$$E(I^v_{i,M_i-1,t-1}) - E(X^v_{i,M_i,t}) = E(I^v_{i,M_i,t}),\ t = 1 + LT_i, \dots, T; i = 1, \dots, n^{(i)} \tag{6.50}$$

$$\boldsymbol{M} \cdot BX^v_{i,b,t} \geq E(X^v_{i,b+1,t}),\ t = 1 + LT_i \dots, T; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 1 \tag{6.51}$$

$$\boldsymbol{M} \cdot (1 - BX^v_{i,b,t}) \geq E(I^v_{i,b,t}),\ t = 1 + LT_i, \dots, T; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 1 \tag{6.52}$$

$$BX^v_{i,b,t} \leq E(X^v_{i,b+1,t}) + E(I^v_{i,b,t}),\ t = 1 + LT_i, \dots, T; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 1 \tag{6.53}$$

$$E(X^v_{i,b,t}) \geq 0,\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 1 \tag{6.54}$$

$$BX^v_{i,b,t} \in \{0,1\},\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 1 \tag{6.55}$$

Variable constraints

Constraints (6.56)-(6.63) represent the non-negativity and binary restrictions imposed upon the decision variables.

$$E\left(I^v_{i,b,t}\right) = 0,\ 1 \leq t \leq LT_i; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 1 \tag{6.56}$$

$$E\left(I^v_{i,b,0}\right) = 0,\ i = 1, \dots, n^{(i)}; b = 1, \dots, M_i - 1 \tag{6.57}$$

$$E\left(I^v_{i,b,t}\right), E(Q^v_{i,t}), E(S^v_{i,t}), E(d^v_{r,i,b,t}) \geq 0,\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; b = 1, \dots, M_i; r = 1, \dots, n^{(r)} \tag{6.58}$$

$$Y_t^v, Y_{i,t}^v, F_{a,t}^v, z_{i,t,j}^v \in \{0,1\},\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; a = 1, \dots, n^{(a)}; j = 1, \dots, M_i \tag{6.59}$$

$$Y_{a,t}^s, z_{a,t,j}^s \in \{0,1\},\ t = 1, \dots, T; a = 1, \dots, n^{(a)}; j = 1, \dots, M_a \tag{6.60}$$

$$E(I_{a,e,t}^s) = 0,\ 1 - LT_{a,max} \leq t < 1; e = 1, \dots, M_a; a = 1, \dots, n^{(a)} \tag{6.61}$$

$$E\left(I_{a,e,t}^s\right) \geq 0,\ t = 1, \dots, T; a = 1, \dots, n^{(a)}; e = 1, \dots, M_a \tag{6.62}$$

$$E(Q_{a,t}^s), E(S_{a,t}^s) \geq 0,\ t = 1 - LT_a, \dots, T; i = 1, \dots, n^{(i)} \tag{6.63}$$

6.3.4 Model solution

To evaluate the fitness of any candidate solution, the mo-MILP model can be solved with the ε-constraint method (Andersson, 2000) and weighted goal programming method (Charnes and Cooper, 1977).

The ε-constraint method has also been employed in other recent studies which have multiple objective models (Chaabane et al., 2012, Soysal et al., 2014). Under the ε-constraint method, one objective is selected for optimisation, whereas the others are reformulated as constraints. In this solution methodology, $E(TC)$ was selected for optimisation whereas $E(TW)$ and $E(TE)$ were formulated as additional constraints. The right hand side values of the additional constraints are ε_1 and ε_2 which represent the limit on waste and emissions respectively. The author derived a Pareto frontier to observe the dependency among the three objectives via progressive changes in the ε values.

Min OF_1

s.t. Constraints (6.4) – (6.63)

$E(TW) \leq \varepsilon_1,$ (Additional constraint) (6.64)

$E(TE) \leq \varepsilon_2,$ (Additional constraint) (6.65)

It is important to note that when using this model, managers should minimise the number of conflicting objective functions. If there are many objective functions that are conflicting, the model will not produce the optimal results for the primary objective. The model aids decision makers by demonstrating choices of actions and its ability to achieve sustainability objectives in a cost-effective manner. Preferences among objectives can be set by decision makers. Tighter limits can be set on the objective's ε-constraint given higher concerns from decision makers and vice versa.

The weighted goal programming method has also been employed in other studies with multiple objectives that allow the user to specify preferences which can be expressed in terms of goals and the relative importance of different objectives (Cakravastia et al., 2002, Das et al., 2004, Mahapatra and Maiti, 2005, Nepal et al., 2011). In this solution methodology, different weights are assigned to the ratio of deviation of each objective from its perspective goal (i.e. the desired expected total cost, total emission and total waste obtained from solving the three base cases; LC, LE and LW) to its means goal for each test instance.

Step1. Solve the LC base case and record the solution value of cost as OF_1 as well as values of emission and waste

Min OF_1

s.t. Constraints (6.4) – (6.63)

Step2. Solve the LW base case and record the solution value of waste as OF_2 as well as values of cost and waste

Min OF_2

s.t. Constraints (6.1) – (6.3), (6.6) – (6.63)

Step3. Solve the LE base case and record the solution value of emission as OF_3 as well as values of cost and emission

Min OF_3

s.t. Constraints (6.1) –(6.5), (6.8) – (6.63)

Step4. The following additional constraints are included in the model whose $E(TC), E(TW), E(TE)$ values can be calculated by constraints (6.3), (6.5) and (6.7) respectively. The values of OF_1, OF_2, OF_3 which represent the required SC performances are obtained from steps 1-3 above if not specified by the decision makers.

$$E(TC) - G1 = OF_1 \tag{6.66}$$

$$E(TW) - G2 = OF_2 \tag{6.67}$$

$$E(TE) - G1 = OF_3 \tag{6.68}$$

$$G1, G2, G3 \geq 0 \tag{6.69}$$

Step5. Each value of $Avg1, Avg2, Avg3$ symbolising an average of the required SC performances can be calculated by taking an average of the lowest and highest values of each objective recorded from steps 1-3. Solve this mo-MILP problem using the goal programming method

$$\text{Min} \quad \left(w_1 \cdot \frac{G1}{Avg1}\right) + \left(w_2 \cdot \frac{G2}{Avg2}\right) + \left(w_3 \cdot \frac{G3}{Avg3}\right)$$

s.t. Constraints (6.1) – (6.63), (6.67) – (6.69).

6.4 Mathematical Modelling of the Make-to-Order Operating System

6.4.1 Assumptions and limitations

In a situation where the producer operates under a make-to-order system, the products are produced in response to customer demand under a JIT schedule with suppliers. Multiple products that may require the same type of raw materials are produced in the production plant. Products that are scheduled to be produced in a given period can be used promptly to satisfy demand. It was assumed that there were no restrictions on manpower and machine, and that each product was manufactured by a dedicated production facility/line, in order to ignore the problem of product scheduling.

The materials held by suppliers are assumed to have a fixed lifetime and there is no decrease in their value during their usable lifetime. It is assumed that there is a known material replenishment transportation lead time LT_a to each supplier. The maximum planned transport lead time $LT_{a,max}$ is introduced at the supply stage. For this reason, the planning interval for the suppliers begins in period $1 - LT_{a,max}$. Materials that are delivered to the supplier can then be delivered instantly to the producer in time for production.

The forecast demand for product i per unit time t, $E(d_{i,t}^{v})$ facing the producer is a nonnegative random variable following a distribution with probability density function $g_t^i(\cdot)$ and cumulative distribution function $G_t^i(\cdot)$. This demand is assumed to have non-stationary stochastic characteristics. Suppliers have adopted time-dependent order-up-to levels and replenishment cycle lengths (R^n, S^n) order policies as part of a service level approach. Replenishment decisions at the suppliers are made in advance of the producer planning horizon using forecast demand data with the idea that a certain customer service level is maintained at the producer.

Over the planning horizon, producer faces demands $d_{r,i,t}^{v}$ for product i from retailer r per unit time t (requested due date). Ideally, the producer would want to fulfil all demands to maximise its profit. However, the availability of raw materials prevents it from doing so. In this situation, the producer has to make a decision about whether to select an optimal set of customer orders or to request suppliers to make a modification to their replenishment plans. However, the replenishment of this additional order can only be done after the transportation lead time LT_a periods have passed. In this particular setting, the problem considered in this study is to determine production and inventory decisions with the aim of finding a trade-off between total associated costs, total spoiled food wastes and total emissions in the SC.

In this section, a quantitative model that can manage economic issues along with sustainability concerns is developed. A model of profit function per unit time for the SC is constructed. In addition to this economic assessment, waste and emissions estimations are modelled for environmental judgment. The mathematical model will be developed using the notations listed below to capture the operations described above.

6.4.2 Notations

The input parameters and decision variables for the retailers, producer, and suppliers are denoted by the subscripts r, v, and s, respectively.

Common Parameters

$E(\cdot)$	The expectation operator representing probability-weighted average of all possible values
$\boldsymbol{M}$	A large positive value
t	Index for time referring to a period, $t = 1 - LT_{a,max}, \dots, T$ where $LT_{a,max}$ is the maximum planned material transportation lead time of suppliers and T is the planning horizon for the SC
w_1, w_2, w_3	Relative importance of objective functions 1, 2 and 3 respectively
$G1, G2, G3$	Gap between the performance of a SC and its requirement for objective functions 1, 2 and 3 respectively

Retailers:

Parameters

r	Index for retailers, $r = 1,2, \dots, n^{(r)}$, where $n^{(r)}$ is the total number of retailers
α_i	Service level for product i

Producer:

Parameters

i	Index for product, $i = 1,2, \dots, n^{(i)}$ where $n^{(i)}$ is the number of product
$E(d_{i,t}^{v})$	Expected demand on the producer for product i in period t (i.e. one realisation of demand)
$d_{r,i,t}^{v}$	Demand on the producer from retailer r for product i in period t
$P_{r,i}$	Profit per unit of sales of product i to retailer r
k^{v}	Fixed setup cost of the producer for all finished products

$k^{v}{}_{i}$	Setup cost for producing product i per production run of the producer
p_a^v	Cost of placing a purchase order for raw material a
q_a^v	Fixed cost of transporting from supplier a to a producer
VC_a^v	Variable cost for transporting each unit of material a to a producer
$f_{r,i}^v$	Cost of rejecting of one unit of demand for product i from retailer r
g_a^v	Additional cost of one unit of material a obtained from adjusted replenishment plan (represents cost incurred due to a change of plan)
Ek^v	Average environmental impacts of setting up the production run for the period
$Ek^{v}{}_{i}$	Environmental impacts of setting up the production run of product i
EP_i	Environmental impacts of producing each unit of product i
ET_a^v	Average environmental impacts of transporting from supplier a to a producer
VT_a^v	Environmental impacts of transporting each unit of material a to a producer

Decision variables

$E(dX_{r,i,t}^v)$	Target demand from retailer r for product i in period t accepted for production under planned raw material inventory
$E(dY_{r,i,t}^v)$	Target demand from retailer r for product i in period t rejected by the producer
$E(dZ_{r,i,t}^v)$	Target demand from retailer r for product i in period t accepted for production with additional raw material requirement

$E(d_{a,t}^v)$	Target additional demand for material a in period t required for the production
$E(qX_{i,t}^v)$	Target quantity of product i planned to produce using planned raw material inventory of suppliers in period t
$E(qZ_{i,t}^v)$	Target quantity of product i planned to produce using additional raw material ordered by suppliers in period t
Y_t^v	Binary variable that equals 1 if there is a production run in period t
$Y_{i,t}^v$	Binary variable that equals 1 if there is a production run of product i in period t
$F_{a,t}^v$	Binary variable that equals 1 if there is a purchase order for raw material a in period t

Suppliers:

Parameters

a	Index for material types, $a = 1,2,\dots,n^{(a)}$ where $n^{(a)}$ is the number of material types
e	Index for material ages, $e = 1,\dots,M_a$ where M_a is the maximum internal shelf life of material a for the supplier
M_a	Maximum internal shelf life for raw material a
k_a^s	Ordering cost of placing an order for material a
h_a^s	Holding cost based on inventory level for material a
q_a^s	Average cost of transporting material a to a supplier of producer
VC_a^s	Variable cost for handling each unit of material a in transport to a supplier
w_a^s	Cost of disposing of one unit of spoiled material a

LT_a	Planned transportation lead time for material a where $LT_{a,max}$ is the maximum planned material replenishment lead time, $LT_{a,max} = max\{LT_a\}$
$Usage_{a,i}$	The usage rate of raw material a per unit product i
EP_a	Environmental impact of purchasing each unit of material a
ES_a	Environmental impact of storing each unit of material a
ET_a^s	Average environmental impact of transporting material a to a supplier
VT_a^s	Environmental impact of transporting each unit of material a to a supplier

Decision variables

$E(I_{a,e,t}^s)$	Target inventory level of material a with the age of $e = 1, \dots, M_a$ at the end of period t
$E(S_{a,t}^s)$	Target order-up-to position of material a in period t where $t = 1 - LT_a, \dots, T$
$E(d_{a,t}^s)$	Target demand on the supplier of material a from the producer in period t where $t = 1, \dots, T$ (that can be fulfilled with planned inventory)
$E(Q_{a,t}^s)$	Target quantity of material a planned to order by the supplier in period t where $t = 1 - LT_a, \dots, T$
$E(iQ_{a,t}^s)$	Target additional quantity of material a ordered by the supplier in period t where $t = 1 - LT_a, \dots, T$
$E(TQ_{a,t}^s)$	Target total quantity of material a ordered by the supplier in period t where $t = 1 - LT_a, \dots, T$
$B_{a,t}^s$	Accummurative quantity of material a used to satisfy producer demand up to period t where $t = 1, \dots, T$

$Y_{a,t}^{s}$	Binary variable that equals 1 if there is a replenishment order of material a in period t
$z_{a,t,j}^{s}$	Binary variable that equals 1 if the most recent order prior to period t was in period $t-j+1-LT_a$ for the supplier

6.4.3 Deterministic Multi Objective Mixed Integer Linear Programming Approximation

This mathematical model represents production/inventory system in two-level perishable food SC. The optimal solution will specify how much and how often the members of this SC should produce/order, the potential retailer orders that should be accepted and the adjustment required in the suppliers' replenishment plans. The author seeks to identify the best possible quantities and periods of production/replenishment for a joint optimisation of costs, waste and emissions.

6.4.3.1 Replenishment policy

The time-dependent order-up-to levels and replenishment cycle lengths (R^n, S^n) policy is employed by suppliers to determine the quantity to order for each period. The order-up-to position is corrected for the estimated amount of outdating such that the perished items are replaced in the next replenishment. The formulations are derived based on standard order-up-to policy and research carried out by Pauls-Worm et al. (2010, 2014) and Rossi et al. (2010b).

6.4.3.2 Determining the replenishment plans for suppliers

In the first stage of the planning, the suppliers make their replenishment decisions in anticipation of the forecast demand facing the producer. The time-dependent order-up-to levels and replenishment cycle lengths (R^n, S^n) order policy using a service level approach is employed with the aim of finding a trade-off solution between economic and environmental performances. The economic objective is evaluated according to the total cost. The environmental performance is evaluated by the total spoiled waste and emissions resulting from operation strategies and manufacturing activities.

The expected total cost for suppliers comprised of ordering costs for all replenishments made, fixed and variable delivery costs of raw materials, holding costs for every material in stock, unit procurement costs and costs of wasted spoil materials. This gives the following objective function:

$$E(TC_s) =$$

$$\sum_{t=1-LT_{a,max}}^{T}\{\sum_{a=1}^{n^{(a)}} k_a^s Y_{a,t}^s + \sum_{a=1}^{n^{(a)}}\left(q_a^s Y_{a,t}^s + E\left(Q_{a,t}^s\right) \cdot VC_a^s\right) + \sum_{a=1}^{n^{(a)}} \sum_{e=1}^{M_a-1} h_a^s E(I_{a,e,t}^s) +$$

$$\sum_{a=1}^{n^{(a)}} s_a^s E(Q_{a,t}^s) + \sum_{a=1}^{n^{(a)}} w_a^s E(I_{a,M_a,t}^s) \tag{6.70}$$

Objective functions (6.71)-(6.72) represent the waste consideration and the CO_2 emissions estimation, respectively.

$$E(TW_s) = \sum_{t=1-LT_{a,max}}^{T} \sum_{a=1}^{n^{(a)}} w_a^s E(I_{a,M_a,t}^s) \tag{6.71}$$

$$E(TE_s) = \sum_{t=1-LT_{a,max}}^{T}\{\sum_{a=1}^{n^{(a)}}\left(\sum_{e=1}^{M_a} E(I_{a,e,t}^s) \cdot ES_a + E(Q_{a,t}^s) \cdot EP_a\right) +$$

$$\sum_{a=1}^{n^{(a)}}(Y_{a,t}^s \cdot ET_a^s + E(Q_{a,t}^s) \cdot VT_a^s)\} \tag{6.72}$$

Emissions are associated with production/purchasing, inventory holding and transportation that involve the use of refrigerated facilities for the preservation of perishables. These objective functions are optimised with respect to the following constraints.

Inventory and product flow balance constraints

The suppliers place their material orders in advance of LT_a periods such that the order arrives in time at the start of the production schedule of the producer. Constraints (6.8) and (6.9) enforce the desired order-up-to positions for the starting periods where no demand has been physically fulfilled.

$$E(Q_{a,t-LT_a}^s) = E(S_{a,t-LT_a}^s),\ t = 1; a = 1, \dots, n^{(a)} \tag{6.73}$$

$$E(S_{a,t-LT_a-1}^s) + E(Q_{a,t-LT_a}^s) = E(S_{a,t-LT_a}^s),\ 1 < t < LT_a + 1; a = 1, \dots, n^{(a)} \tag{6.74}$$

For the rest of the planning period, constraint (6.12) ensures balanced material inventories at the suppliers.

$$\sum_{e=1}^{M_a} E(I_{a,e,t}^s) + \sum_{n=t-LT_a+1}^{t} E(Q_{a,n}^s) = E(S_{a,t}^s) - E(d_{a,t}^s),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \tag{6.75}$$

In the replenishment periods, an order quantity results in an ordering cost. Constraints (6.76) and (6.77) ensure that the cost is incurred. There is no replenishment for suppliers from $LT_a - 1$ periods prior to the end of the planning horizon. Constraint (6.78) guarantees this aspect.

$$E(Q_{a,t}^s) \leq \boldsymbol{M} \cdot Y_{a,t}^s,\ t = 1 - LT_a, \dots, T; a = 1, \dots, n^{(a)} \tag{6.76}$$

$$E(Q_{a,t}^s) \geq Y_{a,t}^s,\ t = 1 - LT_a, \dots, T; a = 1, \dots, n^{(a)} \tag{6.77}$$

$$E(Q_{a,t}^s) = 0,\ t = T - LT_a + 1, \dots, T; a = 1, \dots, n^{(a)} \tag{6.78}$$

Demand satisfaction constraints

Constraint (6.79) relates the net requirements of material a to the forecast demand of products of which a is a component. The data can be taken from the BOM for the products.

$$E(d_{a,t}^s) = \sum_{i=1}^{n^{(i)}} (E(d_{i,t}^v) \cdot Usage_{a,i}),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \tag{6.79}$$

The suppliers hold some additional stock as a safety buffer against market demand uncertainty. The total amount of safety stock for each material can be calculated or possibly read from a table, once the form of $g_t^i(\cdot)$ is selected. Let $z_{a,t,j}^s$ be a binary variable that is equal to 1 if the most recent replenishment schedule prior to period t was in period $t - j + 1 - LT_a$. Constraints (6.80) and (6.81) stipulate that the order-up-to position is at least equal to the safety stock plus the target demand in the current replenishment period until the next review takes place. The constraint (6.82) is developed to ensure that the minimum of the total amount of inventory on hand is equal to the safety stock. Constraints (6.83) and (6.84) ensure that there can only be one most recent order release period prior to period t. These constraints are adopted from Tarim and Kingsman (2004)'s model.

$$E(S^s_{a,t-j+1-LT_a}) \geq \left(\sum_{n=t-j+1-LT_a}^{t} E(d^s_{a,n}) + \left(G^{-1}_{t-j+1-LT_a,t}(\alpha_a) - \sum_{n=t-j+1-LT_a}^{t} E(d^s_{a,n})\right)\right) \cdot z^s_{a,t,j},\ 1 \leq t < M_a + LT_a; j = 1, \dots, t - LT_a; a = 1, \dots, n^{(a)} \quad (6.80)$$

$$E(S^s_{a,t-j+1-LT_a}) \geq \left(\sum_{n=t-j+1-LT_a}^{t} E(d^s_{a,n}) + \left(G^{-1}_{t-j+1-LT_a,t}(\alpha_a) - \sum_{n=t-j+1-LT_a}^{t} E(d^s_{a,n})\right)\right) \cdot z^s_{a,t,j},\ t \geq M_a + LT_a; j = 1, \dots, M_a; a = 1, \dots, n^{(a)} \quad (6.81)$$

$$\sum_{b=1}^{M_a} E(I^s_{a,b,t}) \geq \sum_{j=1}^{M_a} \left(G^{-1}_{t-j+1-LT_a,t}(\alpha_a) - \sum_{n=t-j+1-LT_a}^{t} E(d^s_{a,n})\right) \cdot z^v_{a,t,j},\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \quad (6.82)$$

$$\sum_{j=1}^{M_a} z^s_{a,t,j} = 1,\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \quad (6.83)$$

$$z^s_{a,t,j} \geq Y^s_{a,t-j+1-LT_a} - \sum_{n=t-j+2-LT_a}^{t-LT_a} Y^s_{a,n},\ t = 1, \dots, T; a = 1, \dots, n^{(a)}; j = 1, \dots, M_a \quad (6.84)$$

No predetermined issuing policy constraints

The age-distribution of units of materials used in fulfilling the demand is considered. Constraint (6.85) imposes the flow structure of raw materials at the supplier in each time period. Constraint (6.86) shows that freshly replenished materials in period t that are not used to fulfil the demand in that period will have an age of 1 at the end of the period. Constraint (6.87) keeps track of the age-distribution of inventory on hand.

$$\sum_{e=1}^{M_a-1} E(I^s_{a,e,t-1}) - E(d^s_{a,t}) + E(Q^s_{a,t-LT_a}) = \sum_{e=1}^{M_a} E(I^s_{a,e,t}),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \quad (6.85)$$

$$E(I^s_{a,e,t-1}) \geq E(I^s_{a,e+1,t}),\ t = 1, \dots, T; e = 1, \dots, M_a - 1; a = 1, \dots, n^{(a)} \quad (6.86)$$

$$E(Q^s_{a,t-LT_a}) \geq E(I^s_{a,1,t}),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \quad (6.87)$$

Variable constraints

Constraints (6.88)-(6.91) represent the non-negativity and binary restrictions imposed upon the decision variables.

$$Y_{a,t}^{s}, z_{a,t,j}^{s} \in \{0,1\},\ t = 1, \dots, T; a = 1, \dots, n^{(a)}; j = 1, \dots, M_a \tag{6.88}$$

$$E(I_{a,e,t}^{s}) = 0,\ 1 - LT_{a,max} \leq t < 1; e = 1, \dots, M_a; a = 1, \dots, n^{(a)} \tag{6.89}$$

$$E\left(I_{a,e,t}^{s}\right) \geq 0,\ t = 1, \dots, T; a = 1, \dots, n^{(a)}; e = 1, \dots, M_a \tag{6.90}$$

$$E(Q_{a,t}^{s}), E(S_{a,t}^{s}) \geq 0,\ t = 1 - LT_a, \dots, T; i = 1, \dots, n^{(i)} \tag{6.91}$$

6.4.3.3 Determining the production and inventory decisions under an MTO producer

In the next stage, the producer faces real retailer demands over the planning horizon. The sustainable food SC production and inventory planning described previously has the objective of finding a trade-off solution between economic and environmental performances. The economic dimension includes different costs. Profit maximisation is adopted here to enforce the model that (part of) customer demand is fulfilled. The profit per unit of product is assumed to be equal to sales minus costs of production less materials purchasing costs paid by suppliers. The environmental performance is evaluated according to the total spoiled waste and emissions resulting from operation strategies and manufacturing activities.

The expected total cost for the producer comprises fixed setup costs for every production run, minor setup costs for different products, ordering costs for raw materials, fixed and variable delivery costs of raw materials from suppliers, costs of wasted spoil products and fines charged for rejecting customer orders. This gives the following objective function:

$$E(TC_v) = \sum_{t=1}^{T}\{k^v Y_t^v + \sum_{i=1}^{n^{(i)}} k^v{}_i Y_{i,t}^v + \sum_{a=1}^{n^{(a)}} p_a^v F_{a,t}^v + \sum_{a=1}^{n^{(a)}}(q_a^v F_{a,t}^v + E(d_{a,t}^s) \cdot VC_a^v) + \sum_{i=1}^{n^{(i)}} w_i^v E(I_{i,M_i,t}^v) + \sum_{t=1}^{T}\sum_{i=1}^{n^{(i)}}\sum_{r=1}^{n^{(r)}} E(dY_{r,i,t}^v) \cdot f_{r,i}^v\} \tag{6.92}$$

The expected total cost for suppliers is comprised of ordering costs for all replenishments made, fixed and variable delivery costs of raw materials, holding costs for every material in stock, costs of wasted spoil materials and costs of replenishing additional raw materials.

$$E(TC_s) =$$

$$\sum_{t=1-LT_{a,max}}^{T}\{\sum_{a=1}^{n(a)} k_a^s Y_{a,t}^s + \sum_{a=1}^{n(a)}(q_a^s Y_{a,t}^s + E(Q_{a,t}^s) \cdot VC_a^s) + \sum_{a=1}^{n(a)} \sum_{e=1}^{M_a-1} h_a^s E(I_{a,e,t}^s) +$$

$$\sum_{a=1}^{n(a)} w_a^s E(I_{a,M_a,t}^s) + \sum_{t=1}^{T} \sum_{a=1}^{n(a)} E(iQ_{a,t}^s) \cdot g_a^v\} \tag{6.93}$$

Hence, the SC cost is determined in objective function (6.94). The total profit of the SC can then be calculated as shown in the objective function (6.95).

$$E(TC) = E(TC_v) + E(TC_s) \tag{6.94}$$

$$E(TP) = \sum_{t=1}^{T} \sum_{i=1}^{n(i)} \sum_{r=1}^{n(r)}(E(dX_{r,i,t}^v) + E(dZ_{r,i,t}^v)) \cdot P_{r,i} - E(TC) \tag{6.95}$$

Objective function (6.96)-(6.97) represent the waste consideration and the CO$_2$ emissions estimation, respectively.

$$E(TW_s) = \sum_{t=1-LT_{a,max}}^{T} \sum_{a=1}^{n(a)} w_a^s E(I_{a,M_a,t}^s) \tag{6.96}$$

$$E(TE) = E(TE_v) + E(TE_s)$$

$$= \sum_{t=1}^{T}\{\sum_{i=1}^{n(i)}(Ek^v Y_t^v + \sum_{i=1}^{n(i)} Ek^v{}_i Y_{i,t}^v + (E(qX_{i,t}^v) + E(qZ_{i,t}^v)) \cdot EP_i) +$$

$$\sum_{a=1}^{n(a)}\left(F_{a,t}^v ET_a^v + (E(d_{a,t}^s) + E(d_{a,t}^v)) \cdot VT_a^v\right)\} +$$

$$\sum_{t=1-LT_{a,max}}^{T}\{\sum_{a=1}^{n(a)}\left(\sum_{e=1}^{M_a} E(I_{a,e,t}^s) \cdot ES_a + (E(Q_{a,t}^s) + E(iQ_{a,t}^s)) \cdot EP_a\right) +$$

$$\sum_{a=1}^{n(a)}(Y_{a,t}^s \cdot ET_a^s + (E\left(Q_{a,t}^s\right) + E(iQ_{a,t}^s)) \cdot VT_a^s)\} \tag{6.97}$$

Emissions are associated with production/purchasing, inventory holding (for suppliers) and transportation that involves the use of refrigerated facilities for the conditioning of perishables. These objective functions are optimised with respect to the following constraints.

Inventory and product flow balance constraints

The suppliers place their material orders in advance of LT_a periods such that the order arrives in time at the start of production schedule of the producer. Constraints (6.98) and (6.99) enforce the desired order-up-to positions for the starting periods where no demand has been physically fulfilled. The values of $E(Q_{a,t}^s)$ were determined in the previous stage of suppliers' replenishment plan.

$$E(Q^s_{a,t-LT_a}) + E(iQ^s_{a,t-LT_a}) = E(S^s_{a,t-LT_a}),\ t = 1; a = 1, \dots, n^{(a)} \tag{6.98}$$

$$E(S^s_{a,t-LT_a-1}) + E(Q^s_{a,t-LT_a}) + E(iQ^s_{a,t-LT_a}) = E(S^s_{a,t-LT_a}),\ 1 < t < LT_a + 1; a = 1, \dots, n^{(a)} \tag{6.99}$$

For the rest of the planning period, constraint (6.100) ensures balanced material inventories at the suppliers.

$$\sum_{e=1}^{M_a} E(I^s_{a,e,t}) + \sum_{n=t-LT_a+1}^{t} E(Q^s_{a,n}) + \sum_{n=t-LT_a+1}^{t} E(iQ^s_{a,n}) = E(S^s_{a,t}) - E(d^s_{a,t}) - E(d^v_{a,t}),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \tag{6.100}$$

Constraints (6.101) and (6.102) ensure that the setup cost is incurred when there is a production run. The production quantities are all equal to zero except in the production periods. In the replenishment periods, an order quantity results in an ordering cost. Constraints (6.103) and (6.104) ensure that the cost is incurred. There is no replenishment for suppliers from $LT_a - 1$ periods prior to the end of the planning horizon. Constraint (6.105) guarantees this aspect. Constraint (6.106) ensures that no additional material order is possible for the periods of transportation lead time LT_a from the beginning of the planning horizon.

$$E(qX^v_{i,t}) + E(qZ^v_{i,t}) \le \boldsymbol{M} \cdot Y^v_{i,t},\ t = 1, \dots, T; i = 1, \dots, n^{(i)} \tag{6.101}$$

$$E(qX^v_{i,t}) + E(qZ^v_{i,t}) \ge Y^v_{i,t},\ t = 1, \dots, T; i = 1, \dots, n^{(i)} \tag{6.102}$$

$$E(Q^s_{a,t}) + E(iQ^s_{a,t}) \le \boldsymbol{M} \cdot Y^s_{a,t},\ t = 1 - LT_a, \dots, T; a = 1, \dots, n^{(a)} \tag{6.103}$$

$$E(Q^s_{a,t}) + E(iQ^s_{a,t}) \ge Y^s_{a,t},\ t = 1 - LT_a, \dots, T; a = 1, \dots, n^{(a)} \tag{6.104}$$

$$E(iQ^s_{a,t}) = 0,\ t = T - LT_a + 1, \dots, T; a = 1, \dots, n^{(a)} \tag{6.105}$$

$$E(iQ^s_{a,t}) = 0,\ 1 - LT_{a,max} \le t < 1; a = 1, \dots, n^{(a)} \tag{6.106}$$

Demand satisfaction constraints

Constraints (6.107)-(6.108) impose that customer demand can be rejected, be accepted and produced using planned raw material inventory or be accepted but require an additional material replenishment. Constraints (6.109)-(6.110) express the total production required for each product using the planned inventory of material and the materials obtained from additional replenishment, respectively.

$$d^{v}_{r,i,t} = E(dX^{v}_{r,i,t}) + E(dY^{v}_{r,i,t}) + E(dZ^{v}_{r,i,t}),\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; r = 1, \dots, n^{(r)} \quad (6.107)$$

$$E(dX^{v}_{r,i,t}) \leq d^{v}_{r,i,t},\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; r = 1, \dots, n^{(r)} \quad (6.108)$$

$$d^{v}_{r,i,t} = E(qX^{v}_{i,t}) = \sum_{r=1}^{n^{(r)}} E(dX^{v}_{r,i,t}),\ t = 1, \dots, T; i = 1, \dots, n^{(i)} \quad (6.109)$$

$$E(qZ^{v}_{i,t}) = \sum_{r=1}^{n^{(r)}} E(dZ^{v}_{r,i,t}),\ t = 1, \dots, T; i = 1, \dots, n^{(i)} \quad (6.110)$$

Constraints (6.111)-(6.112) relate the net requirements of material a to the production plan of products of which a is a component.

$$E(d^{s}_{a,t}) = \sum_{i=1}^{n^{(i)}} (E(qX^{v}_{i,t}) \cdot Usage_{a,i}),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \quad (6.111)$$

$$E(d^{v}_{a,t}) = \sum_{i=1}^{n^{(i)}} (E(qZ^{v}_{i,t}) \cdot Usage_{a,i}),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \quad (6.112)$$

Constraints (6.113)-(6.115) ensure that the additional raw materials are replenished to satisfy the producer request. The replenishment can be made any time prior to the producer production schedule. This additional amount of raw materials can be included in the planned replenishment order prior to production period less lead time. Otherwise, an extra order from the supplier can be initiated. Constraint (6.116) expresses the total replenishment orders made by each supplier.

$$E(iQ^{s}_{a,t-LT_a}) \leq E(d^{v}_{a,t}),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \quad (6.113)$$

$$\sum_{n=1}^{t-LT_a} E(iQ^{s}_{a,t-LT_a}) \geq B^{s}_{a,t},\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \quad (6.114)$$

$$B^{s}_{a,t} = B^{s}_{a,t-1} + E(d^{v}_{a,t}),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \quad (6.115)$$

$$E(TQ^{s}_{a,t}) = E(Q^{s}_{a,t}) + E(iQ^{s}_{a,t}),\ t = 1 - LT_a, \dots, T; a = 1, \dots, n^{(a)} \quad (6.116)$$

No predetermined issuing policy constraints

The age distribution of units of materials used to fulfil the demand is considered. Constraint (6.117) imposes the flow structure of raw materials at the supplier in each time period. Constraint (6.118) shows that freshly replenished materials in period t that are not used to fulfil the demand in that period will have an age of 1 at the end of the period. Constraint (6.119) keeps track of the age-distribution of inventory on hand.

$$\sum_{e=1}^{M_a-1} E(I_{a,e,t-1}^s) - E(d_{a,t}^s) - E(d_{a,t}^v) + E(Q_{a,t-LT_a}^s) + E(iQ_{a,t-LT_a}^s) = \sum_{e=1}^{M_a} E(I_{a,e,t}^s), \quad t = 1, \dots, T; a = 1, \dots, n^{(a)} \tag{6.117}$$

$$E(Q_{a,t-LT_a}^s) + E(iQ_{a,t-LT_a}^s) \geq E(I_{a,1,t}^s),\ t = 1, \dots, T; a = 1, \dots, n^{(a)} \tag{6.118}$$

$$E(I_{a,e,t-1}^s) \geq E(I_{a,e+1,t}^s),\ t = 1, \dots, T; e = 1, \dots, M_a - 1; a = 1, \dots, n^{(a)} \tag{6.119}$$

Forcing constraints

Constraints (6.120)-(6.121) relate the major setup cost to the minor product specific setup costs. Constraints (6.122)-(6.123) ensure that the ordering cost is incurred when a producer places a raw material purchase order. In every production run, raw materials are ordered according to the product’s bill of materials.

$$\sum_{i=1}^{n^{(i)}} Y_{i,t}^v \leq \boldsymbol{M} \cdot Y_t^v,\ t = 1, \dots, T \tag{6.120}$$

$$\sum_{i=1}^{n^{(i)}} Y_{i,t}^v \geq Y_t^v,\ t = 1, \dots, T \tag{6.121}$$

$$\boldsymbol{M} \cdot F_{a,t}^v \geq Y_{i,t}^v,\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; a = 1, \dots, n^{(a)} \tag{6.122}$$

$$Usage_{a,i} \cdot Y_{i,t}^v \geq F_{a,t}^v,\ t = 1, \dots, T; i = 1, \dots, n^{(i)}; a = 1, \dots, n^{(a)} \tag{6.123}$$

Variable constraints

Constraints (6.124)-(6.129) represent the non-negativity and binary restrictions imposed upon the decision variables.

$$Y_{a,t}^s, z_{a,t,j}^s \in \{0,1\},\ t = 1, \dots, T; a = 1, \dots, n^{(a)}; j = 1, \dots, M_a \tag{6.124}$$

$$E(I_{a,e,t}^s), E(d_{a,t}^s) = 0,\ 1 - LT_{a,max} \leq t < 1; e = 1, \dots, M_a; a = 1, \dots, n^{(a)} \tag{6.125}$$

$$B_{a,1-LT_{a,max}}^s = 0,\ a = 1, \dots, n^{(a)} \tag{6.126}$$

$$E\left(I_{a,e,t}^s\right) \geq 0,\ t = 1, \dots, T; a = 1, \dots, n^{(a)}; e = 1, \dots, M_a \tag{6.127}$$

$E(Q_{a,t}^{s}), E(iQ_{a,t}^{s}), E(S_{a,t}^{s}) \geq 0,\ t = 1 - LT_a, \dots, T; i = 1, \dots, n^{(i)}$ (6.128)

$E(qX_{i,t}^{v}), E(qZ_{i,t}^{v}) \geq 0,\ t = 1, \dots, T; i = 1, \dots, n^{(i)}$ (6.129)

6.4.4 Model solution

To evaluate the fitness of any candidate solution, the mo-MILP model can be solved with the ε-constraint method and weighted goal programming method.

