MODELING AND ANALYSIS OF SUSTAINABLE SUPPLY CHAIN SYSTEMS

by

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This is to certify that I have examined this copy of a doctoral thesis by

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ABSTRACT

Sustainability is an important requirement in the design and operation of supply chain systems. All of the decisions involved in a sustainable system must incorporate three pillars – namely the economic, environmental and social pillars. Moreover, considering these three pillars simultaneously is termed as triple bottom line accounting. Classical research in the field of supply chain and operations management has focused on pure-economical objectives. Therefore, in order to achieve sustainability in supply chain management, a sustainable decision-making methodology must be adopted. This methodology requires incorporation of environmental and social dimensions in addition to conventional economics in the decision-making process.

In this study, a methodological approach to address sustainable supply chain management problem is proposed that conforms to the above triple bottom line accounting. The proposed approach is based on the revision of standard mathematical programming (optimization) models of classical supply chain and operations management problems with environmental and social factors and the analysis of these revised models. The method is applied to three main decision-making problems and four corresponding standard models from the literature: (i) economic order quantity and newsvendor models for the inventory control problem (ii) aggregate planning model for the production planning problem (iii) uncapacitated facility location model for the network design problem.

The proposed approach illustrates how environmental and social factors can be integrated with the traditional cost accounting in order to achieve sustainability in supply chain management. Furthermore, the analysis of the revised models shows that the optimal policy and the resulting performance measures proposed by pure-economical models change substantially under triple bottom line accounting.

ÖZETÇE

Sürdürülebilirlik, tedarik zinciri sistemlerinin tasarımı ve işletiminde önemli bir gereklilikür. Sürdürülebilir bir sistemde verilen kararların tamamı, ekonomik, çevresel ve sosyal olmak üzere üç temel dayanağı içine almalıdır. Bu üç dayanağın birlikte ele alınması da üç temelli muhasebe olarak tanımlanır. İşletme yönetimi alanında bugüne kadar yapılan klasik çalışmalar, salt-ekonomik amaçlara yoğunlaşmaktadır. Bu sebeple, işletme yönetiminde sürdürülebilirliği sağlamak için, sürdürülebilir bir karar-verme yönteminin benimsenmesi gerekmektedir. Bu metod, ekonomik boyutlara ek olarak, çevresel ve sosyal boyutların da karar-verme sürecine dahil edilmesini gerektirmektedir.

Bu çalışmada sürdürülebilir işletme yönetimi probleminin çözümü için yukarıdaki üç temelli muhasebeye uygun bir metodik yaklaşım önerilmektedir. Önerilen yaklaşım, klasik işletme yönetimi problemlerine ait standart matematiksel programlama (eniyileme) modellerinin, çevresel ve sosyal faktörler dikkate alınarak revize edilmesine ve ortaya çıkan yeni modellerin analizine dayanmaktadır. Bu metod, literatürdeki üç ana karar-verme problemine ve bu problemlere ilişkin dört standart modele uygulanmıştır: (i) envanter kontrolü problemi için ekonomik sipariş miktarı ve gazeteci çocuk modelleri (ii) üretim planlama problemi için bütünleşik planlama modeli (iii) ağ tasarım problemi için kapasite kısıtsız tesis yer seçimi modeli.

Önerilen yaklaşım, işletme yönetiminde sürdürülebilirliğin sağlanması için, klasik maliyet muhasebesine, çevresel ve sosyal faktörlerin nasıl entegre edilebileceğini tanımlamaktadır. Ayrıca, revize edilmiş modellerin analizi, salt-ekonomik modellerin verdiği en iyi çözümlerin ve bu çözümlere dayalı performans ölçütlerinin, üç temelli muhasebe altında büyük ölçüde değiştiğini göstermektedir.

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Chapter 1

INTRODUCTION

1.1. Background and Problem Statement

In this study, the sustainable supply chain management (SSCM) problem is considered. A formal definition of the problem is;

> “the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements” [1]

Except for the environmental and social dimensions mentioned, the above definition reduces to the usual definition of supply chain management (SCM) where purely economic dimension is considered. In other words, the SSCM problem is to extend the traditional approach in supply chain management with the environmental and social dimensions of sustainability. Along with the economic dimension, these three dimensions are called the “three pillars” or the “triple bottom line (TBL)” of sustainability [2, 3].

In order to elaborate further, sustainability, supply chain systems and the management of these systems are discussed in the subsequent sections.

Sustainability

Sustainability is used either as the ability to sustain a practice or process or to refer to environmental consciousness in the literature and most non-academic resources including newspapers and magazines. Both comprehensions are valid but incomplete.

Sustainability is closely related to the concept of sustainable development, which is defined as ‘‘the development that meets the needs of the present without compromising the ability of future generations to meet their own needs’’ [4]. Although this is a well-defined and often cited definition of sustainable development, it does not provide a clear methodology in terms of achieving sustainability in systems. A common approach in achieving sustainability is the concept of triple bottom line accounting as proposed by Elkington [2, 3]. The TBL accounting concept states that for a system to be sustainable, a minimum performance is to be achieved in the economic, environmental, and social aspects [3]. Other phrases are also used to denote these three pillars; e.g. prosperity, planet, and people or the business case, the natural case, and the societal case instead of economic, environmental and social dimensions.

Supply Chain Systems and Management

In simplest terms, when there is a demand either for a product or a service and a supply to fulfill this demand, a supply chain emerges. A more formal definition is as follows:

> “The supply chain encompasses all activities associated with the flow and transformation of goods from raw materials stage (extraction), through to the end user, as well as the associated information flows. Material and information flow both up and down the supply chain.” [5]

In particular, a supply process supplies certain inputs which are then turned into desired outputs via a transformational process to satisfy the demand. This transformation is called the production or operations [6]. Therefore, any activity in fulfilling the demand is in the scope of that supply chain system.

Figure 1.1 Supply chain system and the operations function

With this understanding, any business entity either being a manufacturing or a service business has an underlying supply chain system and in the core of this system is what is called the production or operations function of the business.

The management of a supply chain system requires a continuum of decision-making regarding the production/operations function at the strategic (regarding the design), tactical (regarding the planning), and operational (regarding control) levels [6, 7]. Therefore, the supply chain (operations) management problem in the classical sense is already an important and difficult problem to be addressed by the decision-makers. The problem is important as it is the core of the business [8]; and difficult as supply chain systems are complex and dynamic structures with a number components and uncertainties.