In this solution methodology, total profit was selected for optimisation whereas total waste and emission were formulated as additional constraints. The right hand side values of the additional constraints are ε_1 and ε_2 which represent the limit on waste and emissions respectively.

In the first stage of determining replenishment plans for suppliers, the ε-constraint method can be adopted as follows;

Min $E(TC_s)$

s.t. Constraints (6.71) – (6.91)

$E(TW_s) \leq \varepsilon_1,$ (Additional constraint) (6.130)

$E(TE_s) \leq \varepsilon_2,$ (Additional constraint) (6.131)

Following that, the ε-constraint method can be adopted in the production and inventory planning in a SC with MTO producer as follow;

Max $E(TP)$

s.t. Constraints (6.96) – (6.129)

$E(TW_s) \leq \varepsilon_1,$ (Additional constraint) (6.132)

$E(TE_s) \leq \varepsilon_2,$ (Additional constraint) (6.133)

In the weighted goal programming method, different weights are assigned to the ratio of deviation of each objective from its prospective goal to its means goal as required by the SC members.

In the first stage of determining replenishment plans for suppliers, the weighted goal programming method can be adopted as follows;

$$\text{Min} \quad \left(w_1 \cdot \frac{G1}{Avg1}\right) + \left(w_2 \cdot \frac{G2}{Avg2}\right) + \left(w_3 \cdot \frac{G3}{Avg3}\right)$$

s.t. Constraints (6.70) – (6.91)

$$E(TC_s) - G1 = OF_1 \tag{6.134}$$

$$E(TW_s) - G2 = OF_2 \tag{6.135}$$

$$E(TE_s) - G1 = OF_3 \tag{6.136}$$

$$G1, G2, G3 \geq 0 \tag{6.137}$$

Subsequently, the weighted goal programming method can be adopted in production and inventory planning in a SC with an MTO producer by including the following additional constraints in the model whose $E(TP), E(TW_s), E(TE)$ values can be calculated by constraints (6.95), (6.96) and (6.97) respectively. The values of OF_1, OF_2, OF_3 in addition to $Avg1, Avg2, Avg3$ which represent the required SC performance are specified by the decision makers.

$$E(TP) - G1 = OF_1 \tag{6.138}$$

$$E(TW_s) - G2 = OF_2 \tag{6.139}$$

$$E(TE) - G1 = OF_3 \tag{6.140}$$

Solve this mo-MILP problem using the goal programming method

$$\text{Min} \quad \left(w_1 \cdot \frac{G1}{Avg1}\right) + \left(w_2 \cdot \frac{G2}{Avg2}\right) + \left(w_3 \cdot \frac{G3}{Avg3}\right)$$

s.t. Constraints (6.96) – (6.129), (6.137) – (6.140).

6.5 Summary

In this chapter, the description of the system studied and the mathematical modelling of the production and inventory models in an improved sustainable relative to traditional cost minimisation modelling approach of perishable food SC for multiple items are provided. The make-to-stock model focuses on anticipating and planning to meet demand. The make-to-order model focuses on accepting demand and planning to meet the requested due date. Service level and remaining shelf life product requirements from retailers are employed in the model to reflect the performance. The deterministic multi objective mixed integer linear programming (mo-MILP) approximation is proposed to deal with non-stationary stochastic retailer demands. Trade-offs among cost, spoiled food waste and emission are evaluated in the model objectives. All three objective functions for the SC are derived based on the time-dependent replenishment cycle control policy (R^n, S^n) and studies that have been carried out previously. A number of references are referred to and developed in this research. The understanding of the decision process and its impact facilitated by the models helps provide insights into improving sustainability of the SC.

Chapter 7 Analysis and Discussion

7.1 Introduction

In this chapter, the computational experiment on sets of instances is presented to test, discuss and analyse models developed in chapter 6. In section 7.2 numerical examples are used to illustrate how the models work. Solution methods of achieving sustainability for each numerical example are provided in section 7.3. Sensitivity analysis is presented in section 7.4. Section 7.5 summarises the chapter.

7.2 Computational Experiments

The following numerical examples are used to illustrate the capabilities of the models presented in previous chapter and to investigate the behaviour of the production inventory system proposed. The performance of the mo-MILP MTS model was evaluated by having two inventory problems in an experiment. Afterwards, the performance of the mo-MILP MTO model was evaluated by an experiment of one inventory problem. The values of the input parameters adopted in the problems are very close to those found in related literature (Jaber and Goyal, 2008, Pauls-Worm et al., 2010, Kouki et al., 2013, Rossi, 2013, Pauls-Worm et al., 2014).

First, the author gives an example for the system with a stochastic demand and then the author further addresses cases with non-stationary stochastic demand. In the first example, the numerical results presented in Kouki et al. (2013) are re-examined. Focus is given on the comparison of reorder levels and order sizes calculated from both Kouki’s model and the proposed model. The effect of cost, emission and waste on the optimal ordering plan can be analysed in the three single objective optima cases. Seeing that a non-stationary erratic demand is sometimes used for modelling the retailers’ demand facing perishable food producer in inventory study, this aspect is then included in the second example of mo-MILP MTS model. In the third example, a case of a MTO producer is examined. The author employs an emergency order of raw materials in the suppliers’ cost function to represent the replenishment flexibility of the system.

Subsequently, the author develops examples applying sustainability assessment methodology in the above mentioned examples. First, the shape of the Pareto front using the ε-constraint method is investigated. It is also of interest to illustrate consequences on the SC performances (including total cost, emission and waste) from using the weighted goal programming method.

Another interesting investigation is the importance of centralised decisions to the system performances and the decision variables. A production and inventory problem of two-echelon make-to-stock SC consists of a producer producing perishable products from the forecast demand and multiple suppliers supplying perishable raw materials according to the producer's production schedule. In order to investigate the advantage of SC perspective and the benefits that the suppliers and the producer gain through integrated planning, the inventory system is optimised both with SC and single company point of view. Two different solution methods are used to explore the difference in the expected SC performances. Under a decentralised control, the optimal solution of the model is obtained by a sequencing process. All members of the SC make their replenishment/production decisions independently based on their local information. A mo-MILP method is used by a producer to solve its problem first. Suppliers follow this process in sequence by adopting the optimal solution of a producer. This decentralised decisions-making is practiced in an SC where members have different ownerships and each aims at optimising its own performances. Under centralised control, production/inventory decisions of producer and its suppliers are made simultaneously to directly optimise the SC-wide performance in a system. The optimal solution of the integrated model for the SC is obtained through solving a mo-MILP model. This centralisation of the decisions-making is appropriate in an environment where suppliers dominate. Thus, information sharing from producer is possible. The centralised control strategy is adopted in both example problems 2 and 3 in Section 7.2.2-7.2.3. However, example problem 2 is further used in sensitivity analysis in Section 7.4 to explore the issue of SC controlling strategy by showing its SC performances in comparison with the system adopting decentralised control strategy.

For the sensitivity analysis, further numerical examples have been provided in Section 7.4 in order to illustrate the difference of the assumptions regarding the demand characteristics, maximum lifetime of perishables, perished items' value, demand volatility and service level requirement.

7.2.1 Example problem 1

Kouki et al. (2013) formulated an (*r, Q*) inventory model for perishables having fixed lifetime. It was assumed a positive replenishment lead time and the inventory is depleted by stochastic demand according to a FIFO issuing policy. Various costs are considered in this problem including fixed ordering cost, holding cost, purchase cost, backlog cost and outdated cost. Hence, a demand scenario similar to test problems in the study by Kouki et al. (2013) is simulated in order to investigate a situation with stationary stochastic demand and to show the impact of different parameters on the performance of the waste-compensating (R^n, S^n) approach compared with the classical (*r, Q*) system and Kouki et al.'s (*r, Q*) inventory model for perishables. This is done to study and compare producer behaviour in all solutions. A service level approach is adopted in this work instead of using the backlog cost as in Kouki et al.'s study. The demand $\sum_{r=1}^{n^{(r)}} E(d_{r,i,t}^{v})$ from retailer in each period is assumed normally distributed with a Coefficient of Variation (CV) of 0.1 with $N(10,1)$ and 0.2 with $N(10,2)$. The inventory is depleted using a FIFO issuing policy. A product with a fixed (internal) shelf life of 3 periods with a unit holding cost of $h_i^v = 1$ is considered. A deterministic lead time of one period $LT_i = 1$ is assumed. A service level of $\alpha_{r,i} = 95\%$ is used.

The safety stocks to meet a 95% service level are given in Table 7-1. For example, the safety stock (CV = 0.2) at the end of period $t = 3$ is 6 ($1.6449 \cdot \sqrt{2^2 + 2^2 + 2^2}$) when the most recent order prior to period 3 was in period $t - j + 1 - LT_i = 3 - 2 + 1 - 1 = 1$, for $j = 2$ periods (highlighted in Table 7-1).

Table 7-1 Safety stocks for Problem 1

CV = 0.2

	Time							
j	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0	5	5	5	5	5	5	5
2	0	0	**6**	6	6	6	6	6
3	0	0	0	7	7	7	7	7

CV = 0.1

	Time							
j	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0	3	3	3	3	3	3	3
2	0	0	3	3	3	3	3	3
3	0	0	0	4	4	4	4	4

Twelve test problems are generated by varying the values of purchasing cost ${c^v}_i$, waste disposal cost ${w^v}_i$ and fixed setup cost ${k^v}_i$. As shown in Tables

7-2 and 7-3, the total cost of the proposed model is always lower than Kouki et al.'s model since the backlog cost is not considered. The results received from the proposed model for both cases of demand in Tables 7-4 and 7.5 can be used to calculate the equivalent of an (*r, Q*) inventory review policy for comparison purpose. For the entire range of parameters considered, classical (*r, Q*) policy is inappropriate to control the inventory of perishable products. Two different (R^n, S^n) policies are suggested from the proposed model for each of the demand scenarios under an 8-period planning horizon. The choice of policy depends on the impact between waste disposal and setup costs. When waste disposal cost is high (manipulated over the setup cost on the optimal solution), the model suggests an inventory policy with a larger number of orders such that less safety stock is required, less inventory is carried and there is a reduced chance of perishing. The disposal cost has superior impact on the production plan when in a higher demand volatility scenario (higher CV). In contrast, in both the Kouki et al. and the classical non-perishable items models, the optimal ordering quantity increases as the setup cost $k^v{}_i$ increases. The percentage difference of total cost from the classical model compared to both the proposed model and Kouki et al.'s model becomes higher as $k^v{}_i$ increases until it reaches a steady state when the disposal cost no longer has an effect on the production plan (Figure 7.1).

Table 7-2 Comparison for Normal demand $\boldsymbol{N(10,2)}$

Test problem	**Cost parameters**		**Proposed model**				**Kouki model**				**Classical model**		
	c_i^v=5 w_i^v=5	$k^v{}_i$	r	Q	TC	%	r	Q	TC	%	r	Q	TC
1		50	16	22	87	25.27	18	22	98.796	15.13	19	34	116.415
2		100	16	29	107.3	38.13	17	26	120.198	30.69	18	47	173.426
3		150	16	29	126	41.45	16	28	139.667	35.10	17	57	215.219
4		200	16	29	144.8	41.64	16	29	157.923	36.35	17	66	248.099
	c_i^v=5 w_i^v=15												
5		50	16	22	87	33.48	18	21	100.251	23.35	19	34	130.793
6		100	16	22	112	44.06	17	24	122.814	38.65	18	47	200.201
7		150	16	29	134.8	45.87	16	26	143.129	42.52	17	57	249.028
8		200	16	29	153.5	46.75	15	28	162.068	43.77	17	66	288.277
	c_i^v=5 w_i^v=30												
9		50	16	22	87	42.90	18	20	101.963	33.08	19	34	152.360
10		100	16	22	112	53.40	17	23	125.451	47.81	18	47	240.364
11		150	16	22	137	54.29	16	25	146.612	51.09	17	57	299.741
12		200	16	22	162	53.50	15	27	166.292	52.27	17	66	348.418

Table 7-3 Comparison for Normal demand $\boldsymbol{N(10,1)}$

Test problem	**Cost parameters**		**Proposed model**				**Kouki model**				**Classical model**		
	c_i^v=5 w_i^v=5	$k^v{}_i$	r	Q	TC	%	r	Q	TC	%	r	Q	TC
1		50	13	28	82.5	11.94	18	23	95.4379	11.94	18	34	112.539
2		100	13	28	101.25	10.73	17	26	115.765	10.73	18	47	173.983
3		150	13	28	120	9.79	16	28	134.607	9.79	17	57	215.512
4		200	13	28	138.75	8.31	16	29	152.649	8.31	17	65	246.119
	c_i^v=5 w_i^v=15												
5		50	13	21	83.25	13.22	18	22	96.1744	13.22	18	34	124.557
6		100	13	28	106.25	8.81	17	25	117.342	8.81	18	47	200.929
7		150	13	28	125	5.82	16	27	136.783	5.82	17	57	249.551
8		200	13	28	143.75	5.29	15	28	155.326	5.29	17	65	285.829
	c_i^v=5 w_i^v=30												
9		50	13	21	83.25	14.67	18	21	96.8492	14.67	18	34	142.585
10		100	13	21	108.25	10.72	17	24	118.788	10.72	18	47	241.348
11		150	13	28	132.5	6.56	16	26	138.892	6.56	17	57	300.609
12		200	13	28	151.25	2.58	15	27	157.859	2.58	17	65	345.394

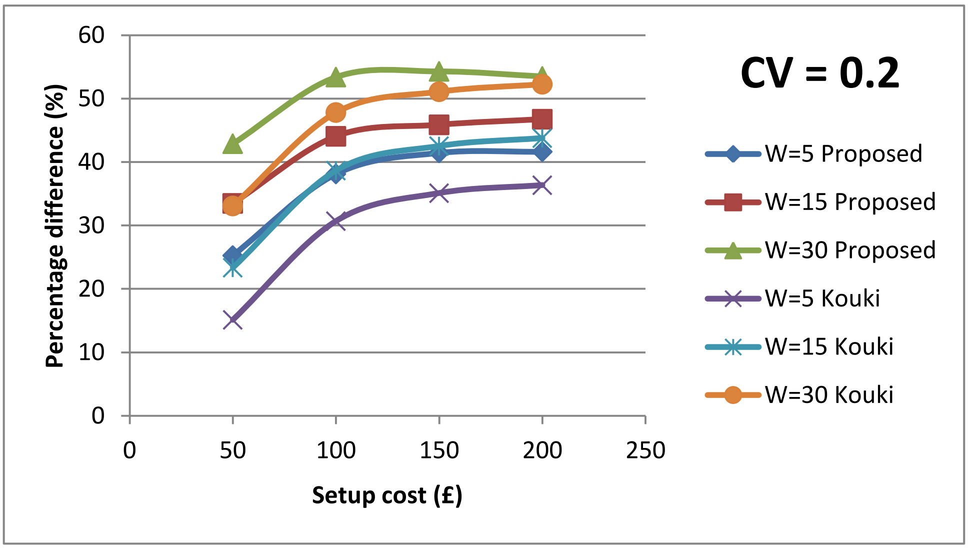


Figure 7.1 Percentage difference of total cost with respect to setup cost

Test problem 3 in the $N(10,2)$ demand case from Table 7-2 is used, which is test problem 7 from Table 5 in Kouki et al. (2013), as an example. The optimisation from this thesis proposed model provides the policy given in Table 7-4. Orders occur in periods 1, 3 and 5. The order-up-to level of period 1 is equal to 36. This is the amount to fulfil the demand of periods 1, 2 and 3 and the safety stock at $t = 3$ and $j = 2$ according to Table 7-1. This result resembles the result from Kouki et al.'s model of an (*r, Q*) review system. Both models give the same reorder level of 16. In Kouki et al.'s (2013) model, an order of size $Q = 28$ is placed whenever the inventory level drops to the replenishment level $r = 16$ with an average total cost of 139.667 (including backlog cost). In the author's proposed model, varying order sizes are determined along with an average total cost of 126 per unit of time. A replenishment order is made the day after the inventory level drops to the replenishment level $r = 16$ (highlighted in Table 7-

4). This confirms that the proposed model is general and can provide solutions for a stationary stochastic demand with a positive lead time scenario as well, although possibly less efficiently as a result of the truncated horizon effect (i.e. the planning horizon is too short to identify the optimal ordering decisions that would be found knowing demand beyond the end of the planning horizon) and unsmooth production plan.

Table 7-4 Order policy and model output for Normal demand $\boldsymbol{N(10, 2)}$

r= 16, Q=29

t	1	2	3	4	5	6	7	8
$E(S^v_{i,t})$	36	26	36	26	47	37	27	17
$E(Q^v_{i,t})$	36	0	20	0	31	0	0	0
$E(d^v_{r,i,t})$	10	10	10	10	10	10	10	10
$\sum_b E(I^v_{i,b,t})$	0	16	6	16	6	27	17	7
$E(I^v_{i,1,t})$	0	16	0	16	0	27	0	0
$E(I^v_{i,2,t})$	0	0	6	0	6	0	17	0
$E(I^v_{i,3,t})$	0	0	0	0	0	0	0	7

r=16, Q=22

t	1	2	3	4	5	6	7	8
$E(S^v_{i,t})$	36	26	36	26	36	26	25	15
$E(Q^v_{i,t})$	36	0	20	0	20	0	9	0
$E(d^v_{r,i,t})$	10	10	10	10	10	10	10	10
$\sum_b E(I^v_{i,b,t})$	0	16	6	16	6	16	6	5
$E(I^v_{i,1,t})$	0	16	0	16	0	16	0	5
$E(I^v_{i,2,t})$	0	0	6	0	6	0	6	0
$E(I^v_{i,3,t})$	0	0	0	0	0	0	0	0

Table 7-5 Order policy and model output for Normal demand $\boldsymbol{N(10, 1)}$

r=13, Q=28

t	1	2	3	4	5	6	7	8
$E(S^v_{i,t})$	33	23	33	23	44	34	24	14
$E(Q^v_{i,t})$	33	0	20	0	31	0	0	0
$E(d^v_{r,i,t})$	10	10	10	10	10	10	10	10
$\sum_b E(I^v_{i,b,t})$	0	13	3	13	3	24	14	4
$E(I^v_{i,1,t})$	0	13	0	13	0	24	0	4
$E(I^v_{i,2,t})$	0	0	3	0	3	0	14	0
$E(I^v_{i,3,t})$	0	0	0	0	0	0	0	0

r=13, Q=21

t	1	2	3	4	5	6	7	8
$E(S^v_{i,t})$	33	23	23	33	23	33	23	13
$E(Q^v_{i,t})$	33	0	10	20	0	20	0	0
$E(d^v_{r,i,t})$	10	10	10	10	10	10	10	10
$\sum_b E(I^v_{i,b,t})$	0	13	3	3	13	3	13	3
$E(I^v_{i,1,t})$	0	13	0	3	13	0	13	0
$E(I^v_{i,2,t})$	0	0	3	0	0	3	0	3
$E(I^v_{i,3,t})$	0	0	0	0	0	0	0	0

In addition to this, three base cases are defined for this test problem: Lowest Cost (LC), Lowest Emission (LE) and Lowest Wastage (LW). Numerical result of the LC base case for a producer is listed in Table 7-4 above (with $r = 16, Q = 29$). The amount of carbon emission associated per production setup initiated is set to $Ek^v{}_i = 10$, the unit production emission to $EP_i = 1$ and the unit holding emission to $ES_i = 2$.

Summary results for all three base cases over the whole planning horizon are presented in Table 7-6. More frequent orders and lower production quantity are suggested in the LE base case. This supports the claim by Chen et al. (2013) that decreasing the order quantity decreases emissions when $\left(\frac{k^v{}_i}{h^v_i}\right) > \left(\frac{Ek^v{}_i}{ES_i}\right)$. The effect of reducing wastage or emissions can be seen from the total cost differences among the base cases. The reason for the cost change in the LE base case is a decrease in the total inventory, including required safety stock, that results in an increase in the number of orders. In the LW case, the age-distribution of items in stock keeps updating as well as avoids reaching the maximum value, whereas in the LE case a production order is made in every period to reduce energy consumption from warehousing operation that results in the highest value of setup cost. Both LW and LE cases give no expected spoil wastage from the determined order policies. Emission differences in every base case are due to production and warehousing operations. The result from the LE case suggests keeping simply 35 units of product inventory for the whole planning horizon which means a maximum of five units of safety inventory every period for seven periods (with $LT_i = 1$). The LW base case results in a policy which gives both total cost and CO$_2$ emission values in a middle range compared to the other two base cases.

Table 7-6 Summary of results for base cases in Problem 1

Case	**Lowest cost**	**Lowest emission**	**Lowest waste**
Cost	1008	1510	1397
-Setup	450	1050	900
-Inventory	88	35	67
-Production	435	425	430
-Wastage	35	0	0
Spoiled waste	7	0	0
Emission	307	225	280
-Setup	30	70	60
-Inventory	190	70	134
-Production	87	85	86
General			
- Replenishment lengths	{2,2,4}	{1,1,1,1,1,2}	{1,1,1,1,3}
-Total inventory	88	35	67

7.2.2 Example problem 2

For the production and inventory problem of two-echelon make-to-stock SC with perishable products, a non-stationary stochastic demand is considered in test problem 2. The demand from retailers is assumed normally distributed in each period of the planning horizon with a CV of 0.2. A demand forecast $\sum_{r=1}^{n(r)} E(d_{r,i,t}^{v})$ in an erratic pattern is given in Table 7-7. The total target demand for a 12-period planning horizon is 7200 units. The safety stocks to meet a 95% service level are given in Table 7-8.

Table 7-7 Forecasts and standard deviations of demand with a CV = 0.2

Period t	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
$\boldsymbol{E(d_{r,i,t}^{v})}$	800	950	200	900	800	150	650	800	900	300	150	600
$\boldsymbol{St.dev.(d_{r,i,t}^{v})}$	160	190	40	180	160	30	130	160	180	60	30	120

Table 7-8 Safety stocks for Problem 2 base case with production lead time = 1

j/t	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	0	409	319	303	396	268	219	339	396	312	110	203
2	0	0	414	436	402	399	343	343	450	408	316	226
3	0	0	0	509	509	405	453	432	453	461	411	373

For the producer, the inventory is depleted using a FIFO issuing policy. A product with a fixed (internal) shelf life of three periods is considered. The fixed amount of cost per production order represents the costs related to setting up the production run, order processing and transportation. The production setup cost is set to ${k^v}_i = 1500$, the unit production cost to $c_i^v = 2$ and the holding cost to $h_i^v = 0.5$. The cost of product wastage w_i^v is 0. The amount of carbon emission can also be associated with the storage of each unit per time unit in refrigerated storage. The amount of carbon emission associated per production order initiated is set to ${Ek^v}_i = 2000$, the unit production emission to $EP_i = 1$ and the unit holding emission to $ES_i = 4$ such that the ratio between the quotient of production order cost divided by holding cost $\left(\frac{{k^v}_i}{h_i^v}\right)$ and the quotient of production order emission divided by holding emission $\left(\frac{{Ek^v}_i}{ES_i}\right)$ is 6 to 1. A deterministic lead time of one period $LT_i = 1$ is considered.

For the supplier stage, values of the parameters are assumed as shown in Table 7-9. Each raw material ordering cost is set to $k_a^s = 300$. Zero planned transport lead time $LT_a = 0$ is assumed.

Table 7-9 Supplier input parameters for Problem 2 base case

Material a	$Usage_{a,i}$	M_a	s_a^s	h_a^s	ET_a^s	ES_a
1	1	2	0.05	0.005	100	0.01
2	5	4	0.05	0.005	100	0.01
3	5	3	0.05	0.005	100	0.01
4	3	4	0.01	0.001	400	0.008
5	1	5	0.02	0.002	250	0.01

For problem 2, three base cases: Lowest Cost (LC), Lowest Emission (LE) and Lowest Waste (LW) are defined. Employing the proposed model, the three single objective optima under a centralised decision making process can be calculated (see Table 7-10). Following a $w_i^v = 0$ assumption, the LC case gives a suggested result that ends with a high amount of total waste. Similar to example problem 1, the LE base case results in a higher number of production/replenishment orders and a decrease in average order quantity as $\left(\frac{k^{v}{}_{i}}{h_{i}^{v}}\right) > \left(\frac{Ek^{v}{}_{i}}{ES_{i}}\right)$. The LW case proposes the ordering plan with high frequency and small quantity as age-distribution of products and raw materials is the only concern.

Table 7-10 Single objective optima for Problem 2 base case

Case	**# orders**	**Avg. order quantity**	**Total cost**	**Total emission**	**Total waste**
Lowest Cost	5[a] 4,2,3,2,2[b]	1596[a] 1995,19945,9903,11967,3989[b]	35983.7	51927.9	778
Lowest Emission	8 5,4,4,3,3	925 1480,9254,9254,7403,2468	39302.3	44180.6	0
Lowest Waste	9 8,9,8,9,9	823 925,4113,4627,2468,823	49259.3	62645.06	0

[a] Producer stage, [b] Supplier stage

The trade-off between the economic function and environmental function is analysed to help the decision maker understand the impact of considering each objective independently (solely costs, solely emissions or solely wastes) which is illustrated in Table 7-11. This simple analysis shows that if the decision maker considers only the emission function to be optimised, it causes the cost function to increase by 18%, while only optimising the cost function and ignoring the emission function ends in an increase of 9% in the emission function. Alternatively, optimising the waste function results in a 37% increase in the cost function value and a 42% increase in the emission function.

Table 7-11 Trade-off of using production and replenishment plans based on economic versus environmental objectives for Problem 2 base case

Case	**Using Lowest cost plans % deviation from optimal**	**Using Lowest emission plans % deviation from optimal**
Lowest cost	0	18
Lowest emission	9	0
Lowest waste	37	42

Summary of results for all three base cases are presented in Table 7-12. The effect of reducing emissions can be seen from the total cost difference between LC and LE base cases. Setup and ordering cost items increase while inventory, production and procurement cost items decrease in the LE base case. The same applies to emission items. The reasons for the cost change and emission difference in LE base case are (i) increasing the number of orders results in an increase in setup and ordering costs, and (ii) using a smaller replenishment quantity results in a decrease in inventory. Setup and ordering cost items are highest in the LW base case due to items' perishability.

Table 7-12 Summary results for base cases of Problem 2

Case	**Lowest cost (P,S)**	**Lowest emission (P,S)**	**Lowest wastage (P,S)**
Cost	35983.73	39302.309	49259.33
-Setup/Ordering	(7500,3900)	(12000,5700)	(13500,12900)
-Inventory	(3458,382.93)	(2109,245.509)	(3611.5,0.03)
-Production/ Procurement	(15956,4786.8)	(14806,4441.8)	(14806,4441.8)
Spoiled waste	(778,0)	(0,0)	(0,0)
Emission	51927.92	44180.59	62645.06
-Setup/Ordering	(10000,2200)	(16000,3250)	(18000,8350)
-Inventory	(30776,973.916)	(16872,655.586)	(28892,0.06)
-Production	(7978,0)	(7403,0)	(7403,0)
General			
-Total inventory	(6916,102593)	(4218,69824)	(7223,6)

*P=Producer; S=Suppliers

A production and inventory problem of two-echelon make-to-order SC consists of a producer producing perishable products for the accepted retailer demand over the planning horizon, and multiple suppliers supplying perishable raw materials from their inventory to the producer just in time for the production. This is enabled through strategic partnerships built between producer and its suppliers. The inventory system is optimised for a SC point of view. The optimal solution of the integrated model for the SC is obtained through solving a two-stage mo-MILP model.

7.2.3 Example problem 3

In this example problem a similar instance to problem 2 is assumed, but the producer operates a make-to-order strategy. Production begins after the retailer demands for the planning horizon are accepted. The producer then requests the deliveries of raw materials from suppliers for its production schedule. The suppliers plan their stock replenishment in advance using the forecast demand from the producer, before the real retailer demands can be realised. The inventory received from the replenishment orders is used to satisfy producer demand of raw materials. However, when there are not enough materials, the suppliers have to make emergency orders or adjust their order quantity to fulfil producer demand. This incurs additional costs.

Therefore, raw material replenishment orders are devised at the start of the supply process. The forecast demand is assumed to be normally distributed in each period of the planning horizon with a CV of 0.2. A demand forecast $E(d_{i,t}^{v})$

in an erratic pattern is given in Table 7-7. The total target demand for a 12-period planning horizon is 7200 units. Values of the parameters are assumed as shown in Table 7-9. Using the BOM values from Table 7-9, the total raw material demand and the safety stocks required to meet a 95% service level for each raw material can be calculated using the information given in Tables 7-7 and 7-8, respectively. Each raw material ordering cost is set to $k_a^s = 300$. Zero planned transport lead time $LT_a = 0$ is assumed.

Three base cases for suppliers are defined: Lowest Cost (LC), Lowest Emission (LE) and Lowest Waste (Piramuthu and Zhou). Employing the proposed model, the three single objective optima can be calculated (see Table 7-13). Following a $w_a^s = 0$ assumption, the LC supply case predicts a high amount of total waste. The LE base case results in a higher number of production/replenishment orders. The LW case proposes the ordering plan with high frequency and small quantity as age-distribution of products and raw materials is the only concern.

Table 7-13 Single objective optima for Problem 3 base case

Case	**# orders**	**Avg. order quantity**	**Total cost**	**Total emission**	**Total waste**
Lowest Cost	6,4,4,3,3	1507,9466,10862,8514,2552	11505	4994.13	15541
Lowest Emission	6,5,5,3,3	1507,7398,8527,8514,2552	11916.2	4949.11	11876
Lowest Waste	12,12,12,12,12	636,3083,3083,1850,617	22603.5	11773	226

Comparing the LC and LE base cases in the table 7-13 above, it shows that order quantity adjustment facilitates emission reduction. As the ratio of economic to environmental parameters is 6:1 (see Table 7-9), $\left(\frac{k^s{}_a}{h_a^s}\right) > \left(\frac{Ek^s{}_a}{ES_a}\right)$, increasing frequency (from four to five orders for raw materials $a = 2{,}3$) along with decreasing quantity when ordering decreases emissions. The trade-off between the economic and environmental functions is analysed to help the decision maker understand the impact of considering each objective independently (solely costs, solely emissions or solely wastes), which is illustrated in Table 7-14. This simple analysis shows that if the decision maker considers only the emission function to be optimised, it causes increases of 3.57% in the cost function. While only optimising the cost function and ignoring the emission function gives rise to an increase of 0.91% in the emission function.

Table 7-14 Trade-off of using production and replenishment plans based on economic versus environmental objectives for Problem 3 base case

Case	**Using LC plans % deviation**	**Using LE plans % deviation**
Lowest cost	0	3.57
Lowest emission	0.91	0
Lowest waste	96.47	137.88

The suppliers then adopted the replenishment plans calculated from the model. This can be one of the three base cases, or after finding advantageous trade-off using either the ε-constraint method or the weighted goal programming method, as will be discussed in the next section. It is assumed that the LC and LE base cases are adopted for the following step.

At the start of the planning horizon, the producer receives demand from retailers. All order information for the planning horizon is presented up front. The producer then decides to accept or reject the demand and schedules the production plan accordingly. The production setup cost is set to ${k^v}_i = 1500$. The amount of carbon emission associated per production order initiated is set to ${Ek^v}_i = 250$, the unit production emission to $EP_i = 1$ such that the ratio between production setup cost ${k^v}_i$ and the production order emission ${Ek^v}_i$ is 6 to 1. Profit per unit of sales of product is set to $P_{r,i} = 10$ and the fine for rejecting demand is $f_{r,i}^v = 10$. However, if the production requires more of material a than the supplier has in stock, then an additional quantity has to be ordered. This incurred additional cost $g_a^v = 0.05, 0.05, 0.05, 0.01, 0.02$ per unit of material $a = 1, 2, \ldots, 5$ obtained from an adjusted replenishment plan (represents cost incurred due to a change of plan). Three different demand scenarios from a retailer are assumed from the forecast demand as shown in Table 7-15. All customers pay the same price for products such that they can be considered as the same person.

Table 7-15 Demand from retailers for the planning horizon

Period t	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1-Avg. demand	800	950	200	900	800	150	650	800	900	300	150	600
2-High demand	960	1140	240	1080	960	180	780	960	1080	360	180	720
3-Low demand	640	760	160	720	640	120	520	640	720	240	120	480

Summary of results for all three demand cases under suppliers adopting LC and LE base cases are presented in Tables 7-16 and 7-17, respectively. From Table 7-16, it can be seen that when the real demand is exactly the mean value of the forecast demand, the planning decision results in the lowest total cost of the SC. However, it can be seen that the SC performs better in the high demand scenario but worst in the low demand case. The amount of spoiled wastes reduces as the demand increases. The production/inventory plan in the high demand scenario gives the lowest emission values, when suppliers adopt the LE plan from Table 7-17.

Table 7-16 Summary results when suppliers using LC plan

Case	**Avg. demand**	**High demand**	**Low demand**
Profit/Cost	47495/24505	60198/26002	32967/24633
Spoiled waste	15541	9961	37141
Emission	15028	17008	14116

Table 7-17 Summary results when suppliers using LE plan

Case	**Avg. demand**	**High demand**	**Low demand**
Profit/Cost	46991/25009	59732/26668	32483/25117
Spoiled waste	12863	17196	33856
Emission	15008	10507	14050

7.2.4 Computational time

Different commercially-available optimisation software exists today to solve Mixed Integer Linear Programming (MILP) and Multi-Objective (Non) Linear Programming (MOLP) optimisation problems. It is currently impossible to use real data to populate the model. However, to demonstrate the practical solvability of the model, some numerical scenarios of parameters and constraints are generated as discussed above, and solve the model using the ILOG-OPL development studio and CPLEX 12.5.1 optimisation solver on an Intel Core i5 2.67 GHz PC running Windows 7 to solve the mo-MILP model.

In CPLEX, both model and data files are needed in the compilation process. First, the parameters and variables are declared with the parameters values given in the data file. Subsequently, the optimisation objective function is stated which is then followed by constraints. Readers are referred to Appendix B for a summary of CPLEX coding of all three numerical examples as discussed above wrote by the author.

The mean and median run times were 0.81 and 0.94 seconds for numerical example problem 1. The model has 10 continuous, 64 binary and 106 integer variables, and 414 constraints. In problem 2, the mean and median run times per base case with default OPL and CPLEX solver settings were 6.37 and 8.82 seconds under centralised control and 1.25 and 1.36 seconds under decentralised control (calculated for later use in sensitivity analysis section). The model has 37 continuous, 504 binary and 704 integer variables, and 2685 constraints. In example problem 3, the mean and median run times for the first and second steps per each base case with default OPL and CPLEX solver settings were 1.61 and 1.63 seconds, and 0.96 and 0.91 seconds respectively. The model has 190 continuous, 360 binary and 506 integer variables, and 2237 constraints for the first step and 108 continuous, 144 binary and 662 integer variables, and 1705 constraints for the second step. These are very practical amounts of time. Although these examples are with a limited number of products and sites (suppliers and retailers), more sophisticated global optimisation approaches for a large scale optimisation problem could be used with a large scale food supply chain network.

Note that in a large scale problem, a stop signal can be set on CPLEX to observe the numbers of variable that can be accommodated along with the time required for processing.

7.3 Achieving supply chain sustainability

7.3.1 Trade-offs between multiple objectives via the ε-constraint method

In the research problem, due to different possibilities for inventory decisions, trade-offs occur among total cost, spoiled wastage and amount of CO_2 emission from production and inventory operations. This means that decreasing expected spoiled wastage from warehousing or decreasing emission from production and inventory operations comes at a cost.

The objective of the firm is to choose an ordering policy that minimises its cost subject to the constraints on the amount of carbon emitted (this cap can reflect either government regulations imposed on the firm or a voluntary effort by the firm to reduce its emission by a specified amount) and the amount of food products spoiled. An evaluation of economic and environmental factors in the trade-off analysis assists managers in setting up sustainability targets. Managerial insights on improving sustainability of the analysed food supply chain can be obtained through determination of the cost of being sustainable from the point of reducing wastage or production and warehousing emission in the trade-off analysis (see Figure 7.2-7.5).

In problem 1, model results suggest that emissions can be reduced by having frequent replenishments. This is reasonable since the total emission from production and inventory operations will be lower for a smaller quantity of items produced and carried. However, this increase in the number of replenishments results in higher ordering costs.

In addition to the aforementioned LC and LE base cases, three additional instances are generated by lowering the ε_2 value (limit on CO_2 emission) by a certain percentage from the highest emission level at each instance. As this numerical example is a small scale problem, the ε_1 value (limit on wastage) can be lowered only once which gives the same result as one of the lower emission limit cases. The derived Pareto frontier in Figure 7.2 represents the trade-off relationships between cost and emission for the problem in question. This is done to observe the dependency between the two objectives.

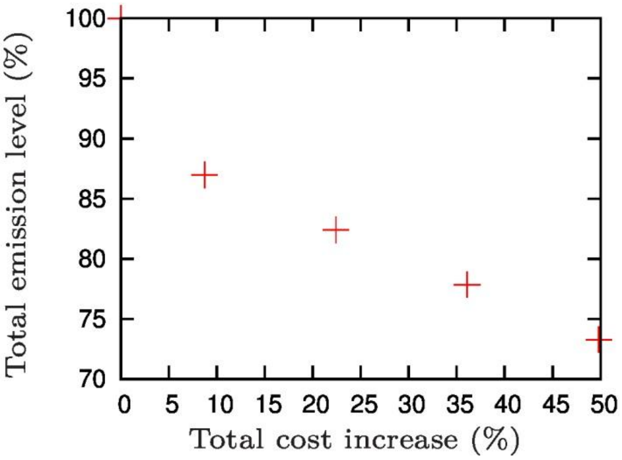


Figure 7.2 Trade-offs between total cost and CO2 emission in Problem 1

Given a certain percentage of the cost increase from the LC base case, the expected level of emission is reduced. For instance, one of the presented solutions can be selected for the analysed food SC. Suppose that the point around the emission level of 87% on the Pareto frontier in Figure 7.2 would be selected. This would ensure in approximate numbers an emission reduction of 13% in return of a cost increase of 9%. This indicates that the cost of being sustainable for this problem can be determined from the point of reducing warehousing emission.

For problem 2, the 20 additional instances were generated by lowering the limit on the CO_2 emission ε_2 value by a certain percentage from the highest emission level at each instance for both centralised and decentralised decision making processes. Due to the non-stationary process of stochastic customer demand, there are more choices for the ordering policy. The derived Pareto frontiers in Figure 7.3A-7.3B represent the trade-off relationships between cost and emission under centralised (shared emission caps) and decentralised (individual emission caps) decision making processes of problem 2, respectively.

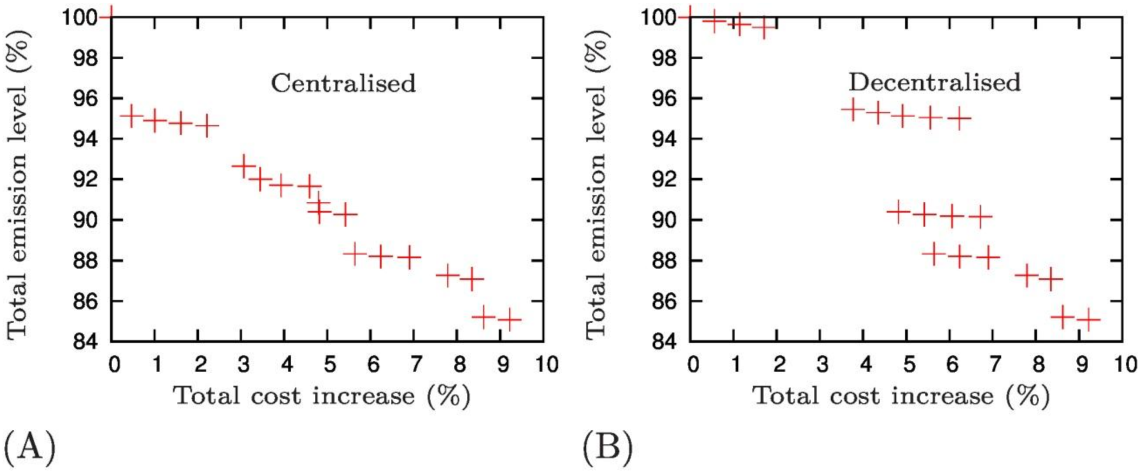


Figure 7.3 Trade-offs using $\boldsymbol{\varepsilon}$-method for Problem 2 under (A) centralised and (B) decentralised controls

It can be observed that the behaviour of trade-offs under the decentralised decision making process in Figure 7.3B is cost overlapping. The model suggests a few alternatives that give approximately the same cost increase but differ in emission reduction. As shown in the figure, as the optimum total cost increases by about 6% from the LC base case, the carbon emission resulting from the SC is reduced by about 5%, 10% or 12% depending on the suggested solutions, for instance. This is owing to the choice of where in the SC and to what extent the limit is placed on emissions as well as a small scale of the problem itself.

Comparing the trade-offs between Figure 7.3A and 7.3B, the results clearly suggest the benefit of using centralised control over decentralised control. Figure 7.3A confirms that adopting a centralised decision making process will offer more economical assistance in improving the perishable food SC sustainability with up to a 12% carbon reduction in comparison with a decentralised one. A shared carbon cap provides the SC with the flexibility of having some firms emit more if they can be offset with less emission from other firms. This allows a firm that is more cost effective at reducing its carbon emission to take on a greater responsibility in meeting the carbon cap. The message is that the producer and its suppliers should look for ways to collaborate with each other in a manner as close to centralised control as possible.

For the replenishment plan of suppliers in example problem 3, the 14 additional instances are generated by lowering the limit on the waste ε_1 value by a certain percentage from the highest expected waste level at each instance. It can be seen from Table 7-13 that the difference of emission generated when adopting LC and LE base cases is not significant so no further trade-off can be done. The derived Pareto frontier in Figure 7.4 represents the trade-off relationships between cost and waste. It can be observed from the impact of varying the waste limit/cap in Figure 7.4 that adjustments in order quantity in each period, could lead to reduction in perished raw material while not significantly compromising cost. As shown in the figure, as the total cost increases by about 1.2% from the LC base case, the perished items at the suppliers is reduced by about 19% due to an increase in replenishment from 4 to 5 orders of raw material $a = 3$, for instance.

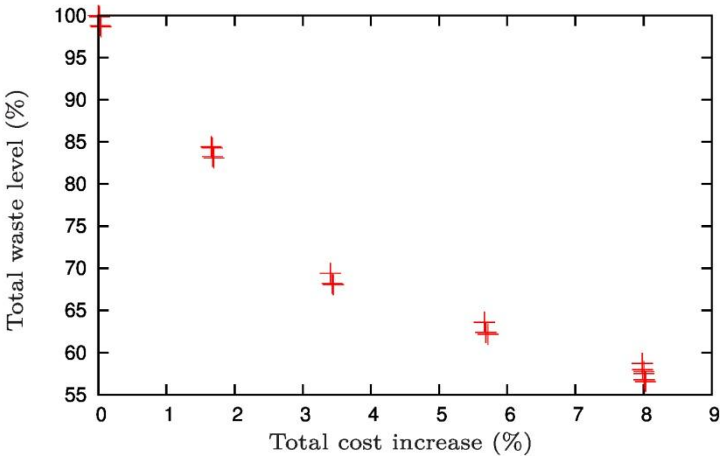


Figure 7.4 Trade-offs between cost and waste using $\boldsymbol{\varepsilon}$-method for Problem 3 for suppliers

For the production/replenishment plans of the SC after demand realisation in example problem 3, the derived Pareto frontier in Figure 7.5 represents the trade-off relationships between cost and emission. Given a certain percentage of the profit decrease, the expected level of emission is reduced. This indicates that the cost of being sustainable for this problem can be determined from an increase in rejected retailer orders such that emissions from SC activities are reduced. As shown in the figure, a sharp decrease of emission level from 99.5% to 97.5% with a profit reduction of 3.15% is resulted from a rejection of orders as twice as much comparing with an instance with 3.02% decrease in profit (i.e. an increase from 72 to 150 demands got rejected).

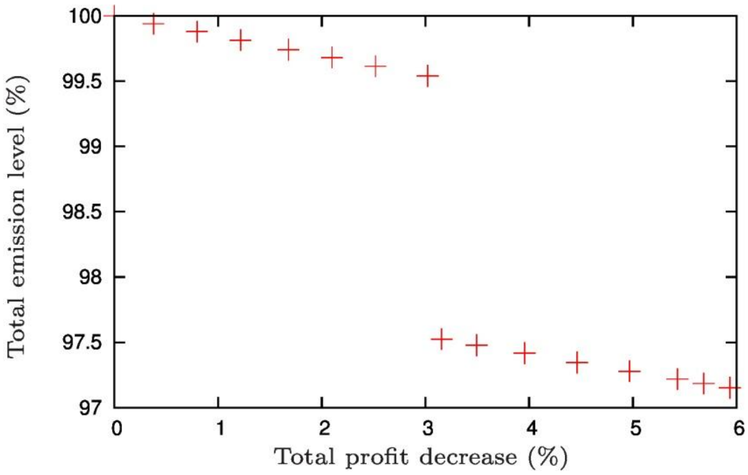


Figure 7.5 Trade-offs between profit and emission using $\boldsymbol{\varepsilon}$-method for Problem 3 for the SC after accepted demand

With the resulting Pareto solutions from example problems discussed above, the final decision is made among them taking the total balance over all SC performances into account. This is a problem of value judgment of decision maker.

7.3.2 Weighted goal programming

A multi-objective optimisation problem allocates additional degrees of freedom by providing a set of solution points which is then constrained by decision maker preferences. In solving this type of problem, the weighted goal programming method allows the user to specify preferences which can be expressed in terms of goals and the relative importance of different objectives. Weights are assigned to the ratio between the deviation of each objective from its perspective goal (i.e. the desired expected total cost, total emission and total waste obtained from solving the three base cases; LC, LE and LW) and its means goal which are then altered in an effort to represent alternatives that can be compared with the ε-constraint method above.

For problem 1, eight instances are generated by varying the ratios among weights for cost, emission and waste as shown in Table 7-18. The average values of different SC performances can be determined from Table 7-6 with $Avg1 = 1259,$ $Avg2 = 266$ and $Avg3 = 3.5$. When the ratio of weight for cost:emission:waste is 1:0:0, it represents the TC base case. As a result of the high relative weight of importance for the cost objective, three cases (0.5:0.25:0.25, 0.5:0.5:0 and 0.5:0:0.5) give the same result. However, when the weight for cost is high enough (e.g. a ratio of 0.7:0.3:0), the model also gives the same result as the LC base case. For the cases when the weight of emission is high in a ratio such as 0:1:0 and 0.3:0.7:0, the LE base case result is suggested. Also, the LW base case gives the same result from the case with a ratio of 0:0:1. All instances represent one of the trade-off between cost and emission objectives.

Table 7-18 Weighted goal programming results for eight cases of Problem 1

Ratios	**Production policy**	**Cost**	**Emission**	**Waste**	**Inventory**
1:0:0	[36,0,20,0,31,0,0,0]	1008	307	7	88
0:1:0	[25,10,10,10,10,10,10,0]	1510	225	0	35
0:0:1	[25,15,10,10,10,16,0,0]	1397	280	0	67
0.5:0.25:0.25	[36,0,20,0,20,0,9,0]	1096	267	0	71
0.5:0.5:0	[36,0,20,020,0,9,0]	1096	267	0	71
0.5:0:0.5	[36,0,20,0,20,0,9,0]	1096	267	0	71
0.3:0.7:0	[25,10,10,10,10,10,10,0]	1510	225	0	35
0.7:0.3:0	[36,0,20,0,31,0,0,0]	1008	307	7	88

For problem 2, the 32 instances are generated by varying the ratios among weights for cost, emission and waste performance for the SC under both centralised and decentralised decision making processes as shown in Table 7-19. Similar to problem 1, there are eight instances for centralised control which are also adopted by the producer in decentralised control. The average values of different SC performances of SC operating under centralised control can be determined from Table 7-10 with $Avg1 = 42621.5,$ $Avg2 = 53412.83$ and $Avg3 = 389$. Suppliers further employ three different ratios between cost and emission under each instance of a producer. When SC operating under decentralised control, the average values of performances for producer can be calculated as $Avg1 = 29356,$ $Avg2 = 46807$ and $Avg3 = 389$. While, the average values of performances for suppliers can be estimated as $Avg1 = 13085.52$ and $Avg2 = 5565.7$.

When the ratio of weight for cost:emission:waste is 1:0:0 for the SC under centralised control as well as when it is 1:0:0 for producer and 0.5:0.5 for suppliers under decentralised control, it represents the LC base case. For the case when a ratio is 0:1:0 under centralised control as well as when it is 0:1:0 for producer and 0:1 for suppliers under decentralised control, the LE base case result is suggested. As employing a decentralised decision making process allows producer and suppliers to have different preferences on the objectives, the effect on optimal result and trade-offs can be seen in Table 7-19. As can be seen in the table, the effect of changing supplier ratio from 1:0 to 0.5:0.5 on the optimal solution varies. It is possible that the model gives result with lower values of cost and emission when the ratio of 0.5:0.5 is adopted. This is due to the effect of standardisation of the units of SC performance measures. However, the solution converts to the lowest emission case when the ratio is 0:1. Furthermore, it is probable that cases in an SC under decentralised control with supplier ratio of 0:1 give the results with lower cost in comparison with when supplier ratio of 0.5:0.5 is adopted in instances 8, 20 and 28 for examples.

Table 7-19 Weighted goal programming results for 32 cases of Problem 2

	Ratios	Supplier	Cost	Emission	Waste	Inventory
1	**1:0:0**[a]		35983.7	51927.9	778	109509
2		1:0	36005.7	51971.9	778	113904
3		0.5:0.5	35983.7	51928	778	109512
4		0:1	36733.9	51927.9	778	79506
5	**0:1:0**		39302.3	44180.6	0	74042
6		1:0	39086.3	44255.4	0	91738
7		0.5:0.5	39383.6	44488.8	0	89862
8		0:1	39302.3	44180.6	0	74042
9	**0:0:1**		52061.4	63861.1	0	6840
10		1:0	41849.8	66574.9	0	95335
11		0.5:0.5	41820.2	66443.9	0	81114
12		0:1	42047	66398.9	0	66616
13	**0.5:0.25:0.25**		37734.3	47226.7	0	81965
14		1:0	38443.7	46267.5	0	112839
15		0.5:0.5	38013.7	45876.6	0	82827
16		0:1	38466.2	45776.5	0	52815
17	**0.5:0.5:0**		39085.1	44246.2	0	90602
18		1:0	39086.3	44255.4	0	91738
19		0.5:0.5	39383.6	44488.8	0	89862
20		0:1	39302.3	44180.6	0	74042
21	**0.5:0:0.5**		37718.2	47188.2	0	122622
22		1:0	38443.7	46267.5	0	112839
23		0.5:0.5	38013.7	45876.6	0	82827
24		0:1	38466.2	45776.5	0	52815
25	**0.3:0.7:0**		39085.1	44246.2	0	90602
26		1:0	39086.3	44255.4	0	91738
27		0.5:0.5	39383.6	44488.79	0	89862
28		0:1	39302.3	44180.6	0	74042
29	**0.7:0.3:0**		36154.6	49398.4	373	122622
30		1:0	37740	46994.2	411	92281
31		0.5:0.5	37716.9	46941.7	411	86821
32		0:1	38402.8	46813.4	411	43996

[a] ratios for centralised control and for producer under decentralised control

For the replenishment plan of suppliers in example problem 3, eight instances are generated as shown in Table 7-20. The average values of SC performances can be determined from Table 7-13 with $Avg1 = 17054.25,$ $Avg2 = 8361.06$ and $Avg3 = 6051$. The LE base case result is suggested when a ratio is 0:1:0. The 0:0:1 ratio of weight represents the LW base case. However, the LC base case gives a different result from the case with a ratio of 1:0:0. As a result of the high relative importance of the cost to emission, the three other cases (0.5:0.5:0, 0.3:0.7:0 and 0.7:0.3:0) with zero weight on waste objective also give similar results. If only cost and/or emission objectives are considered important, the proposed result gives higher expected amount of perished goods. It can be seen that assigning positive weight on the waste objective in supplementary as with 0.5:0.25:0.25 and 0.5:0:0.5 cases, the determined result does not lead to big changes in cost and emission comparing with the reduction in waste.

Table 7-20 Weighted goal programming results for eight cases of Problem 3 for suppliers planning

Ratios	**Cost**	**Emission**	**Waste**
1:0:0	11507.2	5008.85	15085
0:1:0	11916.2	4949.11	11876
0:0:1	22604.2	11770.8	226
0.5:0.25:0.25	13862.7	5981.25	697
0.5:0.5:0	11505	4994.14	15541
0.5:0:0.5	14738.8	6296.69	226
0.3:0.7:0	11507.2	5005.24	15541
0.7:0.3:0	11507.2	5008.85	15085

For the production/replenishment plans of SC in example problem 3, it can be done in the same way but with the values of expected performance specified by decision makers.

As shown above, both methods can be employed such that the SC sustainability can be achieved. Trade-off analysis is preferred in the presence of a sustainability target. It allows an evaluation of the cost of being sustainable in the search for a compromise between economic and environmental factors. Weighted goal programming is preferred in the presence of preferences on SC objectives. It allows a measurement of the level of dissatisfaction that reflects the gap (deviation) between the actual performance and the desired one (goal).

7.4 Sensitivity Analysis

In order to examine some major characteristics of the proposed mechanism of achieving improved sustainability in a perishable food SC, the 18 additional problems from example problem 2 have been solved with different combinations of relevant parameters as shown in Table 7-21. Readers are referred to Appendix C for a summary of data adopted in this analysis. Combinations of these parameters selected are related to practical necessities and challenges taught from the related literature such that a wide variety of representative operating conditions are depicted. Each of these analyses enables the exploration of the effects of possible changes in the current inventory system on cost, wastage and emission. Therefore, the sensitivity analysis serves as a supportive role in evaluating and better understanding the analysed perishable food supply chain. This table also shows the summary results of the percentage differences obtained for each of these 19 problems when applying decentralised control from centralised control.

Table 7-21 Decision making process comparison for all 19 cases of Problem 2

	Costs			**Emissions**			**Wastes**			**Inventory**		
	LC	**LE**	**LW**	**LC**	**LE**	**LW**	**LC**	**LE**	**LW**	**LC**	**LE**	**LW**
	Δ (%)	**Δ (%)**	**Δ (%)**	**Δ (%)**	**Δ (%)**	**Δ (%)**	**Δ (%)**	**Δ (%)**	**Δ (%)**	**Δ (%)**	**Δ (%)**	**Δ (%)**
Base prob.	0	0	-0.7	0	0	-2.2	0	0	0	0	0	226
Erratic demand ->												
Stationary	0	5	1.4	0	0	11.6	0	0	0	0	0	-35
Seasonal	0	1.2	10.8	0	0.1	11.2	0	0	0	0	-5	-55
Life cycle	0.1	0	0	-3	0	-6.3	-36.8	0	0	-33	0	3
Highly erratic	0	0	4.4	0	0	27.7	0	0	0	0	0	96
Max shelf life M = 3 periods ->												
5 periods	3.9	0	-0.1	-27.9	0	-16.2	-100	0	0	0	0	148
$h_i^v 0.005, ES_i 0.04$	0.9	-0.4	3.4	1.7	0.4	3.8	-100	-100	0	71	31	148
11 periods	1.3	0		-0.3	0			0	0	-33	0	-100
$h_i^v 0.005, ES_i 0.04$	0	0		0	0		0	0	0	0	0	-100
Disposal cost = £0 ->												
£(-)0.5	0.6	0	-0.7	12.8	0	-2.2	58.2	0	0	-10	0	226
£2	1.9	0	-0.7	-2.6	0	-2.2	-30.8	0	0	-22	0	226
CV = 0.2 (=Normal distribution) ->												
0.1	2	0	-8.3	-15.5	0	-8	-58.3	0	0	-13	0	315
0.3	3.9	0	6.2	-1.3	0	10.9	74.1	0	0	-24	0	-48
α-service level = 0.95 ->												
0.9	2.2	0	3.4	-3.1	0	1.5	-20.2	0	0	-23	0	183
0.98	0.1	0	-1.9	5.1	0	9.9	99	0	0	-10	0	-22
cost ratio:emission ratio of (product order/holding) = 6:1												
1:1	0.9	0.9	-1.1	2.2	2.2	-3.3	-100	-100	0	-31.2	-31.2	226
1:2	0.9	3.4	-1.1	26.7	8.9	-3.4	-100	10.2	0	-31.2	-34	226
1:6	60.9	-10.7	-1.5	-2.4	9	-3.1	411	-33.7	0	4.5	-5.1	226
2:1	1.6	1.8	-1.1	11.1	9	-3.5	10.2	-100	0	-29.2	-31.2	226

From the comparison in Table 7-21, the results clearly confirm the benefit of using a centralised decision making process over a decentralised one when a particular SC performance is focused on. For all 19 test problems, the percentage differences of the total expected cost and the total expected emission either increase or remain the same in the LC base case and the LE base case, respectively. However, not all SC partners gain benefits. A producer will bear higher costs in a centralised situation than in a decentralised situation as in a test problem with a CV of 0.3 and a 3.9 percentage difference; producer and suppliers incur total expected costs of 28945.5 and 9092.6 with centralised control, respectively. However, it costs a producer 28819.5 and suppliers a total of 10693.5 when applying a decentralised decision making process. This is because the producer adjusts its production plan to reduce the cost of suppliers. The resulting reduction in the cost of suppliers more than offsets the increase in the cost of producer. Therefore, suppliers dominate in this SC since they are higher in number and incurred costs.

The percentage differences from the base test problem of total cost and total emission under both centralised (C) and decentralised (D) decision making processes for each case are reported in Table 7-22. The total waste and total inventory for each case are also reported in Table 7-23.

Table 7-22 Summary of results for all 19 cases of Problem 2

	Costs						**Emissions**					
	LC		**LE**		**LW**		**LC**		**LE**		**LW**	
	C	**D**	**C**	**D**	**C**	**D**	**C**	**D**	**C**	**D**	**C**	**D**
Erratic demand ->												
Stationary	0.6	0.6	11.5	17.1	8.3	10.6	3.2	3.2	4.2	4.2	5.7	20.6
Seasonal	-0.7	-0.7	3.1	4.4	1	12.7	1	1	3	3	6.5	21
Life cycle	0.8	0.9	3.5	3.5	6.8	7.6	7.3	4.1	3	3	20	14.9
Highly erratic	1.6	1.6	-0.1	-0.1	10.6	16.4	0.1	0.1	2.2	2.2	-2.2	27.7
Max shelf life M = 3 periods ->												
5 periods	-4.8	-1.1	0	0	4.3	5	30	-6.3	0	0	13.7	-2.6
11 periods	-4.2	-3	0	0	9.4	-100	11.3	11.0	0	0	-4.7	-100
Disposal cost = £0 ->												
(-)0.5	-1.1	-0.5	0	0	0	0	0	12.8	0	0	0	0
2.0	2.5	4.5	0	0	0	0	-4.9	-7.4	0	0	0	0
CV = 0.2 (=Normal distribution) ->												
0.1	-5.6	-3.7	-2.4	-2.4	5.3	-2.7	-5.9	-20.5	-17	-17	2.8	-3.3
0.3	5.7	9.8	3.8	3.8	6.4	13.8	14	12.5	17.4	17.4	6.4	20.6
α-service level = 0.95 ->												
0.9	-2.3	-0.2	-0.7	-0.7	-4.3	-0.3	-7.6	-10.4	-7.5	-7.5	-4	-0.4
0.98	2.8	3	1.8	1.8	9.8	8.5	4	9.3	8.6	8.6	4.8	17.8

Table 7-23 Summary of results for all 19 cases of Problem 2 (continue)

	Waste						**Inventory**					
	LC		**LE**		**LW**		**LC**		**LE**		**LW**	
	C	**D**	**C**	**D**	**C**	**D**	**C**	**D**	**C**	**D**	**C**	**D**
Base prob.	778	778	0	0	0	0	109509	109509	74042	74042	7229	23576
Erratic demand ->												
Stationary	395	395	0	0	0	0	81032	81032	102069	102069	16108	10439
Seasonal	245	245	0	0	0	0	77924	77924	89893	85622	20893	9434
Life cycle	661	418	0	0	0	0	139353	93428	97654	97654	21767	22484
Highly erratic	1124	1124	677	677	579	579	72809	72809	48226	48212	5273	10352
Max shelf life M = 3 periods ->												
5 periods	504	0	0	0	0	0	83508	83177	74042	74042	12815	31836
11 periods	0	0	0	0	0	0	94982	63347	74042	74042	11360	11360
Disposal cost = £0 ->												
(-)0.5	778	1231	0	0	0	0	109509	98509	74042	74042	7229	23576
2.0	373	258	0	0	0	0	122622	95763	74042	74042	7229	23576
CV = 0.2 (=Normal distribution) ->												
0.1	614	256	0	0	0	0	91924	80310	64368	64368	6966	28936
0.3	703	1224	144	144	144	144	129000	98096	74912	74912	17210	9002
α-service level = 0.95 ->												
0.9	605	483	0	0	0	0	108730	83182	64528	64532	7260	20549
0.98	510	1015	45	45	45	45	124854	111835	74392	74398	12661	9882

The base test problem parameter values have also been applied to four other demand patterns taken from Berry (1971). According to Table 7-22, despite facing stationary demand, the percentage difference is positive. The increase in expected total cost and expected total emission in comparison with the base test problem of the two-echelon SC is due to a higher increase in the suppliers' stage rather than a decrease for the producer. The order policy for the stationary demand is a regular production plan, with production in every other period. As the demand becomes more non-stationary, the percentage differences above the base problem solution of four performance measures as shown in Tables 7-22 and 7-23 tend to become larger. Spoiled wastes can be expected in a highly erratic demand scenario. However, the results indicate that if a financial objective is the key, it is preferable to use the TC base case when demand is seasonal and the LE base case when demand is highly erratic.