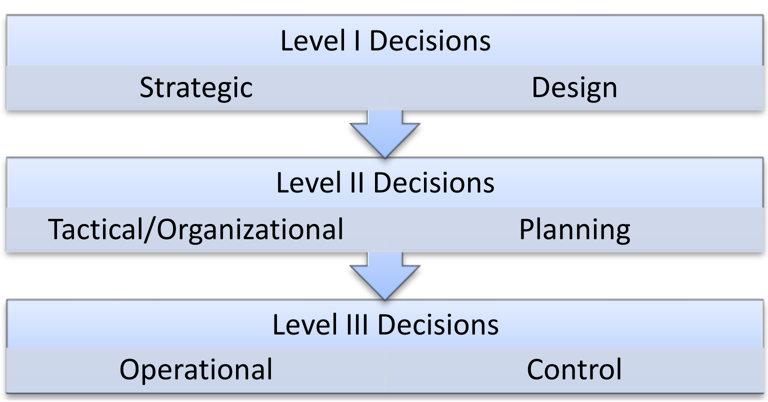


Figure 1.2 Decision-making levels in supply chain management

The SSCM problem is even more important than the usual SCM problem due to the emerging environmental and social considerations in global supply chain and operations management [8]. However, it is also harder than the usual SCM problem due to the added dimensions of sustainability; namely the environmental and social dimensions. Adding further considerations in the decisions increases the complexity of decision-making. However, due to emerging environmental and social concerns along with economical ones, sustainability is a necessary and unavoidable aspect in supply chain management.

1.2. Thesis Statement

The thesis statement is formulated using the above definitions of sustainability, supply chain systems and their management. The argument is as follows:

In order to achieve sustainability in supply chain management, a sustainable decision-making methodology is required. This methodology requires the incorporation of the three pillars of sustainability simultaneously into the decision-making process.

1.3. Thesis Objectives and Outline

The primary objective of this study is to propose a methodological approach for sustainable decision-making as discussed above in order to address sustainability in supply chain management problems. After that, the proposed approach is applied to classical decision-making problems in the supply chain and operations management literature.

In Chapter 2, a review of the related literature in the area of sustainable supply chain and operations management is presented along with the gaps in the literature. In Chapter 3, the proposed approach is presented. In Chapters 4-7, the applications of the proposed approach to three fundamental decision-making problems from three decision-making levels, namely the inventory control, production planning and network design problems, are presented. Finally, Chapter 8 concludes the thesis with a discussion of the contributions, main observations, and implications of the study along with future research opportunities.

1.4. Contributions at a High-level

The proposed methodology based on the thesis statement mentioned above fills the two major gaps of the sustainable supply chain and operations management literature. In particular, a sustainable decision-making methodology with the three pillars of sustainability not only constitutes the conceptual framework with the theoretical background but also incorporates the social dimension of sustainability.

Chapter 2

LITERATURE REVIEW

In this chapter, an overview and a brief review of the literature in the area of sustainable supply chain and operations management is presented along with the observations regarding the major gaps of this literature.

2.1. Overview

The literature on sustainable supply chain and operations management is mainly dated within the last two decades, following the emergence of the term sustainability in 1980s [4]. The readers can refer to the previous efforts of literature reviews in the field of sustainable supply chain and operations management. Corbett [9], Corbett and Klassen [10], Corbett and Kleindorfer [11, 12], Gupta [13], Gupta and Lambert [14], Kleindorfer et al. [15], Linton et al. [16], Sasikumar and Kannan [17], Seuring and Muller [1], and Srivastava [18] are such extensive reviews.

The research conducted in sustainable supply chain management can be categorized into three main groups: surveys, case/conceptual studies, and models.

There are several surveys of methods and applications that are related to sustainable supply chain and operations management. Beamon [19], Boulanger and Brechet [20], Fleischmann et al. [21], Handfield et al. [22], Jones et al. [23], Kim et al. [24], Macharis and Bontekoning [25], Sarkis [26], Seuring [27, 28], Turkay [29], Yeralan and Baker [30] are examples of such surveys.

There are also several case/conceptual studies proposing metrics and frameworks for sustainable supply chain and operations management. Carter [31], Carter and Jennings [32], Clift [33], Gladwin et al. [34], Hutchins and Sutherland [35], Koplin et al. [36], and Sarkis [37, 38] are examples of such studies.

Finally, there exist a number of studies directly concerned with the modeling. Bauer et al. [39], Benjaafar et al. [40], Bonney and Jaber [41], Bouchery et al. [42], Bruglieri and Liberti [43], Cai et al. [44], Chaabane et al. [45], Corbett and DeCroix [46], Erkut et al. [47], Hashim [48], Hoen et al. [49], Hua et al. [50], Hugo et al. [51], Kainuma and Tawara [52], Kim et al. [53], Lee et al. [54], Letmathe and Balakrishnan [55], Linares and Romeo [56], Manikas and Godfrey [57], Nagurney et al. [58, 59], Neto et al. [60], Penkuhn et al. [61], Rentizelas et al. [62], Sheu [63], Sheu et al. [64], Soylu et al. [65], Stuart et al. [66], Turkay et al. [67], Turkay and Soylu [68], and Zhou et al. [69] present model formulations with environmental considerations.

In the next section, a review of the above literature is presented.

2.2. Review

The literature on sustainability within the context of supply chain and operations management can be summarized in three broad categories: surveys, case/conceptual studies and models.

2.2.1. Surveys

There are several surveys of methods and applications that are related to sustainable supply chain and operations management.

Beamon [19] and Handfield et al. [22] both present a review of environmental management issues in supply chain planning and provide a framework of achieving and maintaining a greener supply chain. Boulanger and Brechet [20] survey the generic methods that can be used by the policy-makers in assessing the sustainability performance of their policies. They also discuss the appropriateness of these methods using sector-based applications and conclude that the multi-agent simulation models are best suited with decision-making for sustainability. Fleischmann et al. [21] give a review of quantitative models for reverse logistics. Jones et al. [23] and Macharis and Bontekoning [25] are examples of reviews on transportation centric approaches. In particular, both studies consider inter-modal transportation where separate modes of transportation including railway, sea, highway, and air transportation are coupled with each other in order to minimize the total greenhouse gas (GHG) emissions due to transportation activities. Kim et al. [24] provide a model for remanufacturing as an integral part of reverse logistics activities. Sarkis [26] presents a review of the environmental consciousness practices that could be incorporated in manufacturing firms and propose a framework in pursuing such programs. Seuring [27] provides a review of commonly used and interrelated concepts of industrial ecology, life-cycle management, integrated chain management, and environmental supply chain management. The author tries to identify the concepts, their interrelations, and differences. Seuring [28] assesses the differences between integrated chain management and supply chain management to further develop the notion and importance of industrial ecology. He uses five different case studies from textile industry for illustrating these differences reflected by the objectives of the chain actors. Turkay [29] reviews methods for environmentally conscious supply chain management and lists them as product centric (closed-loop supply chains), production system centric (environmentally conscious production) and transportation system centric (sustainable transportation) approaches. Under closed-loop supply chains, reverse logistics applications are gathering interest. Under environmentally conscious production, supply chain systems with environmental extensions are studied. Finally, Yeralan and Baker [30] present the backgrounds of two courses; one on sustainable systems engineering and the other on sustainable systems management, which are designed for the industrial engineering curriculum.