The results of changing the maximum product shelf life show that the expected values of total cost, total emission, total waste and inventory are sensitive to the product lifetime. When the shelf life is raised from 3 to 5 (or 11) periods, these key performance measures tend to decrease as they converge with the non-perishable inventory model. However, the shelf life shows no effect on the LE base case in this test problem. This shows that longer product shelf life does not have any influence on the frequency of orders suggested by its optimal solution. To explore the effect on the SC solution of the relative change of the setup parameter to a holding parameter, two experiments with $h_i^v = 0.005$ and $ES_i = 4$ are conducted. Results as illustrated in Table 7-24 show that less frequent orders result when either the setup cost is higher than the holding cost or the setup emission is higher than the holding emission.

Table 7-24 Results for test problems with different maximum product shelf life

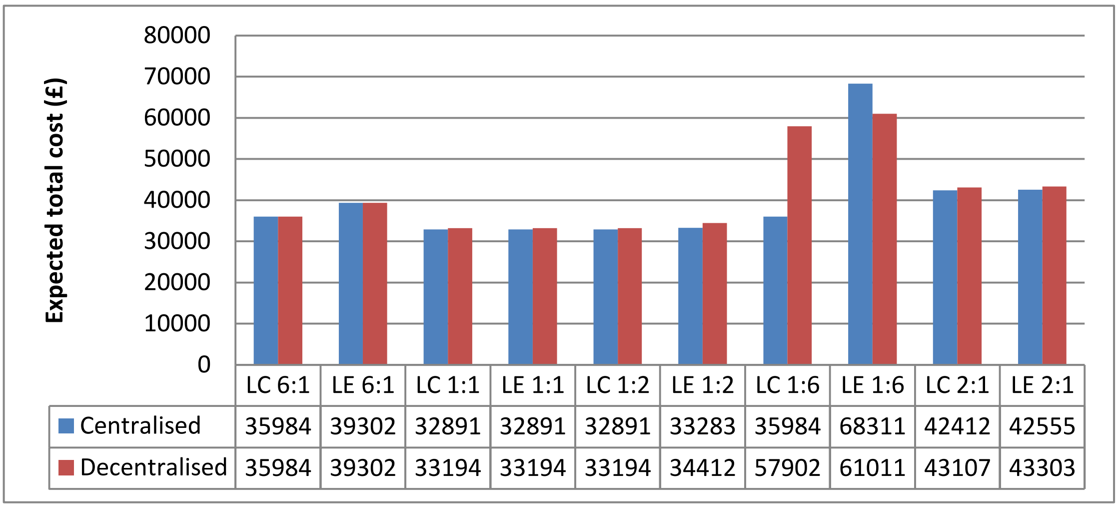
	Production policy under centralised	**Production policy under decentralised**
M = **5 periods**		
LC	[2364,0,2544,0,0,0,2796,0,0,0,0,0]	[2364,0,1841,0,0,1388,0,1418,0,0,392,0]
$h_i^v 0.005, ES_i 0.04$	[3800,0,1108,0,0,0,2796,0,0,0,0,0]	[3359,0,0,2415,0,0,0,1882,0,0,0,0]
LE	[2364,0,789,1046,0,470,920,957,370,0,487,0]	[2364,0,789,1046,0,470,920,957,370,0,487,0]
$h_i^v 0.005, ES_i 0.04$	[2364,0,2544,0,0,0,2796,0,0,0,0,0]	[3359,0,0,2415,0,0,0,1882,0,0,0,0]
M = **11 periods**		
LC	[2364,0,2544,0,0,0,2003,0,0,515,0,0]	[2364,0,841,0,0,2709,0,0,0,512,0,0]
$h_i^v 0.005, ES_i 0.04$	[7964,0,0,0,0,0,0,0,0,0,0,0]	[7964,0,0,0,0,0,0,0,0,0,0,0]
LE	[2364,0,789,1046,0,470,920,957,370,0,487,0]	[2364,0,789,1046,0,470,920,957,370,0,487,0]
$h_i^v 0.005, ES_i 0.04$	[7964,0,0,0,0,0,0,0,0,0,0,0]	[7964,0,0,0,0,0,0,0,0,0,0,0]

The value of a food item at the end of its shelf life has received growing attention due to a global environmental drive for food waste reduction. To understand the effects of the disposal value of an unsold item at the end of its shelf life, experiments with different waste disposal costs are conducted. The results show that the cost of waste has no influence on LE and LW cases. As the cost is negative (the product has salvage value), the amount of waste in the decentralised LC case will increase (with 1626 more inventory items held than the centralised case) for the producer to take advantage of the additional revenue generated at end-of-shelf life, while the total cost will decrease. In the LC base case, when the cost of waste is increased, a lower amount of waste and higher total cost can be expected. However, the expected values of total emission obtained from the model behave in the opposite direction (negative values as highlighted in Table 7-22). This trade-off between cost and emission shows that imposing cost on waste disposal facilitates emission reduction. Clearly, the model can be used to manage the amount of waste and emission.

Every key performance measure in both LC and LE cases is greatly influenced by the demand volatility. When the coefficient of variation is raised, the expected performance values tend to become larger and vice versa. This is easy to explain. As the size of the coefficient of variation increases, higher safety stock is needed to buffer against more erratic demand whilst a decrease in the coefficient of variation improves the performance of the waste-compensating (R^n, S^n) approach.

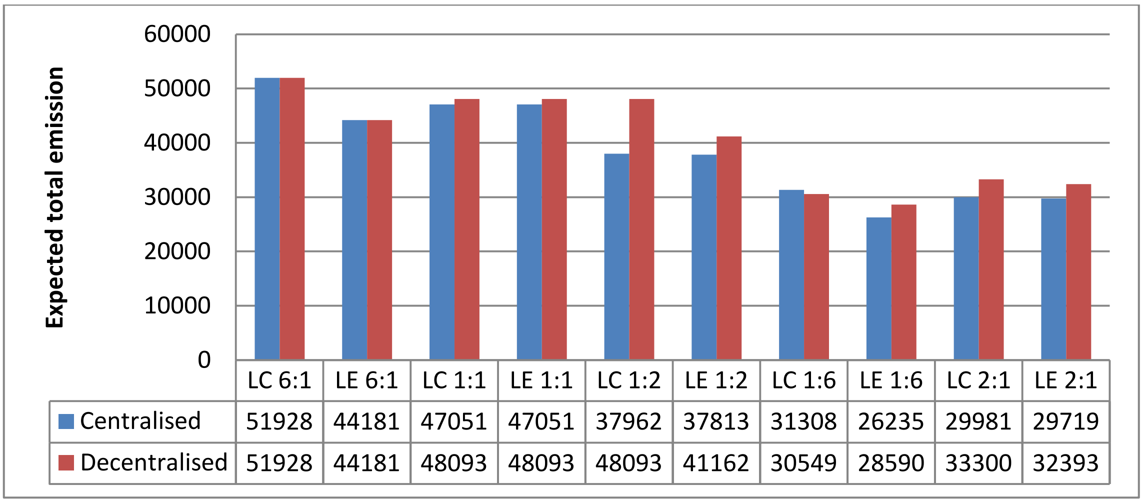
According to Tables 7-22 and 7-23, the effects of service level α on the key performance measures are quite significant. In all the cases, an increase in service level leads to higher expected values of all four performance measures and vice versa. A tighter requirement from customers results in higher safety stocks to be carried by the producer in avoidance of fine payment and lost sales. When the customers' requirements are more relaxed, safety stocks can be reduced which lower all the chain's performance measures.

To explore the effect of financial and environmental parameters on key performance measures, experiments are conducted using the relative values of ratios of two parameters rather than absolute values. Both cost and emission parameters associated with production/replenishment orders initiated and warehousing activity are changed or swapped such that a different relative value results. Therefore, the expected total cost and the expected total emission are used for comparisons as shown in Figure 7.6-7.7, respectively.



	LC 6:1	LE 6:1	LC 1:1	LE 1:1	LC 1:2	LE 1:2	LC 1:6	LE 1:6	LC 2:1	LE 2:1
🟦 Centralised	35984	39302	32891	32891	32891	33283	35984	68311	42412	42555
🟥 Decentralised	35984	39302	33194	33194	33194	34412	57902	61011	43107	43303

Figure 7.6 Total cost under different relative values of ratios for Problem 2



	LC 6:1	LE 6:1	LC 1:1	LE 1:1	LC 1:2	LE 1:2	LC 1:6	LE 1:6	LC 2:1	LE 2:1
🟦 Centralised	51928	44181	47051	47051	37962	37813	31308	26235	29981	29719
🟥 Decentralised	51928	44181	48093	48093	48093	41162	30549	28590	33300	32393

Figure 7.7 Total emissions under different relative ratio values for Problem 2

The LW base case gives the same optimal result for all five instances with relative values of 6:1 (base test problem), 1:1, 1:2, 1:6 and 2:1 under each decision making process. This shows that both financial and emission parameters have no influence on the LW optimal result. When compared with decentralised control, the total expected cost under centralised control is either lower or the same in all LC instances as well as the total expected emission in all LE instances. This explains that managing the SC with a centralised decision making process outperforms the decentralised one when only a single objective is target. In an instance with a relative value of 1:1, both LC and LE base cases give the same expected total cost and emission. This supports the claim made by Hua et al. (2011), Benjaafar et al. (2013) and Chen et al. (2013) that if $\left(\frac{k^{v}{}_{i}}{h_i^v}\right) = \left(\frac{Ek^{v}{}_{i}}{ES_i}\right)$ then the cost-optimal solution is also emission-optimal. Furthermore, it shows that order quantity adjustment facilitates emission reduction. If $\left(\frac{k^{v}{}_{i}}{h_i^v}\right) > \left(\frac{Ek^{v}{}_{i}}{ES_i}\right)$, increasing frequency along with decreasing quantity when ordering decreases emissions. The reverse is true when $\left(\frac{k^{v}{}_{i}}{h_i^v}\right) < \left(\frac{Ek^{v}{}_{i}}{ES_i}\right)$.

Among all these test cases, the LW base case shows the random effect and gives higher values of expected total cost and emission. This verifies the incapability of the LW base case of finding optimum production and inventory plans with a given perishable food SC. However, towards sustainability achievement in the SC, a food waste reduction scheme can be considered with a high waste disposal cost as one of the options as well as the waste cap in the ε-constraint method or given the positive weight in the weighted goal programming method.

For example problem 3, 10 additional problems have been solved with different combinations of relevant parameters. The percentage differences from the base test problem of total profit, total emission and total waste under three demand scenarios for each test case are reported in Table 7-25, 7-26 and 7-27, respectively.

Table 7-25 Summary of SC profit results for 10 cases of Problem 3

	Profits					
	LC			**LE**		
	High	**Avg.**	**Low**	**High**	**Avg.**	**Low**
Erratic demand ->						
Stationary	-0.5	0.2	0.4	-0.4	-1.1	-1.8
Seasonal	-1.4	-0.2	-0.1	-0.7	0.0	-0.1
Life cycle	-1.8	-0.6	-0.7	-0.8	0.0	-0.1
Highly erratic	4.5	3.7	6.8	1.7	2.9	5.6
Disposal cost = £0 ->						
(-)0.03,0.03,0.03,0.01,0.025	1.0	1.4	3.7	0.4	0.6	2.6
0.2	-2.9	-4.0	-17.2	-3.4	-5.1	-19.4
CV = 0.2 (=Normal distribution) ->						
0.1	-5.0	0.5	0.7	-4.5	0.7	0.9
0.3	0.7	-0.1	-0.2	0.0	-0.2	-0.2
α-service level = 0.95 ->						
0.9	-2.3	0.4	0.5	-2.1	0.1	0.1
0.98	0.7	-0.1	-0.1	0.0	-0.1	-0.1

Table 7-26 Summary of SC emission results for 10 cases of Problem 3

	Emissions					
	LC			**LE**		
	High	**Avg.**	**Low**	**High**	**Avg.**	**Low**
Erratic demand ->						
Stationary	3.8	2.2	2.0	0.3	0.4	0.9
Seasonal	4.3	1.0	0.3	3.4	0.3	0.5
Life cycle	3.7	0.0	-0.6	2.9	0.0	0.2
Highly erratic	-6.6	-2.0	-4.1	-3.8	-3.9	-5.6
Disposal cost = £0 ->						
(-)0.03,0.03,0.03,0.01,0.025	-0.4	2.3	2.2	0.0	0.0	0.0
0.2	6.5	2.8	2.0	0.1	0.5	0.2
V = 0.2 (=Normal distribution) ->						
0.1	13.5	-0.2	-0.4	7.3	-1.9	-1.5
0.3	1.3	1.7	1.7	1.2	1.7	1.5
α-service level = 0.95 ->						
0.9	5.1	1.0	0.9	4.9	-0.7	-0.7
0.98	0.7	0.8	0.9	0.6	0.8	0.7

Table 7-27 Summary of SC waste results for 10 cases of Problem 3

	Waste					
	LC			**LE**		
	High	**Avg.**	**Low**	**High**	**Avg.**	**Low**
Erratic demand ->						
Stationary	25.0	18.3	6.3	-35.1	-23.7	-15.7
Seasonal	4.3	-12.3	-7.4	-40.7	-12.9	-5.5
Life cycle	-46.3	-38.9	-16.3	-53.5	-13.4	-4.5
Highly erratic	-11.8	56.0	24.2	-9.8	28.3	11.3
Disposal cost = £0 ->						
(-)0.03,0.03,0.03,0.01,0.025	-85.6	35.8	15.0	0.0	0.0	0.0
0.2	-85.3	-75.3	-38.2	-2.5	-7.7	-7.1
CV = 0.2 (=Normal distribution) ->						
0.1	-32.7	-34.9	-14.6	-57.7	-46.6	-17.7
0.3	50.0	50.0	20.9	47.1	50.0	19.0
α-service level = 0.95 ->						
0.9	4.8	1.5	0.6	-20.7	-22.1	-8.8
0.98	24.8	24.9	10.4	23.4	24.9	9.5

The four other demand patterns taken from Berry (1971) are considered using parameter values of the example problem 3. Considering highly erratic demand, it shows that irregular demand can lead to higher profit and lower emission if the production and inventory plans are properly managed. However, it brings about an increase in waste when facing average and low demand scenario.

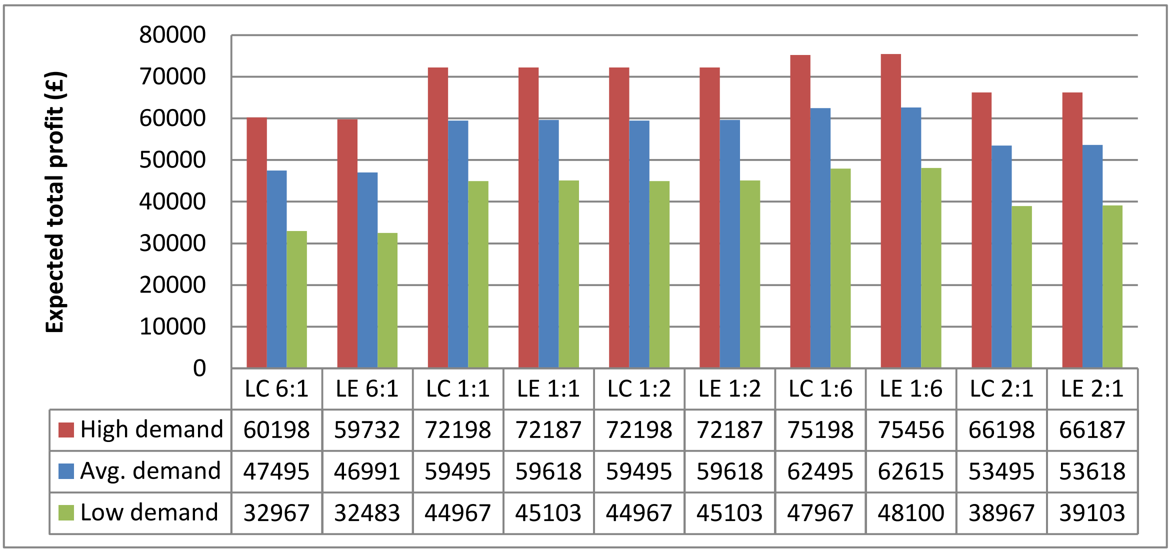
Two experiments with positive and negative waste disposal costs are conducted to demonstrate the effects of the disposal value of an unsold perished item. When perished waste has salvage value (negative disposal cost), levels of emission and waste remain unchanged for suppliers adopting LE base case. However, the profit is increased as the SC aims to maximise profit. The expected amount of waste in the LC case will increase for the SC to take advantage of the additional revenue generated at end-of-shelf life, while the total profit will increase. In contrast, quantity of perished items is reduced in the high demand scenario as the inventory is used in satisfying as many retailer demands as possible. When the cost of waste is increased, a lower amount of waste and lower total profit can be expected.

Every key SC performance measure determined using either LC or LE cases is influenced by the demand volatility. When the coefficient of variation is increased, the expected performance values tend to become larger (i.e. increase in emission and waste, decrease in profit) and vice versa. This can be clarified that higher safety stock is needed to buffer against more erratic demand. However, this does not hold true for the high demand scenario. As the

SC aims to maximise its profit, higher on-hand inventory leads to an increase in accepted customer orders (higher profit) and vice versa.

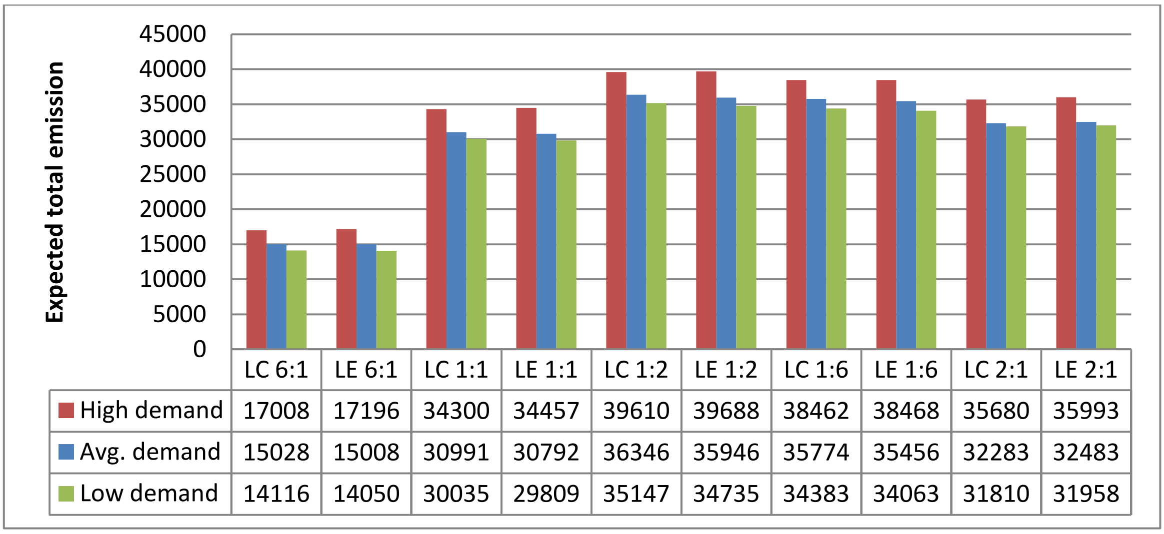
The effects of service level α on the key performance measures are quite significant. An increase in service level leads to higher expected values of cost, emission and waste performance measures. A tighter requirement from customers results in higher safety stocks to be carried. However, more demand can be rejected when the service level is low with lesser safety stock carried. This leads to higher cost and emission when facing high demand scenario. It can also result in higher waste due to the unavailability of raw materials of different lifetime such that they cannot be used in the production and are left to perish.

To explore the effect of financial and environmental parameters on key performance measures, experiments are conducted using the ratios of the expected total cost and the expected total emission parameters for comparisons as shown in Figure 7.8 and Figure 7.9, respectively.



	LC 6:1	LE 6:1	LC 1:1	LE 1:1	LC 1:2	LE 1:2	LC 1:6	LE 1:6	LC 2:1	LE 2:1
🟥 High demand	60198	59732	72198	72187	72198	72187	75198	75456	66198	66187
🟦 Avg. demand	47495	46991	59495	59618	59495	59618	62495	62615	53495	53618
🟩 Low demand	32967	32483	44967	45103	44967	45103	47967	48100	38967	39103

Figure 7.8 Total profit under different relative values of ratios for Problem 3



	LC 6:1	LE 6:1	LC 1:1	LE 1:1	LC 1:2	LE 1:2	LC 1:6	LE 1:6	LC 2:1	LE 2:1
🟥 High demand	17008	17196	34300	34457	39610	39688	38462	38468	35680	35993
🟦 Avg. demand	15028	15008	30991	30792	36346	35946	35774	35456	32283	32483
🟩 Low demand	14116	14050	30035	29809	35147	34735	34383	34063	31810	31958

Figure 7.9 Total emissions under different relative ratio values for Problem 3

Comparing the demand scenarios, the total expected profit and emission correspond with the demand (i.e. high demand gives higher profit and emission) in all instances. However, a change in profit and a change in emission generated for each demand scenario are not the same. This explains that facing higher demand can offer a higher increase of profit comparing to an increase in emission but with a lesser amount. When emission parameter is not very much lower in the ratio, LE case gives higher profit for at least in average and low demand scenarios. Adopting LE base case, higher demand scenario results in higher emissions when comparing with LC base case in all instances. However, average and low demand scenarios give the opposite result. This shows that suppliers adopting LE base case leads to both financially and environmentally friendly result in certain cases.

7.5 Summary

In this chapter, numerical examples are used to demonstrate, test, and discuss the models. The analysis performed demonstrates how environmental concerns can be incorporated into an operational decision making model for production and inventory planning such that perishable food firms are able to model and assess their environmental impact. In the first numerical problem, the model is tested by using the data from literature to see that the model works well with a stationary stochastic demand scenario. In test problem 2, SC collaboration demonstrates its superiority over decentralised control when one objective is optimised at a time. In test problem 3, suppliers adopting the service level approach when facing high demand scenario of the non-stationary stochastic retailer demand leads to higher SC profit. Both the ε-constraint and the weighted goal programming methods verify the possibility of reducing carbon emissions at the expense of increasing cost/decreasing profit. The sensitivity analysis is carried out to examine some major characteristics of the model.

Chapter 8 Conclusion and future work

8.1 Introduction

As an endeavour to fill one of the SCM gaps, this thesis explored production and inventory planning and control and its potential for SC sustainability improvement. The main questions companies in the food industry face are when and how many perishable items they should produce and/or order from other companies in the SC. Companies should be able to analyse how operational adjustments can facilitate achieving improved sustainability and consider the benefits of managing a SC together with supplier(s) and/or customer(s). After a comprehensive literature review, no tool to generate, analyse and evaluate the sustainable production and inventory plans for perishable items in a two-echelon SC facing non-stationary stochastic customer demand was found. Therefore, the objective of this research was to contribute to the continuing evolution of SCM by developing:

1. a tool to manage perishable inventory in general and food products in particular in a make-to-stock operating system.
2. a tool to generate production/replenishment schedule for perishable inventories and to select an optimal set of customer orders in a make-to-order operating system.

These tools should assist the managers in deciding whether and how they can reschedule the production and inventory plans to improve the SC performance towards environmental sustainability. In this final chapter, the author summarises the main findings, discusses the relevance and limitations of the research and concludes this PhD thesis with some directions for possible future work.

8.2 Conclusion

Chapter 1 began with the necessity of the research problem. The chapter describes the requirement for companies to manage their perishable products with efficient planning, coordinate with other SC members and introduce environmental sustainability into their business through waste and/or emission reduction schemes.

To provide a basis for this research, definitions and related concepts of SCM were clarified in Chapter 2. Furthermore, attention was paid to major drivers of SC performance including inventory management and, more importantly, sustainability and its relation to the SC. The focus of Chapter 2 and the following chapters was on answering the author’s research questions (see Section 1.3). The author will discuss the main findings of the research by answering these three questions formulated in Chapter 1.

8.2.1 Research question 1

What is the relationship between sustainability and the supply chain along with potential consequences on the performance of a food supply chain in particular?

With the purpose of examining the relationship between sustainability and the SC, the author first studied the SC and identified its general structure in Chapter 2 in addition to the food SC structure in Chapter 1. Flows of products, information and funds characterise a SC and its success can be achieved when appropriate management of these flows is in place.

The necessity of considering both the financial and sustainability performance measurements in managing the SC was described in Chapters 1-3. It became clear that following the push from various external and internal pressures, companies show their environmental friendliness along with good business sense by adopting sustainable practices into their efficiency-based operations. Furthermore, the author reviewed research studies of sustainable SCM in Chapter 3. The review included the modelling techniques commonly used in studies, the potential carbon emissions associated with each SC process and decision, including production and inventory, and the management of an environmentally sustainable perishable food SC.

Employing sustainability measures such as emission, energy consumption or resource consumption in modelling is one method of managing the environmental impacts to make the perishable food SC more sustainable while maintaining economic performance. The appropriateness of the method was shown in numerical examples discussed in Chapter 7. Overall, the sustainability measure modifications were identified that varied SC performance. As a result, the answer to the first research question is as follows:

Answer to research question 1

The flows of products, information and funds in a SC initiate several activities that result in sustainability issues related to people and the planet. A reflection of sustainability in SC decision-making results in the establishment of achievable goals with minimum performance of, or trade-offs between, different sustainability issues within an economic context to prevent poor performance. Taking sustainability into account for a food SC is preferable in order to reduce waste generation, resource consumption and emissions. The SC performance is mainly affected by perishables. Consequently, implementing the right measures to properly manage the products will improve SC performance.

8.2.2 Research question 2

How can sustainability factors be introduced into the production and inventory planning and control problem with efficiency as the primary goal? How can the multi-objective optimisation problem be solved to provide decision support on possible trade-offs between economic and environmental perspectives when cost, waste and emissions need to be simultaneously minimised?

The methodology to introduce sustainability factors into the production and inventory problem was developed in Chapter 6 from the findings in Chapters 2, 3 and 4, and was tested in Chapter 7. The following essential features were obtained in the development process.

- Key sustainability measures including energy consumption, water consumption, waste generation and greenhouse gas emission can be used to judge sustainability-related efforts in the SC. In addition, an acknowledgement of SC consumption in terms of costs (e.g. costs of production, operation, raw materials, storage, delivery and waste), product quality and shelf life, and storage and delivery of products in temperature-controlled conditions are regarded as sustainability measurements significant to a perishable food SC.
- Different methodologies and/or approaches can be adopted in handling sustainable SCM problems with mathematical modelling serving as one of the practical decision support tools for managers. In model-based quantitative research, the appropriate selection of goal, purpose, type,

technique and solution approach of the model developed is related to the behaviour of SC process and the decision-making problems in consideration. Note that the overall objective of managing a SC is usually a cost minimisation effort.

- In SC decisions regarding transportation, production, and inventory, the associated emissions can be managed and reduced under different regulatory policies including a command-and-control approach, in which government or regulators set standards, as well as a market mechanisms approach through cap-and-trade or emission tax. These environmental management policies can be considered in the mathematical modelling method through additional objectives and/or constraints.

In Chapters 3 and 4, several modelling methods were discussed. The author concluded that because of the necessity to estimate quantitative behaviour of the system such that the best practice can be selected from among alternatives via various logical arguments and the need for practical tools for managers to support their decisions when solving the production and inventory planning and control problem, mathematical programming was chosen in this research.

Chapters 3 and 4 further discussed solution methods to manage possible trade-offs between economic and environmental performances of the SC. It was concluded from the literature search that two solution methods comprising the ε-constraint and the weighted goal programming methods could be adopted to solve the multi-objective optimisation problem in this research. Both methods were modelled and evaluated in the numerical experiments. It can be seen from the results presented in Chapter 7 that the methods provided good support for the identification, evaluation and analysis of trade-offs. Comparison of the overall SC performance from putting alternative production and/or inventory plans into action provides managers with information about the expected benefits of each alternative which will then support their decision of when and how many perishable items they should produce and/or order from other companies in the SC.

Therefore, research question 2 can be answered as follows:

Answer to research question 2

The application of sustainability measures in a mathematical programming method to introduce sustainability factors into the production and inventory planning and control problem will result in additional objectives and/or constraints for the model with a cost minimisation/profit maximisation goal. The consideration of additional objectives establishes a multi-objective optimisation problem in which two or more objectives are considered simultaneously to produce solutions with a higher level of equity. Additionally, limits or caps are set on the sustainability factors when the measurements are taken as constraints of the model. For instance, a waste generation limit is the amount of spoiled waste and a carbon cap is the amount of carbon emissions that the company or SC is allowed or allows. The allowances can either be enforced by government sectors or voluntarily set by the company itself. The amount of perished products during storage can be measured as waste generated from production and inventory planning decisions. The waste-compensating replenishment cycle policy is adopted in this research to deal with spoiled waste generated by producing or ordering the same amount in the next production or replenishment order as a replacement. It was concluded that waste generation is best considered as disposal cost and/or waste limit in the model. The production and inventory related emissions can either be measured by means of energy consumption of related operations or a fixed emission factor per unit produced or stocked. From the findings, it became clear that making operational adjustments in the production and inventory plan when emission and cost parameters were not strongly correlated can lead to effective emissions reduction without a significant increase in costs.

The multi-objective optimisation problem should preferably be solved by using either the ε-constraint method or weighted goal programming method in this research. As follows, the production and inventory plan proposed can be evaluated either by imposing limits on waste generation and carbon emissions in a cost minimisation/profit maximisation effort or assigning weights to each SC performance measurement as an indicator of its relative importance to provide decision support for the managers on possible trade-offs between economic and environmental standpoints. The final decision of which production and/or inventory plan to implement depends on the trade-off between multiple SC performance indicators (i.e. cost, waste and emission in this case) for each SC participant when a decentralised decision making process is adopted and the SC as a whole when the SC is under centralised control, in addition to the feasibility of each plan.

8.2.3 Research question 3

Given production and inventory decision problems under uncertain (erratic) demand, how can practical solutions be constructed using commercial solvers for business use rather than custom-made solution procedures and how can its practical application be improved for the benefit of managers in the food supply chain industry?

The concept of demand uncertainty and its relation to production and inventory decision problems was discussed in Chapter 2. Holding extra stock as a safety buffer against customer demand uncertainty is a common practice adopted. Chapter 4 described and assessed the application of various approaches in solving the production and inventory problem involving stochastic demand for perishable products in particular. The chapter further examined the differences in the use of commercial solvers in the construction of practical solutions.

In Chapter 5, research method that was used in this research was discussed. The chapter presented the reasoning for the choice of the mo-MILP modelling method to address the production and inventory planning and control problem under non-stationary stochastic demand for improved sustainability in a perishable food SC. Chapter 5 also showed the requirements for comparison with the models developed in Chapter 6 between two types of coordination: centralised and decentralised. It showed why a numerical test was thought to be the appropriate methodology to demonstrate and validate the model applicability for this research. Suitable scenarios with which to test the proposed models were identified along with the success criteria against which the models can be validated.

The analysis of the computational results found that a centralised decision making process was the best for the SC scenarios studied when one objective was optimised at a time in MTS operating system. However, the results were varied when trade-offs between multiple SC performance measurements were involved. If the quotient of production order cost divided by holding cost equals to the quotient of production order emission divided by holding emission, the cost-optimal solution is also emission-optimal. As shown in examples depicted in previous chapter, the notion that order quantity adjustment facilitates emission reduction can be practically used by managers. When the ratio of economic to environmental parameters is higher, managers can increase the order frequency along with decreasing quantity to reduce possible emissions generated from the production inventory activities and vice versa. Whilst adopting the ε-constraint method in search for environmentally sustainable decisions, the gaps present in the trade-offs graph imply managers the possibility of paying just a little extra for a higher percentage of emissions reduction (as shown in Figure 7.3). After all, assigning disposal cost, limit and high weight of importance on either perished goods or CO_2 emitted helps improving the environmental sustainability of the system.

Answer to research question 3

The presence of demand uncertainty in SC production and inventory decision making situations leads to the stochastic programming problem. The author approached this problem by applying commercial MILP solver (CPLEX) with the formulated deterministic equivalent mo-MILP models that generate approximation solutions of the problem in a practical amount of time. The stochastic demand facing the system is taken care of with the safety stock held. This method provides a cost effective tool for companies without the expense of getting a “custom-made solution procedure”. In the prospect future when the access to real case industries is possible, the models can be modified such that they become more generalised. Besides, for managers familiar with Microsoft Excel, CPLEX solver provides an easy-to-use spreadsheet interface. This enhances the possibility for the development of proposed models into a toolkit for food industry. Additionally, addressing this production inventory problem involving demand uncertainty with stochastic model can further benefit managers in the perishable food SC to better represent the actual situation that is happening.

8.3 Contribution to knowledge

At this point, it is appropriate to conclude that this research makes the following contributions to knowledge in the area of production and inventory planning and control of perishable inventories for food SCs in particular, which are characterised by non-stationary erratic demand, a two-echelon system, multiple and perishable products and the desire for improved sustainability.

- The identification of practical methodologies for the introduction of environmental sustainability into a deterministic equivalent production and inventory modelling environment.

- The development of a mo-MILP make-to-stock model for making cost-efficient and environmentally friendly production and/or replenishment plans for the planning horizon under either centralised or decentralised SC control with the intention that retailer orders and its prerequisites are expected to be fulfilled.

- The development of a mo-MILP make-to-order model for solving production and inventory problems which involves the planning of suppliers' replenishments and producer's production schedule containing a set of production jobs (accepted customer orders) in order that the job can be completed within a given due date at the highest or near highest profit with improved sustainability for SC participants.