2.2.2. Case/Conceptual Studies

There are also several case/conceptual studies proposing metrics and frameworks for sustainable supply chain and operations management.

Carter [31] deals with purchasing social responsibility (PSR) as an application of corporate social responsibility (CSR) to supply chains. Carter and Jennings [32] analyze the effect of social responsibility projects on supply chain performance and conclude that these projects enhance the supply chain performance. Clift [33] proposes metrics for sustainability in all aspects; i.e. economic, environmental and social. However, the author argues that social metrics are not so common and a public consensus is needed to define and use them in decision-making processes. Moreover, the author also states that aggregation across the dimensions such as expressing ecological impact through monetary units is both unnecessary and undesirable. Gladwin et al. [34] emphasize the fact that sustainability is a concept beyond eco-efficiency and argue that socio-economic aspects are equally important. They propose working principles for the social dimensions of sustainability in business environments. Hutchins and Sutherland [35] present metrics for social sustainability within a supply chain and evaluate these metrics using the public data of a company. Koplin et al. [36] provides a case study of an automobile company regarding environmental and social impacts management and present a sustainable supply chain management concept based on the company mentioned. Finally, Sarkis [37, 38] presents a decision-making framework for environmental conscious business management using analytic network process (ANP).

2.2.3. Models

Lastly, there are a number of studies directly concerned with the models.

Bauer et al. [39] incorporate greenhouse gas emission considerations into freight transportation planning and propose a multi-commodity capacitated network design formulation with the objective of minimizing the amount of greenhouse gas emissions due to transportation activities. They provide a computational illustration on a real-life rail freight transportation problem. Benjaafar et al. [40] integrate carbon emission concerns into simple lot sizing models to illustrate how such useful modifications can be made on simple traditional models to assist operational decision-making. They point out that existing literature in supply chain management lacks such operational models. Moreover, they also provide insights from their models along with useful numerical experiments to show the effect of carbon emissions on optimal operating policies. They argue that instead of costly investments, simple operational modification can reduce carbon footprint. Bonney and Jaber [41], Bouchery et al. [42] and Hua et al. [50] investigate the effect of carbon emissions in inventory control under deterministic demand conditions. In all of these studies, environmentally enhanced economic order quantity (EOQ) models are presented under various settings. Among these studies, only Bouchery et al. [42] aim to propose a social metric as well as the environmental one in order to achieve sustainability. Bonney and Jaber [41] also provide a list of non-cost metrics for incorporating environmental footprint in the inventory context. Bruglieri and Liberti [43] model a biomass-based energy production system using mixed integer linear programming (MILP). Their motivation is to develop models of renewable energy sources like biomass for less environmental impact. Cai et al. [44] present a dynamic linear programming (LP) model for large-scale energy generation plants in the region of Waterloo. They observe the trade-offs between system costs and GHG emissions for the system in consideration. They also state that the model enable analysis of alternative technologies over a number of periods and may be extended to cover a large variety of complexities common in energy systems. Chaabane et al. [45] propose a mathematical programming formulation for the entire life-cycle design of a supply chain which incorporates environmental objectives as well. Corbett and DeCroix [46] analyze shared-savings contract in order to minimize the consumption of indirect materials within a supply chain, including the ones with environmental impact like hazardous materials and CFC-based solvents. They argue that the buyer wants to reduce consumption of such materials already to minimize costs but the supplier does not unless an incentive is placed via a shared-savings contract. Erkut et al. [47] present a multi criteria MILP formulation to solve a location-allocation problem regarding municipal waste management. Hashim [48] provides an MILP model for carbon dioxide emissions reduction for the Ontario power grid. They consider conventional raw materials of electricity generation in addition to alternative energy and impose minimization of carbon dioxide emissions as a secondary objective. Hoen et al. [49] develop models for the transport mode selection problem with emission costs and constraints. Their model is based on the classical newsboy model. The authors argue that emission cost accounting, emission tax or emission trade mechanisms all fail if the aim is to curb the emissions. On the other hand, a direct cap on emissions works. They also calculate emissions for different transport mode choices to estimate the parameters of the proposed models. Hugo et al. [51] give an MILP model to use for investment decisions for future hydrogen-based supply chains as an alternative source of energy supply. They formulate environmental objectives in the form of GHG emissions minimization as well as economic objectives. Kainuma and Tawara [52] provide a multi attribute utility function formulation for the lean and green supply chain management problem using the objectives of Life Cycle Assessment (LCA); i.e. the minimization of environmental impacts and maximization of the social contribution. They conduct a case study to quantify the single-attribute and multi-attribute utility functions for a single decision-maker and observe the preferences. Kim et al. [53] provide a bi-criteria optimization model to examine the relationship between the freight transport costs and carbon dioxide emissions for intermodal and road transportation networks. Lee et al. [54] present deterministic and stochastic programming formulations for logistics network design which account for environmental impacts as well as costs. Letmathe and Balakrishnan [55] present a linear and a mixed-integer program for firms to determine the optimal product mix and production quantities under environmental constraints in addition to the production constraints. Linares and Romeo [56] give a multi criteria decision-making method for electricity planning and model GHG emissions as well as radioactive waste as minimization objectives. Manikas and Godfrey [57] propose a newsvendor model which maximizes the expected profit of a manufacturer in the presence of emission permits and penalties. Nagurney and Toyasaki [58] formulate a multi criteria decision-making model with environmental concerns and provide analyses and computation of the proposed model for supply chain networks with electronic commerce. Nagurney et al. [59] incorporate carbon taxes into the electric power generation industry and determine the optimal carbon taxes applied to power plants. Neto et al. [60] investigate the environmental impact factors along the supply chain and propose a multi objective programming based framework in modeling and optimizing the design of logistic networks. Penkuhn et al. [61] present a constrained nonlinear program (NLP) for a production planning problem in the process industry. Rentizelas et al. [62] develop optimization models for biomass-based energy production and evaluate solutions to their model using a genetic algorithm. Sheu [63] presents a multi-objective optimization model for nuclear power generation. The author also models the reverse logistics of the waste induced along with the operational risks and report improvements in environmental impact when proposed approach is utilized. Sheu et al. [64] present a multi-objective linear programming model for both the forward and reverse logistics operations of a company for green supply chain management. They argue that their model - being a generic mathematical one - is not industry specific. Soylu et al.