8.4 Research limitations

Several observations led the author to the conclusion that the models have some limitations in practice due to certain assumptions made during the development.

In this study, the production capacity in producing different products in different production facilities/lines is assumed to be infinite which is reasonable if the overtime working hours or outsourcing is available at relatively the same cost. However, the model results (i.e. the production quantity) can be used as inputs for the determination of resource requirements including manpower, machines, and materials. The models can not be applied in a manufacturing environment which produces a product family (no setup is required between two products in the same family) using the same production line as timing and sequencing decisions are needed.

Since a concrete case study was not available, the model evaluation was based upon artificial data from related literature. Regarding emission data collection, the energy or fuel consumption for each activity was used to represent the emission amount owing to the difficulty in obtaining the emission value itself. Consequently, the findings are certainly limited and do not represent all the food industries. Further research may provide the generalisation across the range of perishable inventory industries and the SC environment. In addition, the gap between theoretical research and practical application can be reduced following the model evaluation by industrial users.

Despite these limitations, mathematical models and solution methods for the management of production and inventory decisions produced in the course of this PhD research can be strengthened and extended by the author and other researchers to provide models with more rationality and realism which is relevant to food industry in practice.

8.5 Future work

In relation to these PhD research findings, there are still some open issues that remain to be addressed for new and interesting future work.

Future work can update the models developed so as to involve a batch scheduling method to take the production of a product family into account. It should attempt to design a production schedule of the products within the daily production time horizon. A possible way to achieve that is to consider the method as constraints of the model for defining product family processing time, allocating a product family to a processing line, sequencing product families and imposing bounds on timing for instance.

An investigation should be made into the application of an incentive and/or a compensation scheme such as quantity discount, credit option, profit sharing and/or permissible delay in payments to compensate for the disadvantages of some companies when a centralised SC control is adopted.

Future work could be carried out to investigate the methodology for incorporating risk mitigation, food safety and transparency as well as other sustainability measures such as quality, flexibility and responsiveness in addition to cost, waste and emission that were considered in this research.

Emerging technologies such as TTI have the possibilities to evaluate and/or provide the shelf life or the remaining shelf life of products by monitoring their temperatures. It would be interesting to incorporate the proposed model with the technology which has the potential to reduce loss due to perished products and outdating costs, enhance the food safety and transparency and reassure consumers about the freshness of products. Research should be carried out to see how these technologies will change the way perishable food SCs operate as well as whether an economical return on investment is offerred. This claim is also in line with the call for further research work on the sensitivity of perishable products' quality to temperature conditions as discussed by Rong et al. (2011) and Kouki et al. (2013).

Adopting interactive methods for solving a multi-objective optimisation problem is another viable aspect to be addressed (Bouchery et al., 2012). Further study should investigate the interactive role of manager in directing a solution process through saying what is possible and judging the alternatives from a representative set of solutions with his/her preferences that may evolve. Furthermore, the consideration of holding and transportation unit capacities in an inventory problem which gives non-linear model is another promising research topic.

APPENDIX A: LITERATURE SUMMARY TABLES

Abbreviations used in Tables

Column names	**Abbreviations**	
DT	DT = depreciation type:	dec = decreasing,
	Ed = Exponential distribution,	iH = increasing holding cost,
	Nd = Normal distribution,	NI= non-instantaneous,
	Per = perishability,	Rn = random negative,
	s-d = stock-dependent,	Th-p Wbd = Three-parameter Weibull distribution,
	t-v = time-varying,	Tw-p Wbd = Two-parameter Weibull distribution.
DC	DC = deterioration constraint:	ExO = expected outdate,
	FF = fraction formulation,	IT = index transformation,
	QD = quality degradation.	
RP	RP = replenishment policy:	#d = numbers of delivery per cycle time,
	#R = replenishment numbers,	cycleNoS = fraction of cycle with no shortage,
	CycleT = cycle time,	eInv = ending inventory level,
	iInv = initial inventory level,	OrderQ = order quantity,
	PayT = time to complete payment to supplier,	Pchange = periods when production rate changes,
		returnQ = return quantity for remanufacturing,
	Prate = production rate,	ProduceQ = production quantity,
	Ptime = production run time,	safeQ = safety stock,
	sellP = selling price,	shortT = time at which shortages start.
MF	MF = model formulation:	Approx = approximation,
	CP = constraint programming,	DP = dynamic programming,
	EOQ = economic order quantity,	EPQ = economic production quantity,
	faGP = fuzzy additive goal programming,	FnLP = fuzzy non-linear programming,
	GA = genetic algorithm,	GP = goal programming,
	GT = game theory,	LP = linear programming,
	M = Markov model,	MGP = modified geometric programming,
	MILP = mixed integer linear programming,	MInLP = mixed integer non-linear programming,
	MOGA = multi-objective genetic algorithm,	MOLP = multi-objective linear programming,
	MONLP = multi-objective nonlinear problem,	nLP = non-linear programming,
	PS = particle swarm optimisation,	Sim = simulation,
	WFnLP = invert weighted fuzzy non-linear programming,	xSol = exact solution.
PM	PM = performance measure:	C = cost,
	E = emission,	O = outdate,
	P = profit,	ROI = return on investment,
	S = service level,	sh = shortage.
LT	LT = replenishment lead time.	
E	E = echelon:	B = buyer,
	C = customer,	D = distributor,
	G = grower,	M = manufacturer,
	R = retailer,	S = single,
	S-B = supplier-buyer,	S-Bs = supplier-buyers,
	SE = service,	S-P-B = supplier-producer-buyer,
	W = wholesaler.	
S	S = shortages.	
BL	BL = backlogging:	com = completely,
	p = partially.	wt = function of waiting time.
Comments	cent & decent = centralised VS decentralised control,	CR = continuous review,
		ID = inventory-distribution model,
	DCF = discounted cash flow,	JIT = just in time,
	PD model = production-distribution model,	pdp = permissible delay in payments,
	PI model = production-inventory model,	PP model = procurement-production model,
	PR = periodic review,	SP = single period,
	tvm = time value of money.	

Table A 1 Constant demand and fixed lifetime.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Gupta et al. (2003)	Per	iH	CycleT, OrderQ, #R	EOQ	C	No	R	No	No	PR, seasonal
Xu and Sarker (2003)	Per	IT	CycleT	EOQ	C	No	M	Yes	com	PR, product family
Ferguson et al. (2007)	Per	IT	OrderQ	EOQ	C	Yes	R	No	No	PR, price discount
Zanoni and Zavanella (2007)	Per	IT	Lot size	MILP, Heuristics	C	No	S-B	No	No	ID model, PR, FIFO dispatching policy, multiple items
Soysal et al. (2014)	Per	IT	ProduceQ	MOLP	C, E	No	5e	No	No	CR, allocation, logistics network design

Table A 2 Stock-dependent demand and fixed lifetime.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Chu and Chen (2002)	Per	FF	#R, service level	xSol	C	No	S	Yes	p	PR
Yang and Wee (2003)	Per	FF	#d, OrderQ	EPQ	C	No	S-Bs	Yes	No	PR, JIT
Balkhi and Benkherouf (2004)	Per	FF	CycleT, #R	EPQ	C	No	S	No	No	PR

Table A 3 Time-varying demand and fixed lifetime.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Chung and Tsai (2001)	Per	FF	CycleT, OrderQ, #R	EOQ	C	No	S	Yes	com	DCF, PR, tvm
Balkhi and Benkherouf (2004)	Per	FF	CycleT, #R	EPQ	C	No	S	No	No	PR
Hsu et al. (2007)	Per	FF	CycleT, OrderQ, shortT	xSol	P	Yes	S-B	Yes	wt	PR
Leung and Ng (2007)	Per	IT	ProduceQ	GP	C	No	M	Yes	com	PI model, postponement
Dey et al. (2008)	Per	FF	CycleT, shortT, #R	MOGA	P	Yes	S	Yes	p	PR, tvm, inflation, two warehouses
Broekmeulen and van Donselaar (2009)	Per	ExO	OrderQ, reorder level	Heuristics	C	Yes	R	No	No	CR, dynamic
Cheng and Wang (2009)	Per	FF	CycleT, OrderQ	xSol	C	No	S	Yes	com	PR

Bai et al. (2010)	Per	FF	ProduceQ	Approx	C	No	M	Yes	com	PR
He et al. (2010)	Per	FF	OrderQ, Ptime, #d	EPQ	C	No	M	No	No	PR, multiple markets
Jia and Hu (2011)	Per	IT	OrderQ, sellP	DP	P	No	S-B	No	No	PR, dynamic pricing
Avinadav et al. (2013)	Per	IT	CycleT, OrderQ, sellP	xSol	P	No	R	No	No	PR

Table A 4 Price-dependent demand and fixed lifetime.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Mukhopadhyay et al. (2004)	t-v	FF	CycleT, OrderQ, sellP	xSol	P	No	R	No	No	PR, joint pricing
Sezen (2004)	Per	IT	SellP	Approx	P	No	R	No	No	SP, price discount
Chande et al. (2005)	Per	IT	OrderQ, sellP	M	P	No	R	Yes	com	PR, RFID
Hsu et al. (2007)	Per	FF	CycleT, OrderQ, shortT	xSol	P	Yes	S-B	Yes	wt	PR
Chew et al. (2009)	Per	IT	sellP, inventory allocation	DP, Heuristics	P	No	R	No	No	PR, price discount
Frank et al. (2009)	Per	IT	Order-up-to level	DP	P	No	M	Yes	com	multiple items, MTO
Dasu and Tong (2010)	Per	IT	OrderQ, sellP	xSol	P	No	R	No	No	SP, price discount, dynamic pricing
Avinadav et al. (2013)	Per	IT	CycleT, OrderQ, sellP	xSol	P	No	R	No	No	PR

Table A 5 Stochastic demand and fixed lifetime.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Tekin et al. (2001)	Per	IT	OrderQ, reorder level	xSol	C	Yes	S	Yes	No	CR
Katagiri and Ishii (2002)	Per	IT	OrderQ	xSol	P	No	S	Yes	No	PR, fuzzy
Chun (2003)	Per	IT	OrderQ, sellP	xSol	P	No	R	No	No	SP, price discount
Gürler and Özkaya (2003)	Per	IT	OrderQ, reorder level	xSol, Heuristics	C	No	S	No	No	CR
Ferguson and Ketzenberg (2005)	Per	IT	OrderQ	Heuristics	P	Yes	S-B	Yes	No	PR, information sharing
Kanchanasuntorn and Techanitisawad (2006)	Per	IT	CycleT, reorder level, max. inventory level	sim	P	Yes	S-B	Yes	No	PR, agro-food industry

Ramanathan (2006)	Per	IT	OrderQ, sellP	xSol	P	No	R	No	No	Price discount
Bisi and Dada (2007)	Per	IT	safeQ, sellP	M	P	No	R	Yes	No	CR, price discount, dynamic pricing
Ferguson and Koenigsberg (2007)	Per	QD	OrderQ, safeQ, sellP	xSol	P	No	S	No	No	Two-period, price discount
Ketzenberg and Ferguson (2008)	Per	IT	OrderQ	M	P	Yes	S-B	Yes	No	PR, cent & decent
Lodree and Uzochukwu (2008)	Per	IT	ProduceQ	xSol	P	Yes	M	Yes	p	Two-period
Berk et al. (2009)	Per	IT	iInv	DP, Heuristics	P	No	S	No	No	SP, price increase, price discount, dynamic pricing
Broekmeulen and van Donselaar (2009)	Per	ExO	OrderQ, reorder level	sim	C	Yes	R	Yes	No	PR, RFID, EWA policy
Levina et al. (2010)	Per	IT	iInv	Heuristics	P	No	S	No	No	SP
Minner and Transchel (2010)	Per	IT	OrderQ, base stock	DP	S	Yes	R	Yes	No	PR, dynamic
Olsson and Tydesjö (2010)	Per	IT	Order-up-to level	xSol, Approx	C	Yes	S	Yes	com	CR
Pauls-Worm et al. (2010,2014)	Per	IT	Ptime, order-up-to level	MILP	C	No	M	Yes	com	PR
Rossi et al. (2010b)	Per	IT	Ptime, order-up-to level	CP	C	No	M	Yes	com	PR
Xiao et al. (2010)	Per	IT	OrderQ, sellP	GT	P	Yes	S-B	No	No	SP, seasonal
Li et al. (2012)	Per	IT	Order-up-to level, sellP	xSol	P	Yes	R	Yes	No	CR, price discount
Tsai and Huang (2012)	Per	IT	OrderQ	Heuristics	P	No	R	No	No	CR
Duan and Liao (2013)	Per	IT	ProduceQ, OrderQ	Heuristics	O, sh	No	S-Bs	Yes	No	PR
Haijema (2013)	Per	IT	order-up-to level, reorder level	M, DP, sim	C	Yes	S	Yes	No	CR
Kouki et al. (2013)	Per	ExO	OrderQ, reorder level	xSol, Sim	C	No	S	No	No	CR, preservation technology investment
Rossi (2013)	Per	IT	Various control policies	MILP, CP, sim	C	No	M	Yes	com	PR
Govindan et al. (2014)	Per	IT	OrderQ, route, location	Heuristics	C,E	No	M-D-R	No	No	SC design

Table A 6 Constant demand and age-dependent deterioration rate.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Chang and Dye (2001)	Tw-p Wbd	FF	CycleT, shortT	EOQ	C	No	B	Yes	wt	PR, pdp
Chang et al. (2002)	Tw-p Wbd	FF	#R, cycleNoS	EOQ	C	No	B	Yes	com	PR, pdp, tvm
Ouyang et al. (2006)	NI	FF	CycleT, OrderQ	xSol	C	No	R	No	No	PR, pdp
Wee et al. (2008)	Tw-p Wbd	FF	#R, OrderQ	EOQ	C	No	R	No	No	DCF, PR, tvm, amelioration
Chung (2009)	NI	FF	CycleT	xSol	C	No	R	No	No	PR, pdp
Chung (2010)	NI	FF	CycleT, OrderQ	xSol	C	No	R	No	No	PR, pdp

Table A 7 Stock-dependent demand and age-dependent deterioration rate.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Mahapatra and Maiti (2005)	Tw-p Wbd	FF	CycleT	GP, fuzzy	P	No	M	Yes	p	PI model, PR, mp, cent & decent, quality dependent production rate
Chung and Wee (2008)	Tw-p Wbd	FF	Lot-for-lot, OrderQ	EOQ	C	No	P-R	Yes	p	PI model, PR, JIT delivery, warranty period offered by manufacturer, inflation, integration
Roy and Chaudhuri (2009)	Tw-p Wbd	FF	ProduceQ	EOQ	C	No	M	Yes	com	PI model, PR
Konstantaras and Skouri (2011)	Tw-p Wbd	FF	ProduceQ	Lagrange multipliers	C	No	M	Yes	com	PI model, PR

Table A 8 Time-varying demand and age-dependent deterioration rate.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Wu (2001)	Tw-p Wbd	FF	OrderQ, shortT	EOQ	C	No	S	Yes	wt	PR
Chen and Lin (2002)	Nd	FF	CycleT, lot size	DP	C	No	S	Yes	com	PR, tvm, inflation
Wu (2002)	Tw-p Wbd	FF	CycleT, OrderQ	EOQ	C	No	S	Yes	wt	PR

Giri et al. (2003)	Th-p Wbd	FF	CycleT, cycleNoS	EOQ	C	No	S	Yes	com	PR
Banerjee and Agrawal (2008)	Th-p Wbd	FF	CycleT, iInv	EOQ	C	No	R	Yes	com	PR, two warehouses
Skouri and Konstantaras (2009)	Tw-p Wbd	FF	OrderQ, shortT	xSol	C	No	S	Yes	wt	PR
Skouri et al. (2009)	Per, Tw-p Wbd	FF	OrderQ, order-up-to level	EOQ	C	No	S	Yes	p	PR, start with/without shortage
Roy and Maiti (2010)	Tw-p Wbd	FF	#R	GA	C	No	M	Yes	com	PI model, PR, flexible production volume

Table A 9 Price-dependent demand and age-dependent deterioration rate.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Wee and Law (2001)	Tw-p Wbd	FF	CycleT, OrderQ	EOQ	P	No	S	Yes	com	PR, tvm, pricing policy
Papachristos and Skouri (2003)	Tw-p Wbd	FF	CycleT, sellP	EOQ	C	No	S	Yes	wt	PR, quantity discount
Mahapatra and Maiti (2005)	Tw-p Wbd	FF	CycleT	GP, fuzzy	P	No	M	Yes	p	PI model, PR, cent & decent, quality dependent production rate
Mukhopadhyay et al. (2005)	Tw-p Wbd	FF	CycleT, sellP	EOQ	C	No	S	No	No	PR

Table A 10 Stochastic demand and age-dependent deterioration rate.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Gürler and Özkaya (2008)	Rn	IT	*(s,S)* policy	xSol	C	No	R	Yes	com	CR, perishable
Yadavalli et al. (2011)	Ed	FF	*(s,S)* policy	M	C	Yes	M	No	No	CR, multi-server service facility
Yang et al. (2011)	Tw-p Wbd	FF	CycleT, max. order-up-to level	xSol	C	No	D	Yes	p	PR

Table A 11 Constant demand and time-dependent deterioration rate.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Chung et al. (2001)	Per	FF	CycleT	xSol	P	Yes	R	No	No	PR, pdp
Chung and Lin (2001)	Per	FF	OrderQ, #R	xSol	C	No	S	Yes	com	DCF, PR, tvm

Yang et al. (2001)	Per	FF	#R, CycleT, shortT	xSol	C	No	S	Yes	wt	PR, inflation
Yang and Wee (2002)	Per	FF	#d	EPQ	C	No	S-Bs	No	No	PI model, SP
Chang et al. (2003)	Per	FF	CycleT, OrderQ	EOQ	C	No	S	No	No	PR, pdp, inflation
Rau et al. (2003)	Per	FF	#d	EPQ	C	No	S-P-B	No	No	PR
Chang (2004)	Per	FF	CycleT, OrderQ	EOQ	C	No	S	No	No	PR, pdp, inflation
Chung and Liao (2004)	Per	FF	CycleT, OrderQ	EOQ	C	Yes	B	No	No	PR, pdp
Das et al. (2004)	Per	FF	OrderQ, #d, sellP	faGP, MONLP	P,C	No	S-B	No	No	PR, price discount, capacity constraint
Rau et al. (2004)	Per	FF	#R	EPQ	C	No	S-P-B	Yes	com	PR, JIT
Yang (2004)	Per	FF	CycleT, shortT	EOQ	C	No	S-B	Yes	com	PR, tvm, inflation, two warehouses, capacity constraint
Chen and Ouyang (2006)	Per	FF	CycleT, OrderQ	fuzzy	C	No	S	No	No	PR, pdp, inflation
Chung and Liao (2006)	Per	FF	CycleT	xSol	c	No	R	No	No	DCF, PR, pdp, tvm
De and Goswami (2006)	Per	FF	CycleT, OrderQ	fuzzy	C	No	B	Yes	p	PR, pdp, inflation
Lee (2006)	Per	FF	CycleT, OrderQ	EPQ	C	No	S-B	Yes	wt	PR, two warehouses, FIFO dispatching policy
Mandal et al. (2006)	Per	FF	CycleT, OrderQ	nLP, MGP	C	No	R	No	No	PR, limited storage space
Song and Cai (2006)	Per	FF	CycleT, PayT	xSol	C	No	W-R	No	No	PR, pdp
Yang (2006)	Per	FF	CycleT, shortT	xSol	C	No	S-B	Yes	wt	PR, inflation, two warehouses
Chung and Huang (2007)	Per	FF	CycleT, OrderQ	EOQ	C	Yes	S-B	No	No	PR, pdp, two warehouses, capacity constraint
Li et al. (2007)	Per	FF	CycleT, shortT	EOQ	C	No	R	Yes	com	PR, multiple items, postponement
Liao (2007a)	Per	FF	CycleT, OrderQ	EOQ	C	No	B	No	No	PR, pdp
Liao (2007b)	Per	FF	CycleT	EPQ	C	No	B	No	No	PR, pdp
Lin and Lin (2007)	Per	FF	#R	EOQ	C	No	S-B	Yes	com	PR
Hsieh et al. (2008)	Per	FF	CycleT, OrderQ, shortT	EOQ	C	No	S-B	Yes	com	DCF, PR, tvm, two warehouses, capacity constraint
Huang and Liao (2008)	Per	FF	CycleT, lot size	xSol	C	No	R	No	No	PR, pdp, price discount
Liao (2008)	Per	FF	CycleT, sellP	EPQ	C	No	S	No	No	PR, pdp
Niu and Xie (2008)	Per	FF	CycleT, OrderQ	xSol	C	No	S-B	Yes	wt	PR, two warehouses, FIFO dispatching policy
Roy et al. (2008)	Per	FF	OrderQ	MOGA	C	No	S	No	No	PR, multiple items, fuzzy
Wee et al. (2008)	decr	FF	CycleT, OrderQ	EOQ	C	No	R	No	No	DCF, PR, tvm, amelioration

Blackburn and Scudder (2009)	t-v	QD	OrderQ	EOQ	C	No	G-D	No	No	PR, fresh produce, preservation technology investment
Ouyang et al. (2009)	Per	FF	CycleT, OrderQ	EOQ	C	No	R	No	No	PR, pdp
Chang et al. (2010a)	Per	FF	CycleT, OrderQ	EOQ	C	No	S	No	No	DCF, PR, pdp, tvm, price discount
Chang et al. (2010b)	Per	FF	CycleT, OrderQ	EPQ	C	No	M	No	No	PR, pdp
Hsu et al. (2010)	t-v	FF	CycleT, shortT	xSol	P	No	R	Yes	p	PR, preservation technology investment
Liao and Huang (2010)	Per	FF	CycleT, OrderQ	EOQ	P	Yes	R	No	No	PR, pdp, two warehouses
Lin et al. (2010)	Per	FF	#R	EOQ	C	No	S-B	Yes	com	PR, 4 scenarios of cooperative relationship
Chang et al. (2011)	Per	FF	CycleT, OrderQ	EOQ	C	No	B	No	No	PR, price discount
Chung and Wee (2011)	Per	FF	CycleT, #d	xSol	C	Yes	S-B	No	No	PI model, SP, JIT delivery, remanufacturing, return facility
Rong et al. (2011)	Per	QD	ProduceQ, OrderQ	MILP	C	No	P-D	No	No	CR, PD model, temperature effect
Roy and Samanta (2011)	Per	FF	Pchange	xSol	P	No	M	No	No	PR, pdp
Wang et al. (2011)	t-v	FF	CycleT, OrderQ	EOQ	C	No	P-D-R	No	No	PR, strategic alliances
Wee et al. (2011)	Per	FF	#R, OrderQ	EOQ	P	No	M	No	No	PR, LCA, remanufacturing, return facility
Yan et al. (2011)	Per	FF	OrderQ, #d	EOQ	C	No	S-B	No	No	PR, PD model, JIT
Disney and Warburton (2012)	t-v	FF	OrderQ	xSol	C	No	G-D	No	No	PR, tvm, EOQ with perishables
Dye and Hsieh (2012)	t-v	FF	shortT, OrderQ	xSol	P	No	R	Yes	p	PR, preservation technology investment
Zanoni and Zavanella (2012)	Per	QD	OrderQ	EOQ	C	No	P-D	No	No	PR, temperature effect
Fauza et al. (2013)	Per	QD	CycleT, #R, #d	EOQ	P	No	M	No	No	PR, PP model

Table A 12 Stock-dependent demand and time-dependent deterioration rate.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Kar et al. (2001)	t-v	FF	CycleT, OrderQ	xSol	P	No	S	No	No	PR, two items, limited shelf space, price discount, two warehouses
OuYang et al. (2003)	Per	FF	#R, service rate	EO	C	No	R	Yes	p	PR, tvm, inflation
Bhattacharya (2005)	Per	FF	OrderQ, order-up-to level	xSol	P	Yes	S	No	No	PR, multiple items
Dye and Ouyang (2005)	Per	FF	CycleT, shortT	EOQ	P	No	S	Yes	wt	PR

Teng and Chang (2005)	Per	FF	iInv, eInv, sellP, Ptime	EPQ	P	No	R	No	No	PR, price discount
Teng et al. (2005b)	Per	FF	CycleT, max. inventory level	EOQ	P	No	R	No	No	PR
Hou (2006)	Per	FF	CycleT, shortT	EOQ	C	No	R	Yes	com	PR, tvm, inflation, capacity constraint
Hou and Lin (2006)	Per	FF	#R	EOQ	P	No	S	Yes	com	DCF, PR, tvm, inflation
Pal et al. (2006)	Per	FF	OrderQ	EOQ	P	Yes	R	Yes	wt	PR, capacity constraint
Wu et al. (2006)	Per	FF	CycleT, OrderQ, shortT	EOQ	C	No	S	Yes	wt	PR
Maity and Maiti (2009)	s-d	FF	Prate	xSol	P	No	R	No	No	SP, multiple items
Min and Zhou (2009)	s-d	FF	CycleT, shortT	xSol	P	No	R	Yes	p	PR, capacity constraint
Roy et al. (2009a)	Per	FF	CycleT, #R	GA	P	No	R	No	No	PR, tvm, fuzzy inflation
Wee et al. (2009)	Per	FF	CycleT, shortT	WFnLP	P, ROI	No	S	Yes	com	PR, multiple items
Chang et al. (2010c)	Per	FF	CycleT, eInv	xSol	P	No	R	Yes	com	PR, limited shelf space
Hsieh and Dye (2010)	Per	FF	CycleT, shortT	EOQ	P	No	S	Yes	wt	PR, limited shelf space
Yang et al. (2010)	Per	FF	CycleT, shortT	xSol	P	No	S	Yes	wt	PR, inflation
Teng et al. (2011)	Per	FF	CycleT, eInv	xSol	P	No	R	No	No	PR, pdp
Piramuthu and Zhou (2013)	Per	QD	*(r,Q)* policy, shelf space	GA	P	No	R	No	No	SP, multiple items, RFID

Table A 13 Time-varying demand and time-dependent deterioration rate.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Balkhi (2001)	Per	FF	ProduceQ	xSol	C	No	M	Yes	com	PR
Chang et al. (2001)	t-v	FF	CycleT	EOQ	C	No	R	No	No	PR, pdp
Wang and Chen (2001)	Per	FF	CycleT, ProduceQ	xSol	C	No	M	No	No	PR
Skouri and Papachristos (2002)	Per	FF	CycleT, shortT, #R	xSol	C	No	S	Yes	p	CR
Teng et al. (2002)	Per	FF	CycleT, short, Ptime	xSol	C,P	No	S	Yes	wt	PR
Wang (2002)	Per	FF	CycleT, short, #R	EOQ	C	No	S	Yes	wt	PR
Arcelus et al. (2003)	Per	FF	OrderQ	xSol	P	No	R	No	No	PR, pdp, price discount
Goyal and Giri (2003)	t-v	FF	CycleT, shortT	EPQ	C	No	M	Yes	p	PI model, PR, effects of learning on production

Khanra and Chaudhuri (2003)	Per	FF	CycleT, OrderQ	Heuristics	C	No	S	No	No	PR
Skouri and Papachristos (2003a)	Per	FF	CycleT, shortT, #R	EOQ	C	No	S	Yes	wt	CR
Skouri and Papachristos (2003b)	t-v	FF	Ptime	EPQ	C	No	M	Yes	wt	PR
Balkhi (2004)	t-v	FF	CycleT, lot size	EPQ	C	No	M	Yes	p	PR, tvm, inflation, imperfect products
Sana et al. (2004)	Per	FF	#R, service level	xSol	C	No	S	Yes	com	PI model, PR
Chen and Chen (2005)	Per	FF	CycleT, ProduceQ, sellP	DP, EOQ	P	No	S-B	No	No	PR, capacity constraint, multiple products
Maity and Maiti (2005)	Per	FF	Prate	xSol	C	No	M	No	No	SP, fuzzy, multi-objective
Moon et al. (2005)	t-v	FF	shortT, #R	EOQ	C	No	S	Yes	wt	DCF, PR, inflation, amelioration
Yang (2005)	Per	FF	CycleT, shortT	xSol	P	No	S	Yes	wt	PR
Chang et al. (2006)	Per	FF	CycleT, shortT, #R, sellP	xSol	P	No	R	Yes	wt	PR
Dye et al. (2006)	Per	FF	CycleT, shortT, #R	EOQ	P	No	R	Yes	wt	PR
Ghosh and Chaudhuri (2006)	t-v	FF	#R, shortT	EOQ	C	No	S	Yes	com	PR
Jaggi et al. (2006)	Per	FF	shortT, #R	xSol	C	No	S	Yes	com	DCF, PR, inflation
Manna and Chaudhuri (2006)	Per	FF	short, Ptime	EOQ	C	No	M	Yes	com	PR
Tadj et al. (2006)	t-v	FF	Prate, inventory status	EPQ	C,P	No	M	No	No	SP
Deng et al. (2007)	Per	FF	CycleT, shortT, sellP	xSol	C	No	R	Yes	com	PR
Dye (2007)	t-v	FF	CycleT, shortT	EOQ	P	No	R	Yes	wt	PR, joint pricing
Maity et al. (2007)	Per	FF	CycleT, Prate	GA	C	No	M	No	No	PI model, PR, multiple items
Balkhi and Tadj (2008)	t-v	FF	CycleT, shortT	EOQ	C	No	R	Yes	wt	CR, tvm, inflation
Chern et al. (2008)	t-v	FF	CycleT, shortT, #R, sellP	EOQ	C	No	S	Yes	wt	PR, inflation, amelioration
Panda et al. (2008)	t-v	FF	CycleT	EOQ	C	No	R	No	No	PR, seasonal peishables
Tsao and Sheen (2008)	Per	FF	CycleT, OrderQ, sellP	xSol	P	No	R	No	No	PR, pdp, price increase, price discount, dynamic pricing
Lee and Hsu (2009)	Per	FF	CycleT, #R	xSol	C	No	S	No	No	PR, two warehouses
Lin et al. (2009)	t-v	FF	CycleT, OrderQ, #R	EOQ, Heuristics	P	No	S-B	No	No	PR, JIT, partnership
Alamri (2011)	Per	FF	Ptime, returnQ	EPQ	C	No	M	No	No	PR, remanufacturing, return facility
Balkhi (2011)	Per	FF	CycleT	EOQ	C	No	R	No	No	PR, pdp, tvm, inflation
Cheng et al. (2011)	Per	FF	orderQ, shortT	xSol	C	No	S	Yes	p	PR

Dye and Ouyang (2011)	Per	FF	CycleT, sellP, #R	PS, MInLP	P	No	R	No	No	PR, pdp
Jaggi et al. (2011)	Per	FF	CycleT, shortT	xSol	C	No	S	Yes	wt	PR, inflation, two warehouses
Lin (2011)	Per	FF	shortT	xSol	C	No	S	Yes	com	PR
Skouri et al. (2011)	Per	FF	orderQ, short, Ptime	xSol	C	No	M	Yes	com	SP, pdp
Yang (2011)	Per	FF	shortT, Ptime, #R	xSol	C	No	M	Yes	wt	PI model, PR
Maihami and Kamalabadi (2012)	Per	FF	CycleT, OrderQ, sellP	xSol	P	No	R	Yes	p	PR, price discount
Musa and Sani (2012)	Per	FF	CycleT, shortT	xSol	C	No	S	No	No	PR, pdp
Wang and Li (2012)	Per	QD	sellP	xSol	P	No	R	No	No	CR, price discount, dynamic pricing, waste reduction

Table A 14 Price-dependent demand and time-dependent deterioration rate.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Abad (2001)	Per	FF	CycleT, shortT, sellP	EOQ	P	No	R	Yes	wt	PR, price increase, price discount
Kar et al. (2001)	t-v	FF	CycleT, OrderQ	xSol	P	No	S	No	No	PR, two items, limited shelf space, price discount, two warehouses
Abad (2003)	Per	FF	CycleT, shortT, sellP	EOQ	P	No	M	Yes	wt	PR, price increase, price discount
Chen and Chen (2005)	Per	FF	CycleT, ProduceQ, sellP	DP	P	No	M	No	No	PR
Teng and Chang (2005)	Per	FF	iInv, eInv, sellP, Ptime	EPQ	P	No	R	No	No	PR, price discount
Teng et al. (2005a)	Per	FF	CycleT, sellP	xSol	P	No	R	No	No	PR, pdp
Chang et al. (2006)	Per	FF	CycleT, shortT, #R, sellP	xSol	P	No	R	Yes	wt	PR
Hou and Lin (2006)	Per	FF	#R	EOQ	P	No	S	Yes	com	DCF, PR, tvm, inflation
Hsu and Wee (2006)	Per	FF	#R	xSol	P	No	B	No	No	PR, tvm, price discount
Pal et al. (2006)	Per	FF	OrderQ	EOQ	P	Yes	R	Yes	wt	PR, capacity constraint
Dye (2007)	Per	FF	CycleT, shortT	EOQ	P	No	R	Yes	wt	PR
Dye et al. (2007a)	dec	FF	CycleT, shortT, sellP	EOQ	P	No	S	Yes	wt	PR, price discount
Dye et al. (2007b)	Per	FF	CycleT, shortT	EOQ	P	No	S-B	Yes	wt	PR, two warehouses, capacity constraint

Dye et al. (2007c)	t-v	FF	CycleT, shortT, sellP	EOQ	P	No	R	Yes	com	DCF, PR, tvm
Teng et al. (2007)	Per	FF	CycleT, shortT	EPQ	P	No	M	Yes	wt	PI model, PR, price increase, price discount
Tsao and Sheen (2007)	Per	FF	CycleT, sellP	EOQ	P	No	R	No	No	PR, pdp, price discount
Liu et al. (2008)	Per	QD	CycleT, OrderQ, sellP	xSol	P	No	R	No	No	PR, RFID
Rong et al. (2008)	Per	FF	OrderQ, sellP, #d	MInLP	P	Yes	S-B	Yes	com	PR, two warehouses
Tsao and Sheen (2008)	Per	FF	CycleT, OrderQ, sellP	xSol	P	No	R	No	No	PR, pdp, price increase, price discount, dynamic pricing
Bhunia et al. (2009)	Per	FF	CycleT, Prate, Ptime	GA	P	No	M	Yes	wt	PR
Lin et al. (2009)	t-v	FF	CycleT, OrderQ, #R	Heuristics	P	No	S-B	No	No	PR, JIT, partnership
Wu et al. (2009)	Per	FF	CycleT, sellP	xSol	P	No	R	No	No	PR
Dye and Ouyang (2011)	Per	FF	CycleT, sellP, #R	PS, MInLP	P	No	R	No	No	PR, pdp
Pang (2011)	Per	FF	*(s,S)* policy, sellP	DP	P	No	S	Yes	p	PR, dynamic pricing
Maihami and Kamalabadi (2012)	Per	FF	CycleT, OrderQ, sellP	xSol	P	No	R	Yes	p	PR, price discount
Wang and Li (2012)	Per	QD	sellP	xSol	P	No	R	No	No	CR, price discount
Yu and Nagurney (2013)	Per	QD	OrderQ, sellP, demand	Network model	P	No	S-M-D	No	No	Demand price function, alternative production technologies

Table A 15 Stochastic demand and time-dependent deterioration rate.

References	DT	DC	RP	Further specifications						
				MF	PM	LT	E	S	BL	Comments
Kalpakam and Shanthi (2001)	Per	FF	*(S-1,S)* policy	M	C	Yes	S	Yes	com	CR
Berman and Sapna (2002)	Per	FF	mean service times	LP	C	No	SE	No	No	CR
Benkherouf et al. (2003)	Per	FF	CycleT, OrderQ	xSol, DP	C	No	S	Yes	com	PR
De Kumar et al. (2003)	fuzzy	FF	ProduceQ, demand rate	FnLP	C	No	S	No	No	PR, fuzzy demand rate
Chakravarthy and Daniel (2004)	Per	FF	reorder point, order-up-to level	M	C	No	P-D	Yes	com	PR, price discount, preservation technology investment
Mahata and Goswami (2007)	Per	FF	CycleT	EOQ	C	No	R-C	No	No	SP, pdp, fuzzy demand rate
Liu et al. (2008)	Per	QD	CycleT, OrderQ, sellP	DP	P	No	R	No	No	PR, RFID

Manuel et al. (2008)	Per	FF	*(s,S)* policy	M	C	Yes	SE	Yes	wt	CR
De and Goswami (2009)	Per	FF	CycleT	xSol	C	No	R-C	No	No	PR, CR, pdp
Lian et al. (2009)	Per	FF	*(s,S)* policy	M	C	No	S	Yes	wt	CR
Mirzazadeh et al. (2009)	Per	FF	#R, shortT	xSol	C	No	S	Yes	com	PR, tvm, inflation, amelioration
Sivakumar (2009)	Per	FF	*(s,S)* policy	M	C	Yes	S	No	No	CR
Cai et al. (2010)	Per	FF	OrderQ, sellP	xSol	P	No	P-D	Yes	p	SP, cent & decent, investment
Hung (2011)	Per	FF	CycleT, shortT	xSol	C	No	S	Yes	wt	PR
Pang (2011)	Per	FF	*(s,S)* policy, sellP	DP	P	No	S	Yes	p	PR, dynamic pricing
Shen et al. (2011)	Per	FF	CycleT, shortT, #R	EOQ	C	Yes	S-B	Yes	com	PR
Taleizadeh et al. (2013)	Per	FF	OrderQ	Heuristics	C	Yes	M	No	No	Fuzzy, quantity discount, prepayment

APPENDIX B: CPLEX CODES

Example problem 1: Centralised Model in CPLEX

Coding in model file (Kouki.mod)

```
execute{
  writeln("Production Plan");
}
float CO2 = 1;
int Product = 1; // # of consumer products
range Types = 1..Product;
int Material = 1; //# of raw materials
range RawMat = 1..Material;
int Customer = ...;
range Retailer = 1..Customer;
int M = 999999;//large positive value
int LT[Types] = [1];//production lead time
int LTPmax = max(i in 1..Product) LT[i];//max production lead time
int LTM[RawMat] = [1];//transport lead time
int LTmax = max(a in 1..Material) LTM[a];//max planned transport lead time
int NumPeriodsLT = 9; // total planning horizon (+LTmax)
range Periods = (1+LTmax)..NumPeriodsLT; //demand period
range Period1 = (LTmax+LTPmax+1)..NumPeriodsLT;
range Period2 = (LTmax+LTPmax+2)..NumPeriodsLT;
range PeriodT = 1..NumPeriodsLT; //maximum planned lead time
int Usage[RawMat][Types] = [[1]]; //Bill of Material (rawMats, Products)
float pwaste = 0;//production waste as a percentage of production quantity e.g. 0.1

//economic parameters
int setupC = ...;
int setupCC[Types] = ...;
int orderCC[RawMat] = ...;
int holdC[Types] = ...;
int holdPC[Types] = ...;
int prodC[Types] = ...;
int ftranC[RawMat] = ...;
float vtranC[RawMat] = ...;
int wasteC[Types]= ...;
//environmental parameters
float setupE = ...;
float setupEE[Types] = ...;
float SECp[Types] = ...;
float ESp[Types] = ...;
float ET[RawMat] = ...;
int disP[RawMat] = ...;
float vtranE[RawMat] = ...;

int minlot[Types] = ...;
{int} Max[Types] = ...;
{int} B = union (i in Types) Max[i];
{int} ShelfNoWT[Types] = ...;
int ShelfWT[Types] = ...;
int ShelfLifeNoWT[Types] = ...;
{int} X[Retailer][Types] = ...;
{int} A = union (r in Retailer, i in Types) X[r][i];
int demand[Retailer][Types][Periods] = ...;
int SLevel[Types][B][Periods] = ...;
{int} Max2[Types] = ...;
{int} C = union (i in Types) ShelfNoWT[i];

dvar int+ demandR[Retailer][Types][A][Periods];
dvar int+ Inv[Types][B][1..NumPeriodsLT];//inventory level I
dvar int+ UpLevel[Types][Periods];//order-up-to level S
dvar int+ OrderQ[Types][Periods];//production quantity Q
dvar boolean productOrder[Periods];//major setup
dvar boolean AnOrder[Types][Periods];//minor setup
dvar boolean matOrder[RawMat][Periods];//raw mat order
```

```
dvar boolean OPeriod[Types][Periods][B];//previous recent order

-------------------------------------------------------------------------------
//FIFO
dvar int+ Aux[Types][C][Periods];
dvar boolean BAux[Types][C][Periods];
//LIFO
dvar int+ Aux[Types][B][Periods];
dvar boolean BAux[Types][C][Periods];
-------------------------------------------------------------------------------
dvar int+ Mdemand[RawMat][Periods];//raw material quantity require for production
dvar float+ PlanP[Types][Periods];//order quantity = production quantity Q + production waste
dvar int+ Qwaste[Types][Periods];//integer quantity of production waste
dvar float+ QPwaste[Types][Periods];//production waste
dvar int Scost;//setup cost
dvar int Ocost;//order cost
dvar int Wcost;//waste cost
dvar int Icost;//inventory level based holding cost
dvar int IPcost;//inventory position based holding cost
dvar int Pcost;//production cost
dvar int Tcost;//transport cost
dvar int Semiss;//setup cost
dvar int Iemiss;//inventory level based holding cost
dvar int Pemiss;//production cost
dvar int Tinv;//total inventory in the system
-------------------------------------------------------------------------------
//LC
dvar float emission;//quantity of emission
dvar int waste;//quantity of waste
//LE
dvar int waste;//quantity of waste
//LE
dvar float emission;//quantity of emission
-------------------------------------------------------------------------------
dexpr int SetupCost = sum(t in Periods)((setupC*productOrder[t])+(sum(i in
Types)(setupCC[i]*AnOrder[i][t])));
dexpr int OrderCost = sum(t in Periods)(sum(a in RawMat)(orderCC[a]*matOrder[a][t]));
dexpr int WasteCost = sum(t in Periods)(sum(i in Types)(Inv[i][ShelfWT[i]][t]*wasteC[i]));
dexpr int InvCost = sum(t in Periods)(sum(i in Types)(sum(b in ShelfNoWT[i])(holdC[i]*Inv[i][b][t])));
dexpr int InvPCost = sum(t in Periods)(sum(i in Types)(holdPC[i]*(UpLevel[i][t]-(sum(r in
Retailer)demand[r][i][t]))));
dexpr float ProdCost = sum(t in Periods)(sum(i in Types)(PlanP[i][t]*prodC[i]));//include cost in processing
production waste
dexpr float TransCost = sum(t in Periods)(sum(a in
RawMat)((ftranC[a]*matOrder[a][t])+(Mdemand[a][t]*vtranC[a])));
dexpr float TotalCost1 = SetupCost + OrderCost + WasteCost + InvCost + InvPCost + ProdCost +
TransCost;
-------------------------------------------------------------------------------
//LC
minimize TotalCost1;
//LE
dexpr float emission = sum(t in Periods)(sum(i in Types)(sum(b in
Max[i])(Inv[i][b][t]*ESp[i])+(OrderQ[i][t]*SECp[i])))*CO2 + sum(t in
Periods)((setupE*productOrder[t])+(sum(i in
Types)(setupEE[i]*AnOrder[i][t])))+ sum(t in Periods)(sum(a in
RawMat)(matOrder[a][t]*ET[a]*disP[a]+(Mdemand[a][t]*vtranE[a])))*CO2;
minimize emission;
//LW
dexpr float waste = sum(t in Periods)(sum(i in Types)(Inv[i][ShelfWT[i]][t]));
minimize waste;
// Weighted goal programming method
float Givcost = 1008;
float weightC = 0.7;
float normC = 1259;
float Givemiss = 225;
float weightE = 0.3;
float normE = 266;
float Givwaste = 0;
float weightW = 0;
```

```
float normW = 3.5;
dexpr float Cgap = abs(TotalCost1-Givcost);
dexpr float Wgap = abs(waste-Givwaste);
dexpr float Egap = abs(emission-Givemiss);
dexpr float Sustain = weightC*(Cgap/normC) + weightE*(Egap/normE) + weightW*(Wgap/normW);
minimize Sustain;
-----------------------------------------------------------------------------
subject to {
        //demand
        forall (t in Periods, r in Retailer, i in Types)
          demand[r][i][t] == sum(a in X[r][i])demandR[r][i][a][t];
        forall (t in Periods, i in Types)
          ctsellft:
            if (LT[i]+1+LTmax<=t){
              if (t <= NumPeriodsLT-LT[i]){
            OrderQ[i][t] - sum(r in Retailer)demandR[r][i][0][t+LT[i]] == Inv[i][1][t+LT[i]];}}
        forall (t in Periods, i in Types)
          ctsellshelf:
            forall (b in ShelfNoWT[i])
            Inv[i][b][t-1] - sum(r in Retailer)demandR[r][i][b][t] == Inv[i][b+1][t]; //shelf life requirements from
retailers
        forall (t in Periods, i in Types)
          ctProdwaste:
          if (pwaste == 0) {
          PlanP[i][t] == OrderQ[i][t];
          } else {
          QPwaste[i][t] == pwaste*OrderQ[i][t];
          Qwaste[i][t]>=QPwaste[i][t];
          QPwaste[i][t]>=Qwaste[i][t]-1+0.000001;
          PlanP[i][t] == OrderQ[i][t]+Qwaste[i][t];}        //product order quantity calculation
        forall (t in Periods, a in RawMat){
          Mdemand[a][t] == sum(i in Types)(PlanP[i][t]*Usage[a][i]); //material demand

        //material inventory balance
        forall (t in Periods, i in Types)
          ctDemand1:
            if (t == 1+LTmax){
              OrderQ[i][t] == UpLevel[i][t];
   } else if (1+LTmax<t<=LT[i]+1+LTmax) {
            UpLevel[i][t-1] - (sum(r in Retailer)demand[r][i][t-1]) + OrderQ[i][t] == UpLevel[i][t] ;
   } //inventory balance for first LT[i]+1+LTmax periods
        forall (t in Period1, i in Types)
          ctDemand2:
            sum(b in Max[i])Inv[i][b][t] + sum (n in (t-LT[i]+1)..t) OrderQ[i][n] == UpLevel[i][t] - (sum(r in
Retailer)demand[r][i][t]);

        //setup cost
        forall (t in Periods, i in Types)
          ctOrderexist:
            OrderQ[i][t] <= (M * AnOrder[i][t]);
        forall (t in Periods, i in Types)
          ctOrderexist1:
            OrderQ[i][t] >= AnOrder[i][t];
        forall (t in Periods)
          ctMultiPexist:{
            sum (i in Types)(AnOrder[i][t]) <= M * productOrder[t];
            sum (i in Types)(AnOrder[i][t]) >=  productOrder[t];}

        //major&minor ordering cost
        forall (t in Periods, i in Types, a in RawMat)
          ctMatorderC:{
           M * matOrder[a][t]  >= AnOrder[i][t];
           Usage[a][i] *  AnOrder[i][t] >= matOrder[a][t];}

        //minimum quantity to be produced
        forall (t in Periods, i in Types)
          ctminlot:
                OrderQ[i][t] >= minlot[i]*AnOrder[i][t];
```

```
        //order-up-to level(+safety stock)
        forall (t in Periods, i in Types)
          ctSafetyStock1:
        forall (j in 1..(t-LTmax-LT[i]))
        if (t < (ShelfWT[i]+LT[i]+LTmax)){
        UpLevel[i][t-j+1-LT[i]] >= ((sum(n in (t-j+1-LT[i])..t)(sum(r in Retailer)(demand[r][i][n]))) +
SLevel[i][j][t])*OPeriod[i][t][j];}
        forall (t in Periods, i in Types)
          ctSafetyStock2:
            forall (j in Max[i])
            if ( t >= (ShelfWT[i]+LT[i]+LTmax)){
            UpLevel[i][t-j+1-LT[i]] >= ((sum(n in (t-j+1-LT[i])..t)(sum(r in Retailer)(demand[r][i][n])))+
SLevel[i][j][t])*OPeriod[i][t][j];}
        forall (t in Periods, i in Types)
          ctSafetyStock3:
            sum(b in Max[i])Inv[i][b][t] >= sum( j in Max[i])(SLevel[i][j][t]*OPeriod[i][t][j]);
        forall (i in Types)
          ctPriorOrder:
          forall (t in (1+LT[i]+LTmax)..NumPeriodsLT)
            sum(j in Max[i]) (OPeriod[i][t][j]) == 1;
        forall (t in Periods, i in Types)
                ctPOrderexist:
                  forall (j in Max[i])
                  if ( t >= j+LT[i]+LTmax ){
                OPeriod[i][t][j] >= AnOrder[i][t-j+1-LT[i]] - sum (n in (t-j+2-LT[i])..(t-LT[i]))(AnOrder[i][n]);
                  } else {
                    OPeriod[i][t][j] == 0;}
------------------------------------------------------------------------------------
//No issuing policy
        forall (t in Periods, i in Types)
          ctNewInv:
            if (t <= NumPeriodsLT-LT[i]){
            OrderQ[i][t] >= Inv[i][1][t+LT[i]];}
        forall (t in Periods,i in Types)
          ctInventory:
            forall (b in ShelfNoWT[i])
            if (t <= LT[i]+LTmax){
             Inv[i][b][t] == 0;
   } else {
            Inv[i][b][t-1] >= Inv[i][b+1][t];
   }
        forall (t in Period2, i in Types) //Period2
          ctInvBalance:
           (sum(b in ShelfNoWT[i]) Inv[i][b][t-1]) - (sum(r in Retailer)demand[r][i][t]) + OrderQ[i][t-LT[i]] ==
(sum(b in Max[i]) Inv[i][b][t]);
//FIFO issuing policy
        forall (t in Periods, i in Types)
          ctFIFO1:
            Inv[i][ShelfLifeNoWT[i]][t-1] - (sum(r in Retailer)demand[r][i][t]) == Inv[i][ShelfWT[i]][t] -
Aux[i][ShelfLifeNoWT[i]][t];
        forall (t in Periods, i in Types)
          ctFIFO2:
            forall (b in Max2[i])
            Inv[i][b][t-1] - Aux[i][b+1][t] == Inv[i][b+1][t] - Aux[i][b][t];
        forall (t in Period2, i in Types) //Period2
          ctFIFO3:
            OrderQ[i][t-LT[i]] - Aux[i][1][t] == Inv[i][1][t];
        forall (t in Periods, i in Types)
          ctFIFO4:{
            forall (b in ShelfNoWT[i]) {
                M *  (1 - BAux[i][b][t]) >= Aux[i][b][t];
            M * BAux[i][b][t] >= Inv[i][b+1][t];}
                }
        forall (t in Periods, i in Types, c in C)
          ctnotusex:
                if (c > ShelfLifeNoWT[i]){
                BAux[i][c][t] == 0;
                Aux[i][c][t] == 0;}
//LIFO issuing policy
```

```
        forall (t in Period2, i in Types)
          ctLIFO1:
            OrderQ[i][t-LT[i]] - (sum(r in Retailer)demand[r][i][t]) == Inv[i][1][t] - Aux[i][2][t];
        forall (t in Period1, i in Types)
          ctLIFO2:
            forall (b in Max2[i])
            Inv[i][b][t-1] - Aux[i][b+1][t] == Inv[i][b+1][t] - Aux[i][b+2][t];
        forall (t in Period1, i in Types)
          ctLIFO3:
            Inv[i][ShelfLifeNoWT[i]][t-1] - Aux[i][ShelfWT[i]][t] == Inv[i][ShelfWT[i]][t];
        forall (t in Period1, i in Types)
          ctLIFO4:{
            forall (b in ShelfNoWT[i]) {
            (M * BAux[i][b][t]) >= Aux[i][b+1][t];
            (M * (1-BAux[i][b][t])) >= Inv[i][b][t];}
  }
        forall (t in Period1, i in Types)
          ctLIFO5:
          forall (b in ShelfNoWT[i]) {
            BAux[i][b][t] <= (Aux[i][b+1][t] + Inv[i][b][t]);}
        forall (t in Periods, i in Types, c in C)
          ctnotuseBx:
                  if (c > ShelfLifeNoWT[i]){
                  BAux[i][c][t] == 0;}
        forall (t in Periods, i in Types, c in C)
          ctnotuseBx2:{
                  BAux[i][c][1+LTmax] == 0;
                  BAux[i][c][2+LTmax] == 0;}
        forall (t in Periods, i in Types, b in B)
          ctnotusex:
                  if (b > ShelfWT[i]){
                  Aux[i][b][t] == 0;}
        forall (t in Periods, i in Types, b in B)
          ctnotusex2:
                  if (b == ShelfWT[i]){
                  Aux[i][b][1+LTmax] == 0;
                  Aux[i][b][2+LTmax] == 0;}
-------------------------------------------------------------------------------
        //quantity of waste & emission
        waste == sum(t in Periods)(sum(i in Types)(Inv[i][ShelfWT[i]][t]));
        emission == sum(t in Periods)(sum(i in Types)(sum(b in
Max[i])(Inv[i][b][t]*ESp[i])+(OrderQ[i][t]*SECp[i])))*CO2 + sum(t in Periods)((setupE*productOrder[t])+(sum(i
in Types)(setupEE[i]*AnOrder[i][t])))+ sum(t in Periods)(sum(a in
RawMat)(matOrder[a][t]*ET[a]*disP[a]+(Mdemand[a][t]*vtranE[a])))*CO2;

        //auxiliary contraints to make model work
        Scost == SetupCost;
        Ocost == OrderCost;
        Wcost == WasteCost;
        Icost == InvCost;
        IPcost == InvPCost;
        Tcost == TransCost;
        Pcost == ProdCost;
        Semiss == sum(t in Periods)((setupE*productOrder[t])+(sum(i in
Types)(setupEE[i]*AnOrder[i][t])));
        Iemiss == sum(t in Periods)sum(i in Types)sum(b in Max[i])(Inv[i][b][t]*ESp[i]);
        Pemiss == sum(t in Periods)sum(i in Types)(OrderQ[i][t]*SECp[i]);
        Tinv == sum(t in Periods)(sum(i in Types)(sum(b in ShelfNoWT[i])(Inv[i][b][t])));
        forall (t in Periods, i in Types, b in B)
          ctnotusez:
                  if (b > ShelfWT[i]){
                  OPeriod[i][t][b] == 0;}
        forall (t in PeriodT, i in Types)
          ctInitialInv:
                  if (t < 1+LTmax+LT[i]){
                  sum( b in B) Inv[i][b][t] == 0;}
        forall (t in Periods, i in Types, b in B)
          ctdefinition1:
            Inv[i][b][t] >= 0;
```

```
       forall (t in Periods, i in Types) ////////////////////////
        if (t >= NumPeriodsLT){
         sum(b in Max[i])Inv[i][b][t] <= sum( j in Max[i])(SLevel[i][j][t]*OPeriod[i][t][j]);}
       forall (t in Periods, r in Retailer, i in Types,a in A)
        ctdefinition3:
         demandR[r][i][a][t] >= 0;
       forall (t in Periods, i in Types)
        ctdefinition4:{
         UpLevel[i][t] >= 0;
         OrderQ[i][t] >= 0;
       }
       forall (t in Periods, i in Types)
        ctNewInv2:
         if (t > NumPeriodsLT-LT[i]){
         OrderQ[i][t] == 0;}
----------------------------------------------------------------------------
//FIFO&LIFO
forall (t in Periods,i in Types)
        ctdefinition5:
         forall (b in ShelfNoWT[i])
         Aux[i][b][t] >= 0;
----------------------------------------------------------------------------
----------------------------------------------------------------------------
//the ε-constraint method
       emission <= 238;
       waste <= 6;
----------------------------------------------------------------------------
}
execute{
 for (var i in Types){
 writeln("Product", i , thisOplModel.OrderQ[i]);}
 writeln("TotalSus1:",cplex.getObjValue());
 writeln("SetupC1:",Scost.solutionValue);
 writeln("OrderC1:",Ocost.solutionValue);
 writeln("WasteC1:",Wcost.solutionValue);
 writeln("HoldC1:",Icost.solutionValue);
 writeln("HoldPC1:",IPcost.solutionValue);
 writeln("ProdC1:",Pcost.solutionValue);
 writeln("TranC1:",Tcost.solutionValue);
 writeln("TotalCost1:",TotalCost1.solutionValue);
 writeln("TotalWaste1:",waste.solutionValue);
 writeln("TotalEmission1:",emission.solutionValue);
 writeln("SetupE1:",Semiss.solutionValue);
 writeln("HoldE1:",Iemiss.solutionValue);
 writeln("ProdE1:",Pemiss.solutionValue);
 writeln("TotalInv1:",Tinv.solutionValue);
}
```

Coding in data file (Kouki.dat)

```
Customer = 1; //# of retailers
setupC = 0; //major setup cost
setupCC = [150]; //minor setup cost
orderCC = [0]; //ordering or receiving cost
holdC = [1]; //inventory level holding cost
holdPC = [0]; //inventory position holding cost
prodC = [5]; //production cost
ftranC = [0]; //fix delivery cost
vtranC= [0]; //variable delivery cost
wasteC = [5]; //waste disposal cost
setupE = 0;//major setup emission
setupEE = [10]; //minor setup emission
SECp = [1]; //production emission
ESp = [2]; //inventory level holding emission
ET = [0];//fix delivery emission (vary with supplier distance)
disP = [1];//distance between supplier and producer
vtranE = [0];//variable delivery emission
minlot = [0]; //minimum to schedule/produce [tolerance, infeasibilities->safety stock maybe]
Max = [{1,2,3}]; //maximum internal shelf life
```

```
ShelfNoWT = [{1,2}]; //product ages without waste
ShelfWT = [3]; //product age at the end of period considered as waste
ShelfLifeNoWT = [2];
X = [[{0,1,2}]];//shelf life requirements for each retailer..can't use waste from last period
demand = [[[10 10 10 10 10 10 10 10]]];
//Safety stock for product i = sum(retailers)safety stock i
SLevel = [[[ 0, 5, 5, 5, 5, 5, 5, 5]
              [ 0, 0,6, 6, 6, 6, 6, 6]
              [ 0, 0, 0, 7, 7, 7, 7, 7]] ]; //lead time = 1
Max2 = [{1}]; //maximum internal shelf life - 2 //FIFO&LIFO
```