[65] propose a multi-period MILP model for the analysis of collaboration between energy systems with environmental considerations. Stuart et al. [66] give a product and process selection - called the EPPACE model - with environmental considerations. They argue that their mixed integer programming model (EPPACE) provides a quantification of environmental impact drivers for the manufacturers. Turkay et al. [67] investigate the material exchange among companies and try to quantify the effect of such collaboration on financial and environmental performances of those companies. They also add a constraint on sulfur oxide (SO_x) emissions in their MILP model. A similar study for bio-fuel use can be seen in Turkay and Soylu [68]. Zhou et al. [69] provide a case study of a petrochemical complex in addressing sustainability objectives. They use analytic hierarchy process to first assign the priorities of the sustainability goals and weights of the decision variables. Then, they use goal programming to model the constrained multi-objective problem. They illustrate their approach with an application on a petrochemical complex.

2.2. Observations

The analysis of the sustainable supply chain and operations management literature presented above leads to the following observations:

I. The term *sustainability* is an emerging concept and application of it in supply chain and operations management has a limited literature, mainly produced in the last two decades.

II. The research conducted in sustainable supply chain and operations management can be categorized into three main groups:

   i. Reviews/surveys
   ii. Conceptual studies/case studies
   iii. Modeling

Table 2.1 Most Relevant Literature

Papers	Problem Considered	Base Model	Economic Pillar	Environmental Pillar	Social Pillar	Conceptual Framework
Hua et al (2011)	Inventory Control	Economic Order Quantity	Yes	Yes	N/A	N/A
Benjaafar et al (2010)	Inventory Control	Deterministic Lot Sizing	Yes	Yes	N/A	N/A
Hoen et al (2010)	Transportation Planning	Newsvendor	Yes	Yes	N/A	N/A
Bouchery et al (2010)	Inventory Control	Economic Order Quantity	Yes	Yes	Yes	N/A
Lee et al (2010)	Network Design	Deterministic and Stochastic Programming	Yes	Yes	N/A	N/A
Chaabane et al (2010)	Network Design	Mixed Integer Linear Programming	Yes	Yes	N/A	Yes
Bonney and Jaber (2009)	Inventory Control	Economic Order Quantity	Yes	Yes	N/A	N/A
Bauer et al (2009)	Transportation Planning	Multi-commodity Capacitated Network Flow	Yes	Yes	N/A	N/A
Kim et al (2009)	Transportation Planning	Bi-criteria Linear Programming	Yes	Yes	N/A	N/A
Neto et al (2008)	Network Design	Multi-objective Programming	Yes	Yes	N/A	Yes
Erkut et al (2008)	Network Design	Multi-criteria Location-allocation	Yes	Yes	N/A	N/A
Letmathe and Balakrishnan (2005)	Production Planning	Linear and Mixed Integer Programming	Yes	Yes	N/A	N/A
Manikas and Godfrey (2000)	Inventory Control	Newsvendor	Yes	Yes	N/A	N/A
Penkuhn et al (1997)	Production Planning	Constrained Nonlinear Programming	Yes	Yes	N/A	N/A

N/A: *Not Available*

III. An integral part of the research focuses on the environmental improvements/considerations along with the economical objectives. Social aspects are rarely included [1]; and completely ignored in models (see Table 2.1).

IV. The conceptual frameworks and models are not linked to each other to address the need for a methodological approach in analyzing sustainable supply chain systems [1] (also see Table 2.1).

Observation III and IV above represent the two major gaps of the sustainable supply chain and operations management literature. In the next chapter, the proposed approach is presented.

Chapter 3

METHODOLOGICAL PROPOSAL

In this chapter, the methodological proposal for the sustainable supply chain management problem is presented. The method is based on the use of mathematical programming/optimization models of supply chain operations management problems. Therefore, a discussion on the optimization of supply chain systems is first presented in this section.

3.1. Optimization of Supply Chain Systems

Optimization is one of the many available decision-making methods. In simplest terms, optimization may be defined as choosing the best possible decision among competing alternatives. More formally, the decision maker tries to find the maximum or the minimum value of a predefined objective function, sometimes in the presence of constraints [70]. Most of the decision-making situations confronted in real life problems fit into this generic structure. This is why optimization is an important method in decision-making.

An optimization problem can be represented as a mathematical program; that is, the objective(s) to be maximized or minimized as well as the constraints are formulated as equalities or inequalities; thus, the problem is modeled. Depending on the problem structure and the decision maker's modeling preferences, the optimization model takes special forms and requires specific solution methodologies. Since the underlying theory in modeling and the solutions methodologies are well-established, optimization is not only an important but also a powerful method. For different types of optimization models, corresponding solution procedures and applications, one can refer to Dantzig [71], Floudas [72] and Williams [73].

The supply chain and operations management literature consists of a number of optimization models for various decision-making problems at all levels mentioned above (see Figure 1.3). The proposed methodological approach is based on the revision and reformulation of such mathematical programming/optimization models of supply chain operations management problems.

3.2. Proposed Sustainable Decision-making Method

Below, the methodological proposal is described which is a 4-step modeling and analysis procedure. The following figure (Figure 3.1) outlines the flow of the proposed method:

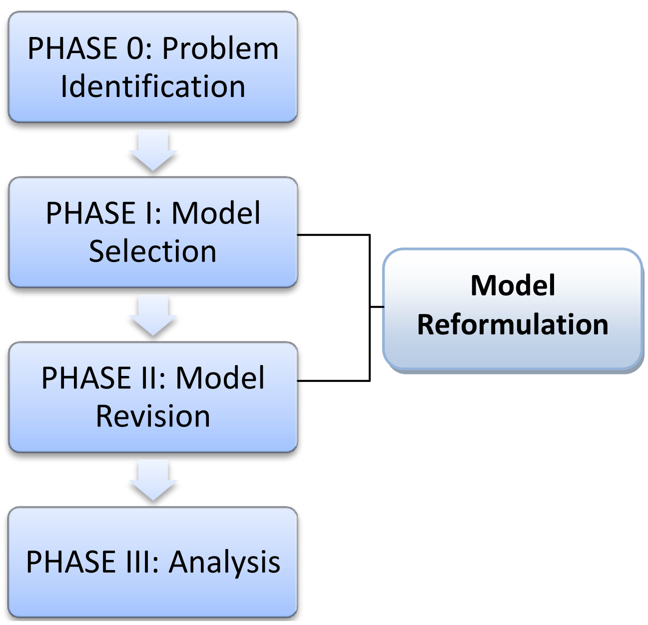


Figure 3.1 Flow-sheet of the proposed method

PHASE 0: Problem Identification

In this phase, the decision maker identifies the supply chain operations decision-making problem. Possible problems include but are not limited to inventory control, job shop scheduling, production planning, transportation and routing, equipment maintenance and replacement, supplier selection/sourcing, project scheduling, facilities layout and location, product and process design, and service/queuing systems design [7].

PHASE I: Model Selection

In this phase, an appropriate mathematical programming formulation corresponding to the problem identified in PHASE 0 is selected and set as the standard model. Available models in the literature have purely economical considerations in most cases.

PHASE II: Model Revision

In this phase, the model selected in PHASE I is revised with the other two dimensions - called the pillars - of sustainability; namely the environmental and social pillars. The effects of the problem on the environment and people are investigated first. Following this step, the identified considerations are quantified using appropriate metrics. Finally, these metrics are incorporated into the model selected in PHASE I by formulating new objectives and/or constraints and by modifying the existing mathematical programming model.

PHASE III: Analysis

In this phase, the revised model obtained in PHASE II is analyzed and the new solution and respective objective function are compared with the ones proposed by the standard model selected in PHASE I. In analyzing the revised model, analytical and numerical methods are used where appropriate, depending on the characteristics of the resulting formulation. A sensitivity analysis may also be performed to test the behavior of the solution and respective objective function with respect to changes in the parameters of the revised model.

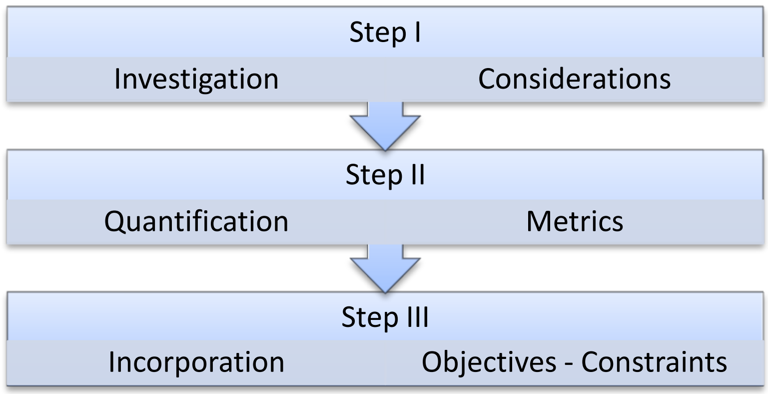


Figure 3.2 Steps in PHASE II

3.3. Evaluation of the Proposed Method: Requirements

In this section, the requirements of the proposed method are evaluated on the basis of PHASE II - Step II and III:

i. The method requires environmental and social metrics.

PHASE II requires the incorporation of environmental and social considerations into mathematical programming formulations; hence, metrics that correspond to these considerations are required in order to quantify them. However, there are a number of metrics that can be used in modeling as outlined in the next section.

ii. The method requires the estimation of environmental and social model parameters.

In order to incorporate the quantified considerations into the models, the environmental and social parameters should be estimated. Although the estimation of environmental and social parameters might be much more difficult than of the economic ones, parameter estimation is a common challenge in modeling and is not specific to the proposed method. Still, a limitation of this thesis is about the numerical experiments which lack real data. This is due to the fact that environmental and social parameter estimates for the problems and models selected in PHASE 0 and I are not available within the companies and estimating them requires conducting field studies, which is beyond the scope of this thesis. Therefore, all of the data employed in numerical experiments are hypothetical.

3.4. Metrics for PHASE II of the Proposed Method

In the previous section, it is stated that the proposed method requires metrics in PHASE II that reflect the environmental and social considerations. Below, several metrics that correspond to certain environmental and social considerations that applies to supply chain operations decision-making are outlined:

3.4.1. Environmental Metrics

These are a number of environmental considerations and metrics that can be associated with these considerations in assessing the environmental impacts of the supply chain operations. Air pollution, water pollution, and soil contamination/land pollution are three broad categories of these environmental impacts.

Among other components of air pollution, GHG emissions, which is also referred to as the carbon footprint [74], is gathering an increasing public interest and is an important environmental metric. These gases which include carbon dioxide, nitrous oxide, methane, water vapor, and ozone lead to global warming; therefore, controlling their emission levels is crucial for the environmental pillar of sustainability. Closely related to GHG emissions is energy production which leads to 80% of the emissions of these gases [29]. On the other hand, sufficient amount of energy is required for industrial production and economic sustainability, whereas conventional energy resources are scarce; hence, becoming more expensive every other day. Therefore, level of energy consumption is another environmental consideration that deserves special importance in fulfilling sustainability objectives. This also explains why a significant number of studies in the literature on sustainable supply chain management consider energy production (see section §2.2 of Chapter 2 for the references on the modeling of energy production systems). Moreover, since the electrical and heat energy are the two primary forms of energy consumption in the industry [75, 76], usage of electricity and heat energy are suitable metrics in modeling energy consumption. Another important metric related to air pollution is the emission of sulfur oxide (SO_x), which is not a greenhouse gas but leads to ozone depletion and contributes into the acidification of the atmosphere [35].

For water pollution and soil contamination, the amount of liquid and solid waste generated by supply chain operations is an appropriate metric [77]. Associated explosion and leakage risks of hazardous materials transportation might also be used as an environmental metric; whereas, these might also be used as social metrics regarding the public health and safety through the quantification of those risk factors [78].

In addition to the above metrics, there are environmental management protocols/programs from which certain other types of metrics may be devised that would fit into a particular industrial setting. ISO 14000 is a family of environmental management standards for companies and organizations, similar to ISO 9000 family [79]. Corporate Environmental Responsibility (CERES) is another one which offers 10 principles for environmental standards that organizations should adopt [80]. Total Quality Environmental Management (TQEM) is the application of Total Quality Management (TQM) principles for environmental objectives [81].