Example problem 2: Centralised Model in CPLEX

Coding in model file (cent1.mod)

```
execute{
  writeln("Centralised Control");
}
int Product = 1; // # of consumer products
range Types = 1..Product;
int Material = 5; //# of raw materials
range RawMat = 1..Material;
int Customer = ...;
range Retailer = 1..Customer;
int M = 999999; //large positive value
int LT[Types] = [1]; //production lead time
int LTPmax = max(i in 1..Product) LT[i]; //max. production lead time
int LTM[RawMat] = [0,0,0,0,0]; //transport lead time
int LTmax = max(a in 1..Material) LTM[a]; //max. planned transport lead time
int NumPeriodsLT = 12; //total planning horizon (including LTmax)
int Usage[RawMat][Types] = [[1],[5],[5],[3],[1]]; //Bill of Material (rawMats, Products)
float pwaste = 0; //production waste as a percentage of production quantity e.g. 0.1
range Periods = (1+LTmax)..NumPeriodsLT; //demand period (program time point starts with 1)
range Period1 = (LTmax+LTPmax+1)..NumPeriodsLT;
range Period2 = (LTmax+LTPmax+2)..NumPeriodsLT;
range PeriodT = 1..NumPeriodsLT; //max. planned lead time

////Producer
//economic parameters
float setupC = ...;
float setupCC[Types] = ...;
float orderCC[RawMat] = ...;
float holdC[Types] = ...;
float holdPC[Types] = ...;
float prodC[Types] = ...;
float ftranC[RawMat] = ...;
float vtranC[RawMat] = ...;
float wasteC[Types]= ...;
//environmental parameters
float setupE = ...;
float setupEE[Types] = ...;
float SECp[Types] = ...;
float ESp[Types] = ...;
float ET[RawMat] = ...;
float vtranE[RawMat] = ...;

int minlot[Types] = ...;
{int} Max[Types] = ...;
{int} B = union (i in Types) Max[i];
{int} ShelfNoWT[Types] = ...;
int ShelfWT[Types] = ...;
int ShelfLifeNoWT[Types] = ...;
{int} X[Retailer][Types] = ...;
{int} A = union (r in Retailer, i in Types) X[r][i];
int demand[Retailer][Types][Periods] = ...;
int SLevel[Types][B][Periods] = ...;
{int} Max2[Types] = ...;
{int} C = union (i in Types) ShelfNoWT[i];

dvar int+ demandR[Retailer][Types][A][Periods]; //demand fulfilled with particular stock age
```

```
dvar int+ Inv[Types][B][0..NumPeriodsLT]; //inventory level I
dvar int+ UpLevel[Types][Periods]; //order-up-to level S
dvar int+ OrderQ[Types][Periods]; //production quantity Q
dvar boolean productOrder[Periods]; //major setup
dvar boolean AnOrder[Types][Periods]; //minor setup
dvar boolean matOrder[RawMat][Periods]; //raw mat order
dvar boolean OPeriod[Types][Periods][B]; //previous recent order
--------------------------------------------------------------------------------
//FIFO
dvar int+ Aux[Types][C][Periods];
dvar boolean BAux[Types][C][Periods];
//LIFO
dvar int+ Aux[Types][B][Periods];
dvar boolean BAux[Types][C][Periods];
--------------------------------------------------------------------------------
dvar int+ Mdemand[RawMat][Periods]; //raw material quantity require for production
dvar float+ PlanP[Types][Periods]; //order quantity = production quantity Q + production waste
dvar int+ Qwaste[Types][Periods]; //integer quantity of production waste
dvar float+ QPwaste[Types][Periods];_//production waste
dvar float Scost;//setup cost
dvar float Ocost;//order cost
dvar float Wcost;//waste cost
dvar float Icost;//inventory level based holding cost
dvar float IPcost;//inventory position based holding cost
dvar float Pcost;//production cost
dvar float Tcost;//transport cost
dvar float Semiss;//setup emission
dvar float Pemiss;//production emission
dvar float Iemiss;//inventory holding emission
dvar float Temiss;//transport emission
dvar int Tinv;//total inventory in the system
--------------------------------------------------------------------------------
//LC
dvar float emission;//quantity of emission
dvar int waste;//quantity of waste
//LE
dvar int waste;//quantity of waste
--------------------------------------------------------------------------------
////Suppliers
//economic parameters
float prodMC[RawMat] = ...;
float orderMCC[RawMat] = ...;
float holdMC[RawMat] = ...;
float holdPMC[RawMat] = ...;
float ftranMC[RawMat] = ...;
float vtranMC[RawMat] = ...;
float wasteMC[RawMat] = ...;

//environmental parameters
float SECm[RawMat] = ...;
float ESm[RawMat] = ...;
float ETm[RawMat] = ...;
float vtranME[RawMat] = ...;
{int} MaxM[RawMat] = ...;
{int} CC = union (a in RawMat) MaxM[a];
{int} ShelfMNoWT[RawMat] = ...;
int ShelfMWT[RawMat] = ...;
int minlotM[RawMat] = ...;

dvar int+ Mdemand2[RawMat][PeriodT];//material demand
dvar int+ InvM[RawMat][CC][0..NumPeriodsLT];//material inventory level
dvar int+ UpLevelM[RawMat][PeriodT];//material order-up-to level
dvar int+ OrderMQ[RawMat][PeriodT];//material order quantity
dvar int+ time[PeriodT];//for excel output when required
dvar boolean rawmatOrder[RawMat][PeriodT];//material order
dvar boolean OPeriodM[RawMat][Periods][CC];//previous recent material order
dvar float OMcost;//material order cost
dvar float MWcost;//material waste cost
dvar float MIcost;//material inventory level based holding cost
```

```
dvar float MIPcost;//material inventory position based holding cost
dvar float MPcost;//material procurement cost
dvar float MTcost;//material transport cost
dvar float OMemiss;//ordering emission
dvar float MIemiss;//inventory holding emission
dvar float MTemiss;//transport emission
dvar int TinvM;//total material inventory in the system
-------------------------------------------------------------------------------
//LC
dvar float TotalEmiss;
dvar float TotalWaste;
dvar float Memission;//quantity of emission
dvar int Mwaste;//quantity of material waste
//LE
dvar float TotalWaste;
dvar int Mwaste;//quantity of material waste
-------------------------------------------------------------------------------
////Suppliers
dexpr float OrderMCost = sum(t in PeriodT)(sum(a in RawMat)(orderMCC[a]*rawmatOrder[a][t]));
dexpr float MWasteCost = sum(t in PeriodT)(sum(a in RawMat)(InvM[a][ShelfMWT[a]][t]*wasteMC[a]));
dexpr float MInvCost = sum(t in PeriodT)(sum(a in RawMat)(sum(c in
ShelfMNoWT[a])(holdMC[a]*InvM[a][c][t])));
dexpr float MInvPCost = sum(t in PeriodT)(sum(a in RawMat)(holdPMC[a]*(UpLevelM[a][t]-
Mdemand2[a][t])));
dexpr float MProdCost = sum(t in PeriodT)(sum(a in RawMat)(prodMC[a]*OrderMQ[a][t]));
dexpr float MTranCost = sum(t in PeriodT)(sum(a in
RawMat)(ftranMC[a]*rawmatOrder[a][t]+OrderMQ[a][t]*vtranMC[a]));
dexpr float TotalCost2 = OrderMCost + MWasteCost + MInvCost + MInvPCost + MProdCost + MTranCost;

////Producer
dexpr float SetupCost = sum(t in Periods)((setupC*productOrder[t])+(sum(i in
Types)(setupCC[i]*AnOrder[i][t])));
dexpr float OrderCost = sum(t in Periods)(sum(a in RawMat)(orderCC[a]*matOrder[a][t]));
dexpr float WasteCost = sum(t in Periods)(sum(i in Types)(Inv[i][ShelfWT[i]][t]*wasteC[i]));
dexpr float InvCost = sum(t in Periods)(sum(i in Types)(sum(b in ShelfNoWT[i])(holdC[i]*Inv[i][b][t])));
dexpr float InvPCost = sum(t in Periods)(sum(i in Types)(holdPC[i]*(UpLevel[i][t]-(sum(r in
Retailer)demand[r][i][t]))));
dexpr float ProdCost = sum(t in Periods)(sum(i in Types)(PlanP[i][t]*prodC[i]));//include cost in processing
production waste
dexpr float TransCost = sum(t in Periods)(sum(a in
RawMat)((ftranC[a]*matOrder[a][t])+(Mdemand[a][t]*vtranC[a])));
dexpr float TotalCost1 = SetupCost + OrderCost + WasteCost + InvCost + InvPCost + ProdCost +
TransCost;
dexpr float TotalCost = TotalCost1 + TotalCost2;
-------------------------------------------------------------------------------
//LC
minimize TotalCost;
//LE
dexpr float emission = sum(t in Periods)(sum(i in Types)(sum(b in
Max[i])(Inv[i][b][t]*ESp[i])+(OrderQ[i][t]*SECp[i]))) + sum(t in Periods)((setupE*productOrder[t])+(sum(i in
Types)(setupEE[i]*AnOrder[i][t])))+ sum(t in Periods)(sum(a in
RawMat)(matOrder[a][t]*ET[a]+(Mdemand[a][t]*vtranE[a])));
dexpr float Memission = sum(t in PeriodT)(sum(a in RawMat)(sum(c in
MaxM[a])(InvM[a][c][t]*ESm[a])+(OrderMQ[a][t]*SECm[a])+(rawmatOrder[a][t]*ETm[a])+(OrderMQ[a][t]*vtra
nME[a])));
dexpr float TotalEmiss= emission + Memission;
minimize TotalEmiss;
// LW
dexpr float emission = sum(t in Periods)(sum(i in Types)(sum(b in
Max[i])(Inv[i][b][t]*ESp[i])+(OrderQ[i][t]*SECp[i]))) + sum(t in Periods)((setupE*productOrder[t])+(sum(i in
Types)(setupEE[i]*AnOrder[i][t])))+ sum(t in Periods)(sum(a in
RawMat)(matOrder[a][t]*ET[a]+(Mdemand[a][t]*vtranE[a])));
dexpr float Memission = sum(t in PeriodT)(sum(a in RawMat)(sum(c in
MaxM[a])(InvM[a][c][t]*ESm[a])+(OrderMQ[a][t]*SECm[a])+(rawmatOrder[a][t]*ETm[a])+(OrderMQ[a][t]*vtra
nME[a])));
dexpr float TotalEmiss= emission + Memission;
dexpr int waste = sum(t in Periods)(sum(i in Types)(Inv[i][ShelfWT[i]][t]));
dexpr int Mwaste = sum(t in PeriodT)(sum(a in RawMat)(InvM[a][ShelfMWT[a]][t]));
dexpr float TotalWaste= waste + Mwaste;
```

```
minimize TotalWaste;
// Weighted goal programming method
float Givcost = 35983.7;
float weightC = 1;
float normC = 42621.5;
float Givemiss = 44180.6;
float weightE = 0;
float normE = 53412.83;
float Givwaste = 0;
float weightW = 0;
float normW = 389;
dexpr float Cgap = abs(TotalCost-Givcost);
dexpr float Wgap = abs(TotalWaste-Givwaste);
dexpr float Egap = abs(TotalEmiss-Givemiss);
dexpr float Sustain = weightC*(Cgap/normC) + weightE*(Egap/normE) + weightW*(Wgap/normW);
minimize Sustain;
----------------------------------------------------------------------------
subject to {

//2nd model: Suppliers
        //demand
        forall (t in Periods, i in Types)
          ctProdwaste:
          if (pwaste == 0) {
          PlanP[i][t] == OrderQ[i][t];
        } else {
          QPwaste[i][t] == pwaste*OrderQ[i][t];
          Qwaste[i][t]>=QPwaste[i][t];
          QPwaste[i][t]>=Qwaste[i][t]-1+0.00001;
          PlanP[i][t] == OrderQ[i][t]+Qwaste[i][t];}        //product order quantity calculation
        //material demand from producer
        forall (t in Periods, a in RawMat){
          Mdemand2[a][t] == sum(i in Types)(PlanP[i][t]*Usage[a][i]);}

        //material inventory balance
        forall (t in Periods, a in RawMat)
          ctDemandM1:
            if (t == 1+LTmax){
              OrderMQ[a][t-LTM[a]] == UpLevelM[a][t-LTM[a]];
        } else if (1+LTmax<t<1+LTmax+LTM[a]) {
            UpLevelM[a][t-1-LTM[a]]  + OrderMQ[a][t-LTM[a]] == UpLevelM[a][t-LTM[a]] ;
        } //material inventory balance for first LTmax+LTM[a] periods
        forall (t in Periods, a in RawMat)
          ctDemandM2:
            sum(c in MaxM[a])InvM[a][c][t] + sum (n in (t-LTM[a]+1)..t) OrderMQ[a][n] == UpLevelM[a][t] -
Mdemand2[a][t];

        //ordering cost
        forall (t in Periods, a in RawMat)
          ctOrderexistM1:
                  if (t > NumPeriodsLT-LTM[a]){
            OrderMQ[a][t] <= (M * rawmatOrder[a][t]);
            OrderMQ[a][t] >= rawmatOrder[a][t];}
        forall (t in Periods, a in RawMat)
          ctOrderexistM2:{
            OrderMQ[a][t-LTM[a]] <= (M * rawmatOrder[a][t-LTM[a]]);
            OrderMQ[a][t-LTM[a]] >= rawmatOrder[a][t-LTM[a]];}

        //minimum material quantity to be ordered
        forall (t in Periods, a in RawMat)
          ctminlotM1:
            if (t > NumPeriodsLT-LTM[a]){
                  OrderMQ[a][t] >= minlotM[a]*rawmatOrder[a][t];}
        forall (t in Periods, a in RawMat)
          ctminlotM2:
                  OrderMQ[a][t-LTM[a]] >= minlotM[a]*rawmatOrder[a][t-LTM[a]];

        //order-up-to level material
        forall (t in Periods, a in RawMat)
```

```
         ctPriorOrderM:
          sum(j in CC) (OPeriodM[a][t][j]) == 1;
        forall (t in Periods, a in RawMat)
               ctPOrderexist1:
                forall (j in CC)
                if ( t >= j+LTM[a] ){
               OPeriodM[a][t][j] >= rawmatOrder[a][t-j+1-LTM[a]] - sum (n in (t-j+2-LTM[a])..(t-
LTM[a]))(rawmatOrder[a][n]);
                } else {
                 OPeriodM[a][t][j] == 0;   }
        forall (t in Periods, j in CC, a in RawMat)
         ctPOrderzero1:
          if (j == 1){
          Mdemand2[a][t] >= OPeriodM[a][t][j];}

        //No predetermined issuing policy
        forall (t in Periods, a in RawMat)
         ctNewInv1:
          OrderMQ[a][t-LTM[a]] >= InvM[a][1][t];
        forall (t in Periods,a in RawMat)
         ctInventory1:
               forall (c in ShelfMNoWT[a])
          InvM[a][c][t-1] >= InvM[a][c+1][t];
        forall (t in Periods, a in RawMat)
         ctInvBalance1:
          (sum(c in ShelfMNoWT[a]) InvM[a][c][t-1]) - Mdemand2[a][t] + OrderMQ[a][t-LTM[a]] == (sum(c
in MaxM[a]) InvM[a][c][t]);

        //quantity of waste & emission
        Mwaste == sum(t in PeriodT)(sum(a in RawMat)(InvM[a][ShelfMWT[a]][t]));
        Memission == sum(t in PeriodT)(sum(a in RawMat)(sum(c in
MaxM[a])(InvM[a][c][t]*ESm[a])+(OrderMQ[a][t]*SECm[a])+(rawmatOrder[a][t]*ETm[a])+(OrderMQ[a][t]*vtra
nME[a])));

        //auxiliary constraints to make model works
        OMcost == OrderMCost;
        MWcost == MWasteCost;
        MIcost == MInvCost;
        MIPcost == MInvPCost;
        MPcost == MProdCost;
        MTcost == MTranCost;
        OMemiss == sum(t in PeriodT)(sum(a in RawMat)(OrderMQ[a][t]*SECm[a]));
        MIemiss == sum(t in PeriodT)(sum(a in RawMat)(sum(c in MaxM[a])(InvM[a][c][t]*ESm[a])));
        MTemiss == sum(t in PeriodT)(sum(a in
RawMat)((rawmatOrder[a][t]*ETm[a])+(OrderMQ[a][t]*vtranME[a])));
        TinvM == sum(t in PeriodT)(sum(a in RawMat)(sum(c in ShelfMNoWT[a])(InvM[a][c][t])));
        sum (a in RawMat) sum( c in CC) InvM[a][c][0] == 0;
        sum (a in RawMat) sum( c in CC) InvM[a][c][NumPeriodsLT] == 0;
        forall (t in PeriodT)
         cttime:
          time[t] == t;
//   forall (t in Periods, j in CC, a in RawMat)
//       ctPOrderzero:
//        if (j > ShelfMWT[a]){
//        OPeriodM[a][t][j] == 0;}
        forall (t in PeriodT)
         ctInitialInv1:
               if (t < 1+LTmax){
               sum (a in RawMat) Mdemand2[a][t]==0;
               sum (a in RawMat) sum( c in CC) InvM[a][c][t] == 0;}
        forall (t in PeriodT, a in RawMat, c in CC)
         ctdefinition11:
          InvM[a][c][t] >= 0;
        forall (t in PeriodT, a in RawMat)
         ctdefinition21:{
          UpLevelM[a][t] >= 0;
          OrderMQ[a][t] >= 0;
         }
        forall (t in PeriodT, a in RawMat)
```

```
        ctdefinition31:
              if(t > NumPeriodsLT-LTM[a]){
         OrderMQ[a][t] == 0;  }

//1st model: Producer
       //demand
       forall (t in Periods, r in Retailer, i in Types)
        demand[r][i][t] == sum(a in X[r][i])demandR[r][i][a][t];
       forall (t in Periods, i in Types)
        ctsellft:
         if (LT[i]+1+LTmax<=t){
          if (t <= NumPeriodsLT-LT[i]){
         OrderQ[i][t] - sum(r in Retailer)demandR[r][i][0][t+LT[i]] == Inv[i][1][t+LT[i]];}}
       forall (t in Periods, i in Types)
        ctsellshelf:
         forall (b in ShelfNoWT[i])
         Inv[i][b][t-1] - sum(r in Retailer)demandR[r][i][b][t] == Inv[i][b+1][t]; //retailer shelf life requirement
satisfaction
       forall (t in Periods, a in RawMat){
        Mdemand[a][t] == sum(i in Types)(PlanP[i][t]*Usage[a][i]);}

       //inventory balance
       forall (t in Periods, i in Types)
        ctDemand1:
         if (t == 1+LTmax){
          OrderQ[i][t] == UpLevel[i][t];
  } else if (1+LTmax<t<=LT[i]+1+LTmax) {
         UpLevel[i][t-1] - (sum(r in Retailer)demand[r][i][t-1]) + OrderQ[i][t] == UpLevel[i][t] ;
  } //inventory balance for first LT[i]+1+LTmax periods
       forall (t in Period1, i in Types)
        ctDemand2:
         sum(b in Max[i])Inv[i][b][t] + sum (n in (t-LT[i]+1)..t) OrderQ[i][n] == UpLevel[i][t] - (sum(r in
Retailer)demand[r][i][t]);

       //setup cost
       forall (t in Periods, i in Types)
        ctOrderexist:
         OrderQ[i][t] <= (M * AnOrder[i][t]);
       forall (t in Periods, i in Types)
        ctOrderexist1:
         OrderQ[i][t] >= AnOrder[i][t];
              forall (t in Periods)
        ctMultiPexist:{
         sum (i in Types)(AnOrder[i][t]) <= M * productOrder[t];
              sum (i in Types)(AnOrder[i][t]) >= productOrder[t];}

       //major & minor ordering cost
       forall (t in Periods, i in Types, a in RawMat)
        ctMatorderC:{
         M * matOrder[a][t]  >= AnOrder[i][t];
         Usage[a][i] *  AnOrder[i][t] >= matOrder[a][t];}

       //minimum quantity to be produced
       forall (t in Periods, i in Types)
        ctminlot:
              OrderQ[i][t] >= minlot[i]*AnOrder[i][t];

       //order-up-to level product (+safety stock)
       forall (t in Periods, i in Types)
        ctSafetyStock1:
       forall (j in 1..(t-LTmax-LT[i]))
       if (t < (ShelfWT[i]+LT[i]+LTmax)){
       UpLevel[i][t-j+1-LT[i]] >= ((sum(n in (t-j+1-LT[i])..t)(sum(r in Retailer)(demand[r][i][n]))) +
SLevel[i][j][t])*OPeriod[i][t][j];}
       forall (t in Periods, i in Types)
        ctSafetyStock2:
         forall (j in Max[i])
         if ( t >= (ShelfWT[i]+LT[i]+LTmax)){
```

```
         UpLevel[i][t-j+1-LT[i]] >= ((sum(n in (t-j+1-LT[i])..t)(sum(r in Retailer)(demand[r][i][n])))+
SLevel[i][j][t])*OPeriod[i][t][j];}
       forall (t in Periods, i in Types)
        ctSafetyStock3:
         sum(b in Max[i])Inv[i][b][t] >= sum( j in Max[i])(SLevel[i][j][t]*OPeriod[i][t][j]);
       forall (i in Types)
        ctPriorOrder:
        forall (t in (1+LT[i]+LTmax)..NumPeriodsLT)
         sum(j in B) (OPeriod[i][t][j]) == 1;
       forall (t in Periods, i in Types)
              ctPOrderexist:
               forall (j in B)
               if ( t >= j+LT[i]+LTmax ){
              OPeriod[i][t][j] >= AnOrder[i][t-j+1-LT[i]] - sum (n in (t-j+2-LT[i])..(t-LT[i]))(AnOrder[i][n]);
               } else {
                OPeriod[i][t][j] == 0;   }
-----------------------------------------------------------------------------
//No issuing policy
       forall (t in Periods, i in Types)
        ctNewInv:
         if (t <= NumPeriodsLT-LT[i]){
         OrderQ[i][t] >= Inv[i][1][t+LT[i]];}
       forall (t in Periods,i in Types)
        ctInventory:
         forall (b in ShelfNoWT[i])
         if (t <= LT[i]+LTmax){
          Inv[i][b][t] == 0;
   } else {
         Inv[i][b][t-1] >= Inv[i][b+1][t];
   }
       forall (t in Period2, i in Types)
        ctInvBalance:
         (sum(b in ShelfNoWT[i]) Inv[i][b][t-1]) - (sum(r in Retailer)demand[r][i][t]) + OrderQ[i][t-LT[i]] ==
(sum(b in Max[i]) Inv[i][b][t]);
//FIFO issuing policy
       forall (t in Periods, i in Types)
        ctFIFO1:
         Inv[i][ShelfLifeNoWT[i]][t-1] - (sum(r in Retailer)demand[r][i][t]) == Inv[i][ShelfWT[i]][t] -
Aux[i][ShelfLifeNoWT[i]][t];
       forall (t in Periods, i in Types)
        ctFIFO2:
         forall (b in Max2[i])
         Inv[i][b][t-1] - Aux[i][b+1][t] == Inv[i][b+1][t] - Aux[i][b][t];
       forall (t in Period2, i in Types)
        ctFIFO3:
         OrderQ[i][t-LT[i]] - Aux[i][1][t] == Inv[i][1][t];
       forall (t in Periods, i in Types)
        ctFIFO4:{
         forall (b in ShelfNoWT[i]) {
       M *  BAux[i][b][t] >= Aux[i][b][t];
         M * (1 - BAux[i][b][t]) >= Inv[i][b+1][t];}
              }
       forall (t in Periods, i in Types, c in C)
        ctnotusex:
              if (c > ShelfLifeNoWT[i]){
              BAux[i][c][t] == 0;
              Aux[i][c][t] == 0;}
//LIFO issuing policy
       forall (t in Period2, i in Types)
        ctLIFO1:
         OrderQ[i][t-LT[i]] - (sum(r in Retailer)demand[r][i][t]) == Inv[i][1][t] - Aux[i][2][t];
       forall (t in Period1, i in Types)
        ctLIFO2:
         forall (b in Max2[i])
         Inv[i][b][t-1] - Aux[i][b+1][t] == Inv[i][b+1][t] - Aux[i][b+2][t];
       forall (t in Period1, i in Types)
        ctLIFO3:
         Inv[i][ShelfLifeNoWT[i]][t-1] - Aux[i][ShelfWT[i]][t] == Inv[i][ShelfWT[i]][t];
       forall (t in Period1, i in Types)
```

```
              ctLIFO4:{
                forall (b in ShelfNoWT[i]) {
                (M * BAux[i][b][t]) >= Aux[i][b+1][t];
                (M * (1-BAux[i][b][t])) >= Inv[i][b][t];}
            }
            forall (t in Period1, i in Types)
              ctLIFO5:
              forall (b in ShelfNoWT[i]) {
                BAux[i][b][t] <= (Aux[i][b+1][t] + Inv[i][b][t]);}
            forall (t in Periods, i in Types, c in C)
              ctnotuseBx:
                        if (c > ShelfLifeNoWT[i]){
                        BAux[i][c][t] == 0;}
            forall (t in Periods, i in Types, c in C)
              ctnotuseBx2:{
                        BAux[i][c][1+LTmax] == 0;
                        BAux[i][c][2+LTmax] == 0;}
            forall (t in Periods, i in Types, b in B)
              ctnotusex:
                        if (b > ShelfWT[i]){
                        Aux[i][b][t] == 0;}
            forall (t in Periods, i in Types, b in B)
              ctnotusex2:
                        if (b == ShelfWT[i]){
                        Aux[i][b][1+LTmax] == 0;
                        Aux[i][b][2+LTmax] == 0;}
--------------------------------------------------------------------------------
            //quantity of waste & emission
            waste == sum(t in Periods)(sum(i in Types)(Inv[i][ShelfWT[i]][t]));
            emission == sum(t in Periods)(sum(i in Types)(sum(b in
Max[i])(Inv[i][b][t]*ESp[i])+(OrderQ[i][t]*SECp[i]))) + sum(t in Periods)((setupE*productOrder[t])+(sum(i in
Types)(setupEE[i]*AnOrder[i][t])))+ sum(t in Periods)(sum(a in
RawMat)(matOrder[a][t]*ET[a]+(Mdemand[a][t]*vtranE[a])));
            TotalWaste == waste + Mwaste;
            TotalEmiss == emission + Memission;

            //auxiliary contraints to make model work
            Scost == SetupCost;
            Ocost == OrderCost;
            Wcost == WasteCost;
            Icost == InvCost;
            IPcost == InvPCost;
            Tcost == TransCost;
            Pcost == ProdCost;
            Semiss == sum(t in Periods)sum(i in Types)((setupE*productOrder[t])+(setupEE[i]*AnOrder[i][t]));
            Pemiss == sum(t in Periods)sum(i in Types)(OrderQ[i][t]*SECp[i]);
            Iemiss == sum(t in Periods)sum(i in Types)sum(b in Max[i])(Inv[i][b][t]*ESp[i]);
            Temiss == sum(t in Periods)(sum(a in
RawMat)(matOrder[a][t]*ET[a]+(Mdemand[a][t]*vtranE[a])));;
            Tinv == sum(t in Periods)(sum(i in Types)(sum(b in ShelfNoWT[i])(Inv[i][b][t])));
            sum (i in Types) sum( b in B) Inv[i][b][0] == 0;
//          forall (t in Periods, i in Types, b in B)
//            ctnotusez:
//                      if (b > ShelfWT[i]){
//                      OPeriod[i][t][b] == 0;}
            forall (t in PeriodT, i in Types)
              ctInitialInv:
                        if (t < 1+LTmax+LT[i]){
                        sum( b in B) Inv[i][b][t] == 0;}
            forall (t in Periods, i in Types, b in B)
              ctdefinition1:
                Inv[i][b][t] >= 0;
            forall (t in Periods, r in Retailer, i in Types,a in A)
              ctdefinition3:
                demandR[r][i][a][t] >= 0;
            forall (t in Periods, i in Types)
              ctdefinition4:{
                UpLevel[i][t] >= 0;
                OrderQ[i][t] >= 0;
```

```
            }
            forall (t in Periods, i in Types)
              ctNewInv2:
                if (t > NumPeriodsLT-LT[i]){
                OrderQ[i][t] == 0;}
-------------------------------------------------------------------------------
//FIFO&LIFO
forall (t in Periods,i in Types)
              ctdefinition5:
                forall (b in ShelfNoWT[i])
                Aux[i][b][t] >= 0;
-------------------------------------------------------------------------------
-------------------------------------------------------------------------------
//the ε-constraint method
            emission + Memission <= 44246.8;
            waste + Mwaste <= 0;
-------------------------------------------------------------------------------
}

//scripting log
execute{
-------------------------------------------------------------------------------
//Weighted goal programming method
writeln("TotalSustain:", cplex.getobjvalue());
-------------------------------------------------------------------------------
  writeln("TotalCost:", TotalCost.solutionValue);
  writeln("TotalEmiss:",TotalEmiss.solutionValue);
  writeln("TotalWaste:",TotalWaste.solutionValue);
  writeln("-----------------------------------");
  writeln("Production Plan");
  for (var i in Types){
  writeln("Product",i, thisOplModel.OrderQ[i]);}
  writeln("SetupC1:",Scost.solutionValue);
  writeln("OrderC1:",Ocost.solutionValue);
  writeln("WasteC1:",Wcost.solutionValue);
  writeln("HoldC1:",Icost.solutionValue);
  writeln("HoldPC1:",IPcost.solutionValue);
  writeln("ProdC1:",Pcost.solutionValue);
  writeln("TranC1:",Tcost.solutionValue);
  writeln("TotalCost1:",TotalCost1.solutionValue);
  writeln("TotalWaste1:",waste.solutionValue);
  writeln("TotalEmission1:",emission.solutionValue);
  writeln("SetupE1:",Semiss.solutionValue);
  writeln("ProdE1:",Pemiss.solutionValue);
  writeln("HoldE1:",Iemiss.solutionValue);
  writeln("TranE1:",Temiss.solutionValue);
  writeln("TotalInv1:",Tinv.solutionValue);
  writeln("-----------------------------------");
  writeln("Raw Material Plan");
  for (var a in RawMat){
  writeln("RawMat", a , OrderMQ[a]);}
  writeln("OrderC2:",OMcost.solutionValue);
  writeln("ProdMC2:",MPcost.solutionValue);
  writeln("WasteC2:",MWcost.solutionValue);
  writeln("HoldC2:",MIcost.solutionValue);
  writeln("HoldPC2:",MIPcost.solutionValue);
  writeln("Delivery2:",MTcost.solutionValue);
  writeln("TotalCost2:",TotalCost2.solutionValue);
  writeln("Expired Waste:", Mwaste.solutionValue);
  writeln("TotalEmission2:", Memission.solutionValue);
  writeln("OrderE2:",OMemiss.solutionValue);
  writeln("HoldE2:",MIemiss.solutionValue);
  writeln("TranE2:",MTemiss.solutionValue);
  writeln("TotalInv2:",TinvM.solutionValue);
}
```

Coding in data file (cent1.dat)

```
Customer = 1; //# of retailers
```

```
////Producer
setupC = 0; //major setup cost
setupCC = [1500]; //minor setup cost
orderCC = [0 0 0 0 0]; //ordering or receiving cost
holdC = [0.5]; //inventory level holding cost
holdPC = [0]; //inventory position holding cost
prodC = [2]; //production cost
ftranC = [0 0 0 0 0]; //fix delivery cost
vtranC= [0 0 0 0 0]; //variable delivery cost
wasteC = [0]; //waste disposal cost
setupE = 0;//major setup emission
setupEE = [2000]; //minor setup emission
SECp = [1]; //production emission
ESp = [4]; //inventory level holding emission
ET = [0 0 0 0 0];//fix delivery emission (vary with supplier distance)
vtranE = [0 0 0 0 0];//variable delivery emission
minlot = [0]; //minimum to schedule/produce
Max = [{1,2,3}]; //maximum internal shelf life
ShelfNoWT = [{1,2}]; //product ages without waste
ShelfWT = [3]; //product age at the end of period considered as waste
ShelfLifeNoWT = [2];
X = [[{0,1,2}]];//shelf life requirements for each retailer..can't use waste from last period
demand = [[[800 950 200 900 800 150 650 800 900 300 150 600]]];
//Safety stock for product i = sum(retailers)safety stock i
SLevel = [[[ 0,409,319,303,396,268,219,339,396,312,110,203]
             [ 0,0,414,436,402,399,343,343,450,408,316,226]
             [ 0,0,0,509,509,405,453,432,453,461,411,373]]]; //lead time = 1 erratic
Max2 = [{1}]; //maximum internal shelf life - 2 //FIFO&LIFO

////Suppliers
prodMC = [0.05,0.05,0.05,0.01,0.02];//procurement cost
orderMCC = [300 300 300 300 300]; // ordering cost
holdMC = [0.005,0.005,0.005,0.001,0.002]; //inventory level based holding cost
holdPMC = [0,0,0,0,0]; //inventory position based holding cost
ftranMC = [0 0 0 0 0]; //fix delivery cost
vtranMC = [0 0 0 0 0]; //variable delivery cost
wasteMC = [0 0 0 0 0]; //waste disposal cost
SECm = [0 0 0 0 0];//ordering or receiving emission
ESm = [0.01,0.01,0.01,0.008,0.01];//inventory level holding emission
ETm = [100 100 100 400 250];//fix delivery emission (vary with external supplier distance)
vtranME = [0 0 0 0 0];//variable delivery emission
MaxM = [{1,2},{1,2,3,4},{1,2,3},{1,2,3,4},{1,2,3,4,5}]; //max possible shelf life ranges
ShelfMNoWT = [{1},{1,2,3},{1,2},{1,2,3},{1,2,3,4}]; //possible shelf life ranges without waste
ShelfMWT = [2,4,3,4,5]; //max shelf life
minlotM = [0 0 0 0 0]; //minimum quantity to be scheduled/produced
```

Example problem 2: Decentralised Model in CPLEX

Coding in common file (common_d1.mod)

```
int Product = 1; // # of consumer products
range Types = 1..Product;
int Material = 5; //# of raw materials
range RawMat = 1..Material;
int LT[Types] = [1];//production lead time
int LTPmax = max(i in 1..Product) LT[i];//max production lead time
int LTM[RawMat] = [0,0,0,0,0];//transport lead time
int LTmax = max(a in 1..Material) LTM[a];//max planned transport lead time
int NumPeriodsLT = 12; // total planning horizon (+LTmax)
range Periods = (1+LTmax)..NumPeriodsLT; //demand period
range Period1 = (LTmax+LTPmax+1)..NumPeriodsLT;
range Period2 = (LTmax+LTPmax+2)..NumPeriodsLT;
range PeriodT = 1..NumPeriodsLT; //maximum planned lead time
int Usage[RawMat][Types] = [[1],[5],[5],[3],[1]]; //Bill of Material (rawMats, Products)
float pwaste = 0;//production waste as a percentage of production quantity e.g. 0.1
```

Coding in Cplex-Flow control file (MTS_combine_d1.mod)

```
include "common_d1.mod";
```

```
int Produce[Types][(1+LTmax)..NumPeriodsLT];
main
{
        var planP = new IloOplRunConfiguration("producer_d1.mod","producer_d1.dat");
        planP.cplex = cplex;
        planP.oplModel.generate();
        if (planP.cplex.solve()){
                planP.oplModel.postProcess();
                for (var i in thisOplModel.Types){
          for (var t in thisOplModel.Periods){
                thisOplModel.Produce[i][t] = planP.oplModel.OrderQ[i][t];}}}

                var f = new IloOplOutputFile();
                f.open("Production_d1.dat");
                f.writeln("Produce=");
                f.writeln(thisOplModel.Produce);
                f.writeln(";");
                f.close();
        planP.end();

        var planR = new IloOplRunConfiguration("supplier_d1.mod","supplier_d1.dat","Production_d1.dat");
        planR.cplex = cplex;
        planR.oplModel.generate();
        if (planR.cplex.solve()){
          writeln("obj is " + planR.cplex.getObjValue());
                planR.oplModel.postProcess();
        }
        planR.end();
```

Coding in producer model file (producer_d1.mod): extra

```
include "common_d1.mod";
execute{
  writeln("Decentralised Control");
}
subject to {
        //demand
        forall (t in Periods, i in Types)
          ctProdwaste:
          if (pwaste == 0) {
          PlanP[i][t] == OrderQ[i][t];
          } else {
          QPwaste[i][t] == pwaste*OrderQ[i][t];
          Qwaste[i][t]>=QPwaste[i][t];
          QPwaste[i][t]>=Qwaste[i][t]-1+0.000001;
          PlanP[i][t] == OrderQ[i][t]+Qwaste[i][t];}          //product order quantity calculation
}
```

Coding in supplier model file (supplier_d1.mod): extra

```
include "common_d1.mod";
execute{
  writeln("Raw Material Ordering Plan");
}
//using values from previous model as inputs
dvar int+ OrderQ[Types][(1+LTmax)..NumPeriodsLT];
int Produce[Types][(1+LTmax)..NumPeriodsLT] = ...;
dvar float+ QPwaste[Types][1..NumPeriodsLT];//production waste
dvar float+ PlanP[Types][1..NumPeriodsLT];//order quantity = production quantity Q + production waste
subject to {
        //demand
        forall (t in Periods, i in Types)
          QPwaste[i][t] == ceil(pwaste*Produce[i][t]);
        forall (t in Periods, i in Types)
          PlanP[i][t] == Produce[i][t] + QPwaste[i][t];    //product order quantity calculation
}
```