3.4.2. Social Metrics

Compared to the environmental considerations, social considerations are much more diverse, complicated, and vague; making it challenging to propose metrics to quantify them. This might be one reason for the social pillar of sustainability to have gathered the least interest by the operations research and operations management community. As stated in the literature observations in Chapter 2, the comprehension of sustainability is often reduced to environmental improvements together with economical ones in the sustainable supply chain and operations management literature. Since this literature lacks the social aspects, one needs to investigate other domains to identify the social considerations and the associated metrics.

The social considerations should be addressed on the basis of the parties affected by the decisions in supply chain operations; primarily the employees and customers. Although other groups of people within the general public might also be affected though more indirectly, assessing and quantifying the impact of supply chain operations on these groups is much more difficult than doing it for the employees and direct customers.

The social considerations due to supply chain operations regarding the employees include but are not limited to working hours, health and safety, job-security, morale-motivation, and work-family balance. Some of these considerations are in the international labor standards put forth by the International Labor Organization (ILO) [82, 83]. The regular man-hour requirement of the operations, number of hired and fired employees, overtime hours, amounts of illumination, vibration, heat, and noise, worker idle time distribution in assembly, worker body motions are metrics that can be used to account for the social interests of the employees.

The main social consideration due to supply chain operations regarding the customers is customer satisfaction, since the existence of the supply chain depends upon the fulfillment of their demand. In the classical operations research/management science literature, customer (demand) satisfaction is often used to measure the economic performance of the companies. This is due to the fact that unsatisfied demand leads to sales loss in the first place and might even lead to the loss of customer goodwill/loyalty in the long run, which is difficult to establish and critical to retain. Both of these result in poor financial performance for the company.

In this thesis, on the other hand, customer demand satisfaction is incorporated into the models revised in Chapters 5 and 6 as a social consideration. In doing so, our approach is not to ignore the economic impact of customer demand satisfaction but to point out to the fact that customers might also suffer from their demand being unsatisfied in a physical manner in certain cases. This situation emerges when the timely possession of the demanded product is critical and backlogging is not an option for the customer. Products related to customer’s physical health and safety (e.g. medical products or certain drugs which should be used on a continuous basis by the patients) constitute an example to this situation. Therefore, provision of a certain service level is not only economically desirable for the company but might also be socially crucial for the customers. In order to quantify customer satisfaction, fill rate and lost sales are appropriate and common metrics.

The social considerations due to supply chain operations regarding the parties outside the employees and customers include job/employment creation, regional development and public health and safety. Unemployment and underdevelopment rates, regional tax incentives/reductions are typical metrics to quantify employment and development [84, 85]. The public health and safety issue, on the other hand, reduces to the environmental footprint of the organization. Hence, considering environmental impacts of the organization is also to account for the social impacts via public health and safety. Still, considering only the environmental footprint towards sustainability objective cannot also be interpreted as social management through the consideration of public health and safety; since such an interpretation misses the other two groups: the employees and customers.

In addition to the above, other metrics may also be devised that would fit into a particular industrial setting through the analysis of the industrial engineering literature [86], CSR literature [87], the industrial and organizational psychology literature [88], and the human resources (HR) management literature [89]. For the industrial engineering literature, work analysis and design, financial compensation, human factors/ergonomics, and personnel management subjects are the primary areas to be investigated [86].

An aggregate metric from work design that accounts for all three pillars of sustainability is total productivity. It is stated as the amount of units output over the total inputs; i.e. the man-hours, pounds of material, and million British Thermal Units (BTUs) of energy [86]. This metric may also be disaggregated to account for each input type separately. Furthermore, Supply Chain Operations Reference (SCOR) model lists a large number of metrics including environmental ones in greenSCOR and social ones in the form of risk to be used in modeling [90].

3.5. Overview of the Applications of the Proposed Method

The proposed methodology is applied to various decision-making problems from diverse decision-making levels. Each of these applications constitutes a separate study and illustrates the effectiveness of the proposed method. In this section, these applications are summarized; however, the details of the applications might be found in the following chapters (Chapters 4-7), respectively.

Application 1: In the first application, an operational level supply chain operations decision-making - the *inventory control* - problem is addressed with the assumption of known demand [91]. The deterministic continuous review inventory control (EOQ) model is selected as the standard model. The model is then revised with carbon footprint and employee working hours considerations which are quantified by GHG emissions and required man-hours metrics, respectively. Based on these metrics, five environmentally revised (direct accounting, carbon tax, direct cap, cap and trade, and carbon offsets), two socially revised (direct accounting and direct cap), and two TBL accounting (direct accounting and direct cap) models are built. Except for the cap and trade and carbon offsets models, closed form solutions and sensitivity analyses are presented. Furthermore, for all of the revised models, corresponding mixed-integer nonlinear programming (MINLP) and NLP formulations are analyzed with illustrative data along with numerical sensitivity analyses.

Application 2: In the second application, again the inventory control problem is investigated except that the demand is assumed to be uncertain [92]. The single period stochastic inventory (newsvendor) model is selected as the standard model. The model is then revised with carbon footprint and customer satisfaction considerations. The carbon footprint consideration is again quantified by GHG emissions metric. On the other hand, the customer satisfaction consideration is quantified by fill rate and lost sales metrics. Based on these metrics, three environmentally revised (emissions cap, emissions tax, and cap and tax), three socially revised (target service level, penalty on lost sales, and penalty and target), and one TBL accounting models are built. For all of the revised models, closed form solutions and sensitivity analyses are presented. Furthermore, except for the cap and tax and penalty and target models, the NLP formulations corresponding to the rest of the revised models are analyzed with illustrative data along with numerical sensitivity analyses.

Application 3: In the third application, a tactical level supply chain operations decision-making – the *production planning* - problem is addressed [93]. The aggregate planning model is selected as the standard model. The model is then revised with carbon footprint, energy consumption, employee job-security and morale-motivation, employee health and work-family balance, and customer satisfaction considerations. The carbon footprint consideration is quantified by GHG emissions and the energy consumption consideration by the electricity/heat usage metrics. On the other hand, employee job-security and morale-motivation consideration is quantified by hirings and firings whereas employee health and work-family balance consideration by the overtime hours metrics. Finally, the customer satisfaction consideration is quantified by the fill rate metric. Based on these metrics, two environmentally revised (emissions cap and energy consumption cap), three socially revised (smoothing and layoff limits, overtime limit, and service level target), and one TBL accounting models are built. For all of the revised models, MILP formulations are analyzed with illustrative data along with numerical sensitivity analyses.

Application 4: In the fourth application, a strategic level supply chain operations decision-making – the *network design* - problem is addressed [94]. The uncapacitated facility location model is selected as the standard model. The model is then revised with carbon footprint, water pollution and soil contamination/land pollution, employment and regional development, and customer satisfaction considerations. The carbon footprint consideration is quantified by GHG emissions and water and land pollution consideration by the liquid and solid waste metrics. On the other hand, employment and regional development is quantified by the unemployment/underdevelopment rate or tax incentive/reduction rate metrics. Finally, the customer satisfaction consideration is already quantified by the fill rate metric and incorporated in the standard model with a service level target. Based on these metrics, two environmental objectives (GHG emissions and waste generation) and one social objective (employment and regional development) are constructed and one TBL accounting model is built. The TBL accounting model which is a multi-objective MILP is then analyzed with illustrative data using the weighted-sum method and solving the resulting MILP formulation.

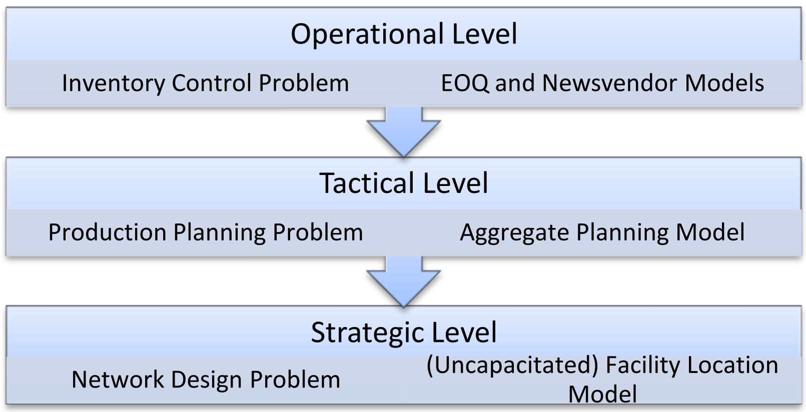


Figure 3.3 Selected problems and base models

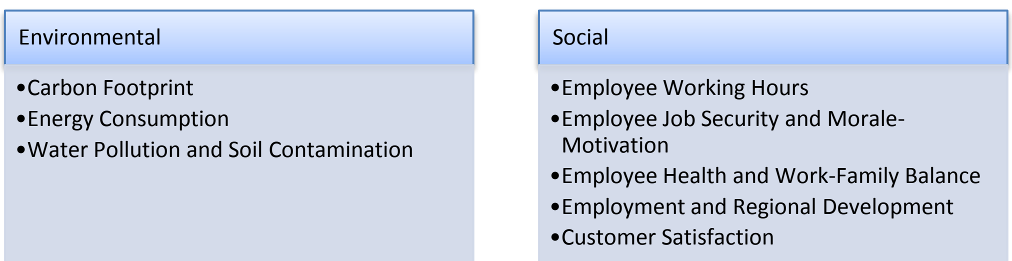


Figure 3.4 Some environmental and social considerations

The motivation of this research lies in the idea of enlarging the system boundary of supply chain decision-making by taking further considerations into account which stem from sustainability objective. Consequently, the proposed methodology is based on this motivation. Nevertheless, all of the problems considered in this thesis as an application of the proposed approach are from the point of a decision-maker who acts in a decentralized system.

On the other hand, a single decision-maker's effort in achieving sustainability is valuable for that particular entity but does not lead to the sustainability of the whole supply chain/network. Sustainability is a concept that has to be addressed system-wide, or globally. In other words, optimization with sustainability considerations at a particular entity of the supply chain system/network leads to a local optimum in terms of the sustainability performance of the overall chain/network. For instance, the carbon enhanced plan in Chapter 6 (see Table F.2) leads to an optimal solution where a considerable number of products are subcontracted from an outside party. This is due to the fact that the subcontractor is kept responsible for the carbon footprint of the transportation. However, this is not sustainable when the total emissions generated by the overall chain are considered.

Still, there are two reasons for constructing the methodology for a decentralized system:

i. It is hard to persuade the decision-makers to act in a coordinative manner rather than acting independently. In order to achieve coordination, certain incentives should be in place such as supply chain contracts. In a sustainable context, on the other hand, these contracts should be devised such that they coordinate the chain not only on cost but also on environmental and social considerations as well.

ii. Even if the decision-makers independently consider the environmental and social pillars of sustainability, the environmental and social benefits are already shared by all parties in a supply chain/network. Therefore, in an ideal situation where all of the parties consider their environmental and social footprint as well as their economic benefits, a significant progress in achieving sustainability can be made in a decentralized system.

3.6. Evaluation of the Proposed Method: Benefits

In this section, the benefits of the proposed method are evaluated based on its applications as discussed in the previous section:

i. The method prescribes a comprehensive treatment of sustainability with all three pillars.

Since environmental and social considerations are incorporated into the models along with the economical considerations, all three pillars of sustainability is addressed.

ii. The method addresses sustainability during decision-making.

The decisions made using the proposed method are based on the solution of revised models that consider the three dimensions of sustainability simultaneously. Therefore, the approach is fundamentally different than taking corrective actions to deal with the environmental and social problems resulting from the decisions made by using pure economical approaches.

iii. The method can be applied for all levels of supply chain operations decision-making.

The literature contains mathematical programming models for all three levels of supply chain operations decision-making. These models can be revised with environmental and social considerations.

iv. The method constitutes a quantitative framework with a theoretical basis.

The method is based on the revision of models of which the validity and applicability are already tested and the analysis of these models with the appropriate solution methods. Hence, it utilizes the strength of optimization theory. Furthermore, it allows the analysis of dynamic changes and what-if scenarios; hence is a quantitative framework of assessing sustainability in supply chain systems.

3.7. Conclusions

In this chapter, a methodological approach for sustainable supply chain management is proposed. In the sustainable supply chain and operations management literature, a conceptual framework with a theoretical background in analyzing sustainable supply chain systems is missing. Moreover, the social pillar is almost completely ignored. Adopting the proposed method fills both of these gaps, since it constitutes a quantitative framework with a theoretical basis and accounts for the three pillars of sustainability simultaneously.

The proposed method addresses sustainability during decision-making and can be applied for all levels of supply chain operations decisions. Therefore, using the proposed methodology in decision-making is a completely different treatment of sustainability than the conventional methods where the environmental and social outcomes of the decisions are to be dealt with later by taking corrective actions. It might be difficult to take such actions since the environmental and social impacts might be extremely hard to be reversed in many cases as they might be irreversible.

Chapter 4

Application to the Economic Order Quantity (EOQ) Model

4.1. Introduction

The EOQ model is a pure economic model in the classical inventory control theory. The model is designed to find the order quantity so as to minimize the total average cost of replenishment under deterministic demand and some simplifying assumptions. These assumptions (listed in section §4.2.1) are unrealistic; however, the simplicity and robustness of the model make it practical in most cases.

In this chapter, this practical model is revised to encompass a wider perspective of sustainability. The standard model is modified to further account for environmental and social criteria. These added criteria stem from the emerging requirement of sustainability in supply chain management. To achieve sustainability, the decision maker should incorporate these added dimensions into the decision-making process as well as the conventional economics. This approach is referred to as the "triple bottom line accounting" [2].

The triple bottom line accounting approach is applied in a methodological manner. The method is based on revising the standard EOQ model with additional objectives and/or constraints regarding those added criteria. Models for a number of different settings are proposed and these revised models are analyzed to characterize the optimal policy analytically and numerically. The analysis shows how these additional criteria can be appended to traditional cost accounting in order to achieve sustainability in supply chain management. A number of useful and practical results for managers and policy makers are presented.

4.2. Model Formulations and Analysis

4.2.1. The Standard Economic Order Quantity Model

The EOQ model arises from the simplest form of economies of scale [95]. The model assumes a single item at a single location with a continuous demand. The demand is known and has a constant rate, λ, over time. A supply of the required item is needed in order to satisfy the demand. Therefore, either the items are produced or an order to the supplier is placed. The model assumes constant lead times with an infinite supply capacity where stock-outs are not allowed. Under these assumptions, the EOQ problem is to decide on the order or production quantity Q which minimizes the total average cost of replenishment; i.e. we have a single decision variable, Q, which satisfies $Q^* = argmin\, C(\mathrm{Q})$ optimally; where $C(\mathrm{Q})$ denotes the total average cost of replenishment. $C(\mathrm{Q})$ has two components: replenishment cost and the inventory holding cost. The replenishment cost consists of purchasing/production cost and the ordering cost [7].

Let $I(t)$ denote the inventory level at time t. The inventory level in the EOQ model is assumed to be cyclic, each cycle starting from the inventory level $I(t) = Q$ with $I(0) = 0$ and gradually depleted until the end of the cycle with the constant demand rate. Therefore, we obtain an average inventory of ${}^{Q}\!/_{2}$ at each cycle and since the cycles are identical as Q units are ordered/produced each time, this result holds for any time horizon of many cycles [7]. Let h denote the cost per unit item held per unit time. Then the inventory holding part of $C(\mathrm{Q})$ becomes $h\,{}^{Q}\!/_{2}$. Let K denote the fixed/setup cost of ordering/production and c

denote the variable cost per unit ordered/produced. Then the sum of purchasing and ordering/production costs become $K + cQ$ at each cycle. Since each cycle is of length $T = {}^{Q}/_{\lambda}$, C(Q) is given by,

$$C(\mathrm{Q}) = \frac{K + cQ}{{}^{Q}/_{\lambda}} + h\,{}^{Q}/_{2} = \frac{K\lambda}{Q} + \lambda c + \frac{hQ}{2} \tag{4.1}$$

The optimal Q is then found by solving $C'(\mathrm{Q}) = 0$ and checking if $C''(\mathrm{Q}) > 0$ for convexity of the cost function. Since C(Q) is convex, the first order condition ensures optimality. Therefore the economic order quantity or the optimal Q to the above optimization problem is given by,

$$Q^* = \sqrt{\frac{2K\lambda}{h}} \tag{4.2}$$

which is also known as the Wilson's or Harris' formula [7, 96].

The EOQ model accounts solely for the economics of the replenishment and inventory holding activity related to the provision of the required items. Apart from the economic aspects, these activities also have impacts on the environment and the society which should be considered as well, as elaborated in the next sections.

4.2.2. EOQ Model with Environmental Consideration

In this section, the standard EOQ model is revised by taking carbon footprint into account. A typical environmental effect caused by most industrial operations is the inevitable release of greenhouse gases [29]. As a result, in order to assess the environmental performance of an organization, the amount of GHG emissions is commonly used in the green/environmentally conscious supply chain and operations management literature (see [29] and the references therein). The set of greenhouse gases including carbon dioxide released by an organization due to its operations is commonly referred to as the carbon footprint [74].

In this chapter, carbon footprint is considered in modeling the environmental criterion. Costs, emissions and the refined order/production quantities are observed under a number of different settings. In the following sections, five environmental management approaches each with different characteristics are modeled and analyzed.

4.2.2.1. Direct Accounting Model

The first approach to model carbon footprint is to treat it as an additional source of economic cost. Let f be the fixed cost of environmental impact for each replenishment cycle due to setups, order processing or transportation; v be the variable cost of environmental impact due to the production and related activities, and finally g be the cost of environmental impact due to the inventory holding as a result of material handling and warehousing activities. Environmental cost components as mentioned above (f, v, g) are in the form of monetary units as other EOQ parameters $K, c,$ and h. These cost parameters can be extracted from the cost accounting of environmental management activities of the organization or from the cost of energy used. More specifically, these parameters would be estimated through life cycle assessment data, production data and inventory management data. Although this is not an easy task, the organizations should estimate these parameters in order to comply with the emerging regulatory policies. One can refer to GHG Protocol [97], ISO [79], WRI [98], EcoTransIT [99] and Carbontrust [100] for carbon footprint measurement standards and methodologies.

With these additional parameters, we can rewrite $C(\mathrm{Q})$ as

$$C(\mathrm{Q}) = \frac{K+f+(c+v)Q}{Q/\lambda} + (h+g)\frac{Q}{2} = \frac{(K+f)\lambda}{Q} + \lambda(c+v) + \frac{(h+g)Q}{2} \tag{4.3}$$

and by a similar analysis as in the EOQ model, the optimal order/production quantity is found as

$$Q_{ee}^{*} = \sqrt{\frac{2(K+f)\lambda}{(h+g)}} \tag{4.4}$$

along with the optimal cost

$$C(Q_{ee}^{*}) = \frac{(K+f)\lambda}{\sqrt{\frac{2(K+f)\lambda}{(h+g)}}} + \lambda(c+v) + \frac{(h+g)\sqrt{\frac{2(K+f)\lambda}{(h+g)}}}{2}$$
$$= \lambda(c+v) + \sqrt{2(K+f)\lambda(h+g)} \tag{4.5}$$

where Q_{ee