Example problem 3: Suppliers Model in CPLEX

Coding in model file (calOrderQ.mod)

```
include "common_d1.mod";
execute{
  writeln("-----------------------------------");
  writeln("Raw Material Ordering Plan");
}

//using values from previous model as inputs
dvar int+ OrderQ[Types][(1+LTmax)..NumPeriodsLT];
int Produce[Types][(1+LTmax)..NumPeriodsLT] = ...;
int M = 999999; //large positive value

//economic parameters
float orderMCC[RawMat] = ...;
float prodMC[RawMat] = ...;
float holdMC[RawMat] = ...;
float ftranMC[RawMat] = ...;
float vtranMC[RawMat] = ...;
float wasteMC[RawMat] = ...;

//environmental parameters
float SECm[RawMat] = ...;
float ESm[RawMat] = ...;
float ETm[RawMat] = ...;
float vtranME[RawMat] = ...;

{int} MaxM[RawMat] = ...;
{int} CC = union (a in RawMat) MaxM[a];
{int} ShelfMNoWT[RawMat] = ...;
int ShelfMWT[RawMat] = ...;
int SLevel[RawMat][CC][Periods] = ...;

dvar float+ QPwaste[Types][1..NumPeriodsLT];//production waste
dvar int+ Mdemand2[RawMat][PeriodT];//material demand
dvar int+ InvM[RawMat][CC][0..NumPeriodsLT];//material inventory level
dvar int+ UpLevelM[RawMat][PeriodT];//material order-up-to level
dvar int+ OrderMQ[RawMat][PeriodT];//material order quantity
dvar int+ time[PeriodT];//for excel output when required

dvar boolean rawmatOrder[RawMat][PeriodT];//material order
dvar boolean OPeriodM[RawMat][Periods][CC];//previous recent material order

dvar float OMcost;//material order cost
dvar float MWcost;//material waste cost
dvar float MIcost;//material inventory level based holding cost
dvar float MIPcost;//material inventory position based holding cost
dvar float MPcost;//material procurement cost
dvar float MTcost;//material transport cost

dexpr float OrderCost = sum(t in PeriodT)(sum(a in RawMat)(orderMCC[a]*rawmatOrder[a][t]));
dexpr float MWasteCost = sum(t in PeriodT)(sum(a in RawMat)(InvM[a][ShelfMWT[a]][t]*wasteMC[a]));
dexpr float MInvCost = sum(t in PeriodT)(sum(a in RawMat)(sum(c in
ShelfMNoWT[a])(holdMC[a]*InvM[a][c][t])));
dexpr float MProdCost = sum(t in PeriodT)(sum(a in RawMat)(prodMC[a]*OrderMQ[a][t]));
dexpr float MTranCost = sum(t in PeriodT)(sum(a in
RawMat)(ftranMC[a]*rawmatOrder[a][t]+OrderMQ[a][t]*vtranMC[a]));
dexpr float TotalCost2 = OrderCost + MWasteCost + MInvCost + MProdCost + MTranCost;

dvar float Memission;//quantity of emission
//dexpr float Memission = sum(t in PeriodT)(sum(a in RawMat)(sum(c in
MaxM[a])(InvM[a][c][t]*ESm[a])+(OrderMQ[a][t]*SECm[a])+(rawmatOrder[a][t]*ETm[a])+(OrderMQ[a][t]*vtra
nME[a])));
//dvar int Mwaste;//quantity of material waste
dexpr float Mwaste = sum(t in PeriodT)(sum(a in RawMat)(InvM[a][ShelfMWT[a]][t]));

-------------------------------------------------------------------------------
//Weighted goal programming method
```

```
float Givcost = 11504.98;
float weightC = 0.7;
float normC = 17054.25;
float Givemiss = 4949.11;
float weightE = 0.3;
float normE = 8361.06;
float Givwaste = 226;
float weightW = 0;
float normW = 6051;
dexpr float Cgap = abs(TotalCost2-Givcost);
dexpr float Wgap = abs(Mwaste-Givwaste);
dexpr float Egap = abs(Memission-Givemiss);
dexpr float Sustain = weightC*(Cgap/normC) + weightE*(Egap/normE) +
weightW*(Wgap/normW);
minimize Sustain;
--------------------------------------------------------------------------------

minimize TotalCost2;
//minimize Memission;
//minimize Mwaste;

subject to {

        //demand
        forall (t in Periods, a in RawMat)
          Mdemand2[a][t] == sum(i in Types)(Produce[i][t]*Usage[a][i]);    //material demand from producer


        //material inventory balance
        forall (t in Periods, a in RawMat)
          ctDemand1:
            if (t == 1+LTmax){
              OrderMQ[a][t-LTM[a]] == UpLevelM[a][t-LTM[a]];
   } else if (1+LTmax<t<1+LTmax+LTM[a]) {
            UpLevelM[a][t-1-LTM[a]]  + OrderMQ[a][t-LTM[a]] == UpLevelM[a][t-LTM[a]] ;
   }
  forall (t in Periods, a in RawMat)
          ctDemand2:
            sum(c in MaxM[a])InvM[a][c][t] + sum (n in (t-LTM[a]+1)..t) OrderMQ[a][n] == UpLevelM[a][t] -
Mdemand2[a][t];

        //ordering cost
        forall (t in Periods, a in RawMat)
          ctOrderexistM1:
                  if (t > NumPeriodsLT-LTM[a]){
            OrderMQ[a][t] <= (M * rawmatOrder[a][t]);
            OrderMQ[a][t] >= rawmatOrder[a][t];}
        forall (t in Periods, a in RawMat)
          ctOrderexistM2:{
            OrderMQ[a][t-LTM[a]] <= (M * rawmatOrder[a][t-LTM[a]]);
            OrderMQ[a][t-LTM[a]] >= rawmatOrder[a][t-LTM[a]];}

        //order-up-to level material
        forall (t in Periods, a in RawMat)
          ctSafetyStock1:
        forall (j in 1..(t-LTmax))
        if (t < (ShelfMWT[a]+LTmax)){
        UpLevelM[a][t-j+1-LTM[a]] >= ((sum(n in (t-j+1-
LTM[a])..t)(Mdemand2[a][n]))+SLevel[a][j][t])*OPeriodM[a][t][j];}
        forall (t in Periods, a in RawMat)
          ctSafetyStock2:
            forall (j in MaxM[a])
            if ( t >= (ShelfMWT[a]+LTmax)){
            UpLevelM[a][t-j+1-LTM[a]] >= ((sum(n in (t-j+1-
LTM[a])..t)(Mdemand2[a][n]))+SLevel[a][j][t])*OPeriodM[a][t][j];}
        forall (t in Periods, a in RawMat)
          ctSafetyStock3:
            sum(b in MaxM[a])InvM[a][b][t] >= sum( j in MaxM[a])(SLevel[a][j][t]*OPeriodM[a][t][j]);
        forall (t in Periods, a in RawMat)
          ctPriorOrderM:
```

```
            sum(j in CC) (OPeriodM[a][t][j]) == 1;
          forall (t in Periods, a in RawMat)
                  ctPOrderexist1:
                    forall (j in CC)
                    if ( t >= j+LTM[a] ){
                  OPeriodM[a][t][j] >= rawmatOrder[a][t-j+1-LTM[a]] - sum (n in (t-j+2-LTM[a])..(t-
LTM[a]))(rawmatOrder[a][n]);
                    } else {
                      OPeriodM[a][t][j] == 0;
           }

          //No predetermined issuing policy
          forall (t in Periods, a in RawMat)
            ctNewInv1:
              OrderMQ[a][t-LTM[a]] >= InvM[a][1][t];
          forall (t in Periods,a in RawMat)
            ctInventory1:
                  forall (c in ShelfMNoWT[a])
              InvM[a][c][t-1] >= InvM[a][c+1][t];
          forall (t in Periods, a in RawMat)
            ctInvBalance1:
             (sum(c in ShelfMNoWT[a]) InvM[a][c][t-1]) - Mdemand2[a][t] + OrderMQ[a][t-LTM[a]] == (sum(c
in MaxM[a]) InvM[a][c][t]);

          //quantity of waste & emission
          Mwaste == sum(t in PeriodT)(sum(a in RawMat)(InvM[a][ShelfMWT[a]][t]));
//        Mwaste <= 8070;
          Memission == sum(t in PeriodT)(sum(a in RawMat)(sum(c in
MaxM[a])(InvM[a][c][t]*ESm[a])+(OrderMQ[a][t]*SECm[a])+(rawmatOrder[a][t]*ETm[a])+(OrderMQ[a][t]*vtra
nME[a])));
//        Memission <= 6200;

          //auxiliary contraints to make model work
          OMcost == OrderCost;
          MWcost == MWasteCost;
          MIcost == MInvCost;
          MPcost == MProdCost;
          MTcost == MTranCost;
//        sum (a in RawMat) sum( c in CC) InvM[a][c][NumPeriodsLT] == 0;
          forall (t in PeriodT)
            ctInitialInv1:
                  if (t < 1+LTmax){
                  sum (a in RawMat) Mdemand2[a][t]==0;
                  sum (a in RawMat) sum( c in CC) InvM[a][c][t] == 0;}
          forall (a in RawMat, c in CC)
            ctInitialInv2:
                  InvM[a][c][0] == 0;
          forall (t in PeriodT, a in RawMat, c in CC)
            ctdefinition11:
              InvM[a][c][t] >= 0;
          forall (t in PeriodT, a in RawMat)
            ctdefinition21:{
              UpLevelM[a][t] >= 0;
              OrderMQ[a][t] >= 0;
            }
          forall (t in PeriodT, a in RawMat)
            ctdefinition31:
                  if(t > NumPeriodsLT-LTM[a]){
              OrderMQ[a][t] == 0;
            }
}

execute{
  for (var a in RawMat){
  writeln("RawMat", a , OrderMQ[a]);}
  writeln("TotalEmission:" , cplex.getObjValue());
  writeln("OrderC2:",OMcost.solutionValue);
  writeln("ProdMC2:",MPcost.solutionValue);
  writeln("WasteC2:",MWcost.solutionValue);
```

```
  writeln("HoldC2:",MIcost.solutionValue)
  writeln("Delivery2:",MTcost.solutionValue);
  writeln("TotalCost2:",TotalCost2.solutionValue);
  writeln("Expired Waste:", Mwaste.solutionValue);
  writeln("TotalEmission2:", Memission.solutionValue); }
```

Coding in supplier data file (calOrderQ.dat)

```
prodMC = [0.05,0.05,0.05,0.01,0.02];//procurement cost
orderMCC = [300 300 300 300 300]; // ordering cost
holdMC = [0.005,0.005,0.005,0.001,0.002]; //inventory level based holding cost
ftranMC = [0 0 0 0 0]; //fix delivery cost
vtranMC = [0 0 0 0 0]; //variable delivery cost
wasteMC = [0 0 0 0 0]; //waste disposal cost
SECm = [0 0 0 0 0];//ordering or receiving emission
ESm = [0.01,0.01,0.01,0.008,0.01];//inventory level holding emission
ETm = [100 100 100 400 250];//fix delivery emission (vary with external supplier distance)
vtranME = [0 0 0 0 0];//variable delivery emission
MaxM = [{1,2},{1,2,3,4},{1,2,3},{1,2,3,4},{1,2,3,4,5}]; //max possible shelf life ranges
ShelfMNoWT = [{1},{1,2,3},{1,2},{1,2,3},{1,2,3,4}]; //possible shelf life ranges without waste
ShelfMWT = [2,4,3,4,5]; //max shelf life
Produce = [[800 950 200 900 800 150 650 800 900 300 150 600]];

SLevel = [                 [[263,313,66,296,263,49,214,263,296,99,49,197]
                           [ 0,409,319,303,396,268,219,339,396,312,110,203]
                           [ 0,0,0,0,0,0,0,0,0,0,0,0]
                           [ 0,0,0,0,0,0,0,0,0,0,0,0]
                           [ 0,0,0,0,0,0,0,0,0,0,0,0]]

                           [[1316,1563,329,1480,1316,247,1069,1316,1480,493,247,987]
                           [ 0,2043,1597,1517,1981,1339,1097,1696,1981,1560,552,1017]
                           [ 0,0,2069,2178,2008,1996,1713,1713,2251,2041,1580,1131]
                           [ 0,0,0,2544,2544,2023,2264,2160,2264,2304,2056,1863]
                           [ 0,0,0,0,0,0,0,0,0,0,0,0]]

                           [[1316,1563,329,1480,1316,247,1069,1316,1480,493,247,987]
                           [ 0,2043,1597,1517,1981,1339,1097,1696,1981,1560,552,1017]
                           [ 0,0,2069,2178,2008,1996,1713,1713,2251,2041,1580,1131]
                           [ 0,0,0,0,0,0,0,0,0,0,0,0]
                           [ 0,0,0,0,0,0,0,0,0,0,0,0]]

                           [[790,938,197,888,790,148,642,790,888,296,148,592]
                           [ 0,1226,958,910,1188,803,658,1017,1188,936,331,610]
                           [0,0,1242,1307,1205,1198,1028,1028,1351,1225,948,678]
                           [0,0,0,1527,1527,1214,1359,1296,1359,1383,1234,1118]
                           [ 0,0,0,0,0,0,0,0,0,0,0,0]]

                           [[263,313,66,296,263,49,214,263,296,99,49,197]
                           [ 0,409,319,303,396,268,219,339,396,312,110,203]
                           [ 0,0,414,436,402,399,343,343,450,408,316,226]
                           [ 0,0,0,509,509,405,453,432,453,461,411,373]
                           [ 0,0,0,0,573,511,458,524,524,464,464,456]]]; //lead time = 1 erratic
```

Example problem 3: SC Model in CPLEX

Coding in model file (MTO.mod)

```
execute{
  writeln("MTO");
}

int Product = 1; // # of consumer products
range Types = 1..Product;
int Material = 5; //# of raw materials
range RawMat = 1..Material;
int Customer = ...;
range Retailer = 1..Customer;
int M = 999999;//large positive value
int LT[Types] = [0];//production lead time
```

```
int LTPmax = max(i in 1..Product) LT[i];//max production lead time
int LTM[RawMat] = [0,0,0,0,0];//transport lead time
int LTmax = max(a in 1..Material) LTM[a];//max planned transport lead time
int NumPeriodsLT = 12; // total planning horizon (+LTmax)
range Periods = (1+LTmax)..NumPeriodsLT; //demand period
range Period1 = (LTmax+LTPmax+1)..NumPeriodsLT;
range Period2 = (LTmax+LTPmax+2)..NumPeriodsLT;
range PeriodT = 1..NumPeriodsLT; //maximum planned lead time
//Bill of Material (rawMats, Products)
int Usage[RawMat][Types] = [[1],[5],[5],[3],[1]]; ///

int demand[Retailer][Types][Periods] = ...;

//Producer
//economic parameters
float setupC = ...;
float setupCC[Types] = ...;
float orderCC[RawMat] = ...;
float ftranC[RawMat] = ...;
float vtranC[RawMat] = ...;
float price[Retailer][Types] = ...;
float fine[Retailer][Types] = ...;
//environmental parameters
float setupE = ...;
float setupEE[Types] = ...;
float SECp[Types] = ...;
float ET[RawMat] = ...;
float vtranE[RawMat] = ...;

dvar boolean productOrder[Periods];//major setup
dvar boolean AnOrder[Types][Periods];//minor setup
dvar boolean matOrder[RawMat][Periods];//raw mat order
dvar int+ X[Retailer][Types][Periods];
dvar int+ Y[Retailer][Types][Periods];
dvar int+ Z[Retailer][Types][Periods];
dvar int+ Mdemand[RawMat][Periods];//raw material quantity require for production //increased orderQ
dvar float+ PlanP[Types][Periods];//order quantity = production quantity Q + production waste
dvar float+ PlanO[Types][Periods];//order quantity = production quantity Q + production waste
dvar float Scost;//setup cost
dvar float Ocost;//order cost
dvar float Wcost;//waste cost
dvar float Tcost;//transport cost
dvar float Semiss;//setup emission
dvar float Pemiss;//production emission
dvar float Temiss;//transport emission
dvar float emission;//quantity of emission

////Suppliers
//economic parameters
float prodMC[RawMat] = ...;
float orderMCC[RawMat] = ...;
float holdMC[RawMat] = ...;
float ftranMC[RawMat] = ...;
float vtranMC[RawMat] = ...;
float wasteMC[RawMat] = ...;
//environmental parameters
float SECm[RawMat] = ...;
float ESm[RawMat] = ...;
float ETm[RawMat] = ...;
float vtranME[RawMat] = ...;

{int} MaxM[RawMat] = ...;
{int} CC = union (a in RawMat) MaxM[a];
{int} ShelfMNoWT[RawMat] = ...;
int ShelfMWT[RawMat] = ...;

int OrderMQ[RawMat][PeriodT] = ...;//material order quantity
dvar float+ Q[RawMat][0..NumPeriodsLT];
```

```
dvar int+ Mdemand2[RawMat][PeriodT];//material demand
dvar int+ InvM[RawMat][CC][0..NumPeriodsLT];//material inventory level
dvar int+ UpLevelM[RawMat][PeriodT];//material order-up-to level
dvar int+ FinalOrderMQ[RawMat][PeriodT];//material order quantity
dvar int+ IncOrderMQ[RawMat][PeriodT];//material order quantity

dvar boolean rawmatOrder[RawMat][PeriodT];//material order
dvar boolean rawmatOrderP[RawMat][PeriodT];//planned material order
dvar boolean rawmatOrderO[RawMat][PeriodT];//increased material order

dvar float OMcost;//material order cost
dvar float MWcost;//material waste cost
dvar float MIcost;//material inventory level based holding cost
dvar float MPcost;//material procurement cost for extra replenishment orders
dvar float MTcost;//material transport cost
dvar float OMemiss;//ordering emission
dvar float MIemiss;//inventory holding emission
dvar float MTemiss;//transport emission
dvar float costTotal;

dvar int Mwaste;//quantity of material waste
dvar float Memission;//quantity of emission
dvar float TotalEmiss;

////Suppliers
dexpr float OrderMCost = sum(t in PeriodT)(sum(a in RawMat)(orderMCC[a]*rawmatOrder[a][t]));
dexpr float MWasteCost = sum(t in PeriodT)(sum(a in RawMat)(InvM[a][ShelfMWT[a]][t]*wasteMC[a]));
dexpr float MInvCost = sum(t in PeriodT)(sum(a in RawMat)(sum(c in
ShelfMNoWT[a])(holdMC[a]*InvM[a][c][t])));
dexpr float MProdCost = sum(t in PeriodT)(sum(a in RawMat)(prodMC[a]*IncOrderMQ[a][t]));
dexpr float MTranCost = sum(t in PeriodT)(sum(a in RawMat)(ftranMC[a]*rawmatOrder[a][t]+
(OrderMQ[a][t]+IncOrderMQ[a][t])*vtranMC[a]));
dexpr float TotalCost2 = OrderMCost + MWasteCost + MInvCost + MProdCost + MTranCost;

////Producer
dexpr float SetupCost = sum(t in Periods)((setupC*productOrder[t])+(sum(i in
Types)(setupCC[i]*AnOrder[i][t])));
dexpr float OrderCost = sum(t in Periods)(sum(a in RawMat)(orderCC[a]*matOrder[a][t]));
dexpr float TransCost = sum(t in Periods)(sum(a in RawMat)((ftranC[a]*matOrder[a][t])+((Mdemand2[a][t]+
Mdemand[a][t])*vtranC[a])));
dexpr float TotalCost1 = SetupCost + OrderCost + TransCost;
dexpr float Tfine = sum(t in Periods)(sum(i in Types)(sum(r in Retailer) (Y[r][i][t]*fine[r][i])));

dexpr float TotalCost = TotalCost1 + TotalCost2;
dexpr float Sales = sum(t in Periods)(sum(i in Types)(sum(r in Retailer)((X[r][i][t]+Z[r][i][t])*price[r][i])));
dexpr float Profit = Sales - TotalCost - Tfine;

maximize Profit;

subject to {

//2nd model: Suppliers

        costTotal == TotalCost+Tfine;

        //ordering cost
        forall (t in Periods,a in RawMat)
          ctOrderexista:
            if (t > NumPeriodsLT-LTM[a]){
           (OrderMQ[a][t]+IncOrderMQ[a][t]) <= (M * rawmatOrder[a][t]);
           (OrderMQ[a][t]+IncOrderMQ[a][t]) >= rawmatOrder[a][t];}
        forall (t in Periods,a in RawMat)
          ctOrderexista1:{
           (OrderMQ[a][t-LTM[a]]+IncOrderMQ[a][t-LTM[a]]) <= (M * rawmatOrder[a][t-LTM[a]]);
           (OrderMQ[a][t-LTM[a]]+IncOrderMQ[a][t-LTM[a]]) >= rawmatOrder[a][t-LTM[a]];}

        //demand
        forall (t in Periods, i in Types, r in Retailer)
         X[r][i][t]<=demand[r][i][t];
```

```
        forall (t in Periods, i in Types, r in Retailer)
        demand[r][i][t]== X[r][i][t]+Y[r][i][t]+Z[r][i][t];
        forall (t in Periods, i in Types)
          ctProd:
          PlanP[i][t] == sum (r in Retailer) (X[r][i][t]);
        forall (t in Periods, i in Types)
          ctOuts:{
          PlanO[i][t] == sum (r in Retailer) (Z[r][i][t]);
           PlanO[i][t] >= 0;}
        forall (t in Periods, a in RawMat){
          Mdemand2[a][t] == sum(i in Types)(PlanP[i][t]*Usage[a][i]);}    //material demand from producer
        forall (t in Periods, a in RawMat){
          Mdemand[a][t] == sum(i in Types)(PlanO[i][t]*Usage[a][i]);}
        forall (t in Periods, a in RawMat){
          FinalOrderMQ[a][t-LTM[a]] == OrderMQ[a][t-LTM[a]]+ IncOrderMQ[a][t-LTM[a]];}
        forall (t in Periods, a in RawMat){
          IncOrderMQ[a][t-LTM[a]] <= Mdemand[a][t];}
        forall (t in PeriodT, a in RawMat)
          ctSafetyStock1:
        sum (n in 1..(t-LTM[a]))IncOrderMQ[a][n] >=  Q[a][t];
        forall (t in Periods, a in RawMat)
        Q[a][t] ==  Q[a][t-1]+ Mdemand[a][t];
        forall (a in RawMat)
          Q[a][1] == 0;

        //material inventory balance
        forall (t in Periods, a in RawMat)
          ctDemandM1:
            if (t == 1+LTmax){
              OrderMQ[a][t-LTM[a]] + IncOrderMQ[a][t-LTM[a]] == UpLevelM[a][t-LTM[a]];
  } else if (1+LTmax<t<1+LTmax+LTM[a]) {
            UpLevelM[a][t-1-LTM[a]]  + OrderMQ[a][t-LTM[a]] + IncOrderMQ[a][t-LTM[a]] == UpLevelM[a][t-
LTM[a]] ;
  }            //material inventory balance for first LTmax+LTM[a] periods
  forall (t in Periods, a in RawMat)
          ctDemandM2:
            sum(c in MaxM[a])InvM[a][c][t] + sum (n in (t-LTM[a]+1)..t) OrderMQ[a][n] + sum (n in (t-
LTM[a]+1)..t)IncOrderMQ[a][n] == UpLevelM[a][t] - Mdemand2[a][t] - Mdemand[a][t];


        //No predetermined issuing policy
        forall (t in Periods, a in RawMat)
          ctNewInv1:
            OrderMQ[a][t-LTM[a]] + IncOrderMQ[a][t-LTM[a]] >= InvM[a][1][t];
        forall (t in Periods,a in RawMat)
          ctInventory1:
                    forall (c in ShelfMNoWT[a])
            InvM[a][c][t-1] >= InvM[a][c+1][t];
        forall (t in Periods, a in RawMat)
          ctInvBalance1:
           (sum(c in ShelfMNoWT[a]) InvM[a][c][t-1]) - Mdemand2[a][t] - Mdemand[a][t] + OrderMQ[a][t-
LTM[a]] + IncOrderMQ[a][t-LTM[a]] == (sum(c in MaxM[a]) InvM[a][c][t]);

        //quantity of waste & emission
        Mwaste == sum(t in PeriodT)(sum(a in RawMat)(InvM[a][ShelfMWT[a]][t]));
//      Mwaste <= 15540;
        Memission == sum(t in PeriodT)(sum(a in RawMat)(sum(c in
MaxM[a])(InvM[a][c][t]*ESm[a])+((OrderMQ[a][t]+IncOrderMQ[a][t])*SECm[a])+(rawmatOrder[a][t]*ETm[a])
+((OrderMQ[a][t]+IncOrderMQ[a][t])*vtranME[a])));

        //auxiliary contraints to make model work
        OMcost == OrderMCost;
        MWcost == MWasteCost;
        MIcost == MInvCost;
        MPcost == MProdCost;
        MTcost == MTranCost;
        OMemiss == sum(t in PeriodT)(sum(a in RawMat)(OrderMQ[a][t]+IncOrderMQ[a][t]));
        MIemiss == sum(t in PeriodT)(sum(a in RawMat)(sum(c in MaxM[a])(InvM[a][c][t]*ESm[a])));
```

```
        MTemiss == sum(t in PeriodT)(sum(a in
RawMat)((rawmatOrder[a][t]*ETm[a])+((OrderMQ[a][t]+IncOrderMQ[a][t])*vtranME[a])));
//      sum (a in RawMat) sum( c in CC) InvM[a][c][0] == 0;
        forall (t in PeriodT)
          ctInitialInv1:
                if (t < 1+LTmax){
                sum (a in RawMat) Mdemand2[a][t]==0;
                sum (a in RawMat) sum( c in CC) InvM[a][c][t] == 0;}
        forall (t in PeriodT, a in RawMat, c in CC)
          ctdefinition11:
            InvM[a][c][t] >= 0;
        forall (t in PeriodT, a in RawMat)
          ctdefinition21:{
            UpLevelM[a][t] >= 0;
            IncOrderMQ[a][t]>=0;
          }
        forall (t in PeriodT, a in RawMat)
          ctdefinition31:
                if(t<1+LTmax){
            IncOrderMQ[a][t] == 0;
          }

//1st model: Producer

        //setup cost
        forall (t in Periods, i in Types)
          ctOrderexist:
            (PlanP[i][t]+PlanO[i][t]) <= (M * AnOrder[i][t]);
        forall (t in Periods, i in Types)
          ctOrderexist1:
           (PlanP[i][t]+PlanO[i][t]) >= AnOrder[i][t];
        forall (t in Periods)
          ctMultiPexist:{
            sum (i in Types)(AnOrder[i][t]) <= M * productOrder[t];
                sum (i in Types)(AnOrder[i][t]) >= productOrder[t];}      //major&minor setup cost

        //major&minor ordering cost
        forall (t in Periods, i in Types, a in RawMat)
          ctMatorderCP:{
           M * matOrder[a][t]  >= AnOrder[i][t];
           Usage[a][i] *  AnOrder[i][t] >= matOrder[a][t];}

        //quantity of waste & emission
        emission == sum(t in Periods)(sum(i in Types)((PlanP[i][t]+PlanO[i][t])*SECp[i])) + sum(t in
Periods)((setupE*productOrder[t])+(sum(i in Types)(setupEE[i]*AnOrder[i][t])))+ sum(t in Periods)(sum(a in
RawMat)(matOrder[a][t]*ET[a]+((Mdemand2[a][t]+Mdemand[a][t])*vtranE[a])));

        TotalEmiss == emission + Memission;
//      TotalEmiss <= 14960;

        //auxiliary contraints to make model work
        Scost == SetupCost;
        Ocost == OrderCost;
        Tcost == TransCost;
        Semiss == sum(t in Periods)sum(i in Types)((setupE*productOrder[t])+(setupEE[i]*AnOrder[i][t]));
        Pemiss == sum(t in Periods)sum(i in Types)((PlanP[i][t]+PlanO[i][t])*SECp[i]);
        Temiss == sum(t in Periods)(sum(a in
RawMat)(matOrder[a][t]*ET[a]+((Mdemand2[a][t]+Mdemand[a][t])*vtranE[a])));
        forall (t in Periods, i in Types)
          ctdefinition4:{
            PlanP[i][t] >= 0;
            PlanO[i][t] >= 0;
        }
}
```

Coding in data file (MTO.dat)

```
Customer = 1; //# of retailers
```

```
////Producer
setupC = 0; //major setup cost
setupCC = [1000]; //minor setup cost
orderCC = [0 0 0 0 0]; //ordering or receiving cost
ftranC = [0 0 0 0 0]; //fix delivery cost
vtranC = [0 0 0 0 0]; //variable delivery cost
price = [[10]];
fine = [[10]];
setupE = 0;//major setup emission
setupEE = [500]; //minor setup emission
SECp = [1]; //production emission
ET = [0 0 0 0 0];//fix delivery emission (vary with supplier distance)
vtranE = [0 0 0 0 0];//variable delivery emission
demand = [[[800 950 200 900 800 150 650 800 900 300 150 600]]];
////Suppliers
prodMC = [0.05,0.05,0.05,0.01,0.02];//procurement cost   ////extra cost for additional replenishment
orderMCC = [300 300 300 300 300]; // ordering cost
holdMC = [0.005,0.005,0.005,0.001,0.002]; //inventory level based holding cost
ftranMC = [0 0 0 0 0]; //fix delivery cost
vtranMC = [0 0 0 0 0]; //variable delivery cost
wasteMC = [0 0 0 0 0]; //waste disposal cost
SECm = [0 0 0 0 0];//production/replenishment emission
ESm = [0.02,0.02,0.02,0.008,0.02];//inventory level holding emission
ETm = [600 600 600 1200 1500];//fix delivery emission (vary with external supplier distance)
vtranME = [0 0 0 0 0];//variable delivery emission
MaxM = [{1,2},{1,2,3,4},{1,2,3},{1,2,3,4},{1,2,3,4,5}]; //max possible shelf life ranges
ShelfMNoWT = [{1},{1,2,3},{1,2},{1,2,3},{1,2,3,4}]; //possible shelf life ranges without waste
ShelfMWT = [2,4,3,4,5]; //max shelf life
OrderMQ = [[2159 0 1403 0 1218 0 1789 0 1512 0 953 0]
                    [11819 0 0 9177 0 0 6950 0 9917 0 0 0]
                    [11819 0 0 11246 0 0 14001 0 0 6381 0 0]
                    [10077 0 0 0 8496 0 0 0 6968 0 0 0]
                    [2364 0 0 2539 0 0 0 2753 0 0 0 0]];//material order quantity
```

APPENDIX C: SENSITIVITY ANALYSIS DATA IN MTS MODEL

Example problem 2:

1. Stationary

demand = [[[600 600 600 600 600 600 600 600 600 600 600 600]]];

SLevel = [[[0,279,279,279,279,279,279,279,279,279,279,279]

[0,0,342,342,342,342,342,342,342,342,342,342]

[0,0,0,395,395,395,395,395,395,395,395,395]]];

2. Seasonal

demand = [[[600 730 850 900 850 730 600 470 350 300 350 470]]];

SLevel = [[[0,311,369,407,407,369,311,251,193,152,152,193]

[0,0,418,473,494,473,418,347,276,217,190,217]

[0,0,0,512,549,549,512,446,366,293,245,245]]];

3. Life cycle

demand = [[[150,200,350,600,800,850,900,1050,950,650,500,200]]];

SLevel = [[[0,82,133,229,329,384,407,455,466,379,270,177]

[0,0,141,238,349,432,485,534,552,513,413,278]

[0,0,0,243,355,447,524,595,619,592,538,418]]];

4. Highly erratic

demand = [[[1900,950,40,80,30,150,800,950,1100,350,150,700]]];

SLevel = [[[0,699,313,29,28,50,268,409,478,380,125,236]

[0,0,699,314,31,57,268,412,546,492,383,262]

[0,0,0,699,314,58,269,412,548,558,494,447]]];

5. Max shelf life = 5

Max = [{1,2,3,4,5}];

ShelfNoWT = [{1,2,3,4}];

ShelfWT = [5];

ShelfLifeNoWT = [4];

X = [[{0,1,2,3,4}]];

SLevel = [[[0,409,319,303,396,268,219,339,396,312,110,203]

[0,0,414,436,402,399,343,343,450,408,316,226]

[0,0,0,509,509,405,453,432,453,461,411,373]

[0,0,0,0,573,511,458,524,524,464,464,456]

[0,0,0,0,0,575,554,528,602,533,466,504]]];

Max2 = [{3}];

5a. Max shelf life = 5, high setup: low holding

```
holdC = [0.005];

ESp = [0.04];
```

6. Max shelf life = 11

```
Max = [{1,2,3,4,5,6,7,8,9,10,11}];

ShelfNoWT = [{1,2,3,4,5,6,7,8,9,10}];

ShelfWT = [11];

ShelfLifeNoWT = [10];

X = [[{0,1,2,3,4,5,6,7,8,9,10}]];

SLevel = [[[0,409,319,303,396,268,219,339,396,312,110,203]

            [0,0,414,436,402,399,343,343,450,408,316,226]

            [0,0,0,509,509,405,453,432,453,461,411,373]

            [0,0,0,0,573,511,458,524,524,464,464,456]

            [0,0,0,0,0,575,554,528,602,533,466,504]

            [0,0,0,0,0,0,613,613,605,610,535,506]

            [0,0,0,0,0,0,0,668,681,613,612,571]

            [0,0,0,0,0,0,0,0,730,688,615,643]

            [0,0,0,0,0,0,0,0,0,737,690,646]

            [0,0,0,0,0,0,0,0,0,0,739,718]

            [0,0,0,0,,0,0,0,0,0,0,0,764]]];

Max2 = [{9}]; //maximum internal shelf life - 2 //FIFO&LIFO
```

6a. Max shelf life = 11, high setup: low holding

```
holdC = [0.005];

ESp = [0.04];
```

7. Disposal cost = -0.5

```
wasteC = [-0.5];
```

8. Disposal cost = 2

```
wasteC = [2];
```

9. CV = 0.1

```
SLevel = [[[ 0,204,160,152,198,134,110,170,198,156,55,102]

            [ 0,0,207,218,201,200,171,171,225,204,158,113]

            [ 0,0,0,254,254,202,226,216,226,230,206,186]]];
```

10. CV = 0.3

```
SLevel = [[[ 0,613,479,455,594,402,329,509,594,468,166,305]

            [ 0,0,621,653,602,599,514,514,675,612,474,339]

            [ 0,0,0,763,763,607,679,648,679,691,617,559]]];
```

11. Service level = 0.9

```
SLevel = [[[0,318,249,236,309,209,171,264,309,243,86,159]
          [0,0,322,339,313,311,267,267,351,318,246,176]
          [0,0,0,396,396,315,353,337,353,359,320,290]]];
```

12. Service level = 0.98

```
SLevel = [[[0,510,399,379,495,334,274,423,495,390,138,254]
          [0,0,517,544,501,498,428,428,562,510,395,282]
          [0,0,0,635,635,505,565,539,565,575,513,465]]];
```

13. Cost:Emissions for setup/holding = 1:1

```
///////////////producer_d1.dat
setupEE = [3000];
ESp = [1];
///////////////supplier_d1.dat
ESm = [0.01,0.01,0.01,0.004,0.01];
ETm = [600 600 600 1200 1500];
```

14. Cost:Emissions for setup/holding = 1:2

```
///////////////producer_d1.dat
setupEE = [3000];
ESp = [0.5];
///////////////supplier_d1.dat
ESm = [0.005,0.005,0.005,0.002,0.005];
ETm = [600 600 600 1200 1500];
```

15. Cost:Emissions for setup/holding = 1:6

```
///////////////producer_d1.dat
setupEE = [3600];
ESp = [0.2];
///////////////supplier_d1.dat
ESm = [0.001,0.001,0.001,0.0005,0.001];
ETm = [360 360 360 900 900];
```

16. Cost:Emissions for setup/holding = 2:1

```
///////////////producer_d1.dat
setupEE = [3000];
ESp = [2];
///////////////supplier_d1.dat
ESm = [0.02,0.02,0.02,0.008,0.02];
ETm = [600 600 600 1200 1500];
```

17. Cost:Emissions for setup/holding = 1:1

```
///////////////producer_d1.dat
setupCC = [500];
holdC = [1];
setupEE = [1500];
ESp = [3];
///////////////supplier_d1.dat
ESm = [0.01,0.01,0.01,0.004,0.01];
ETm = [600 600 600 1200 1500];
```

18. Cost:Emissions for setup/holding = 1:2

```
///////////////producer_d1.dat
setupCC = [500];
holdC = [1];
setupEE = [1500];
ESp = [1.5];
///////////////supplier_d1.dat
ESm = [0.005,0.005,0.005,0.002,0.005];
ETm = [600 600 600 1200 1500];
```

19. Cost:Emissions for setup/holding = 1:6

```
///////////////producer_d1.dat
setupCC = [2000];
holdC = [4];
setupEE = [1500];
ESp = [0.5];
///////////////supplier_d1.dat
ESm = [0.001,0.001,0.001,0.0005,0.001];
ETm = [360 360 360 900 900];
```

20. Cost:Emissions for setup/holding = 2:1

```
///////////////producer_d1.dat
setupCC = [1500];
holdC = [1.5];
setupEE = [500];
ESp = [1];
///////////////supplier_d1.dat
ESm = [0.02,0.02,0.02,0.008,0.02];
ETm = [600 600 600 1200 1500];
```

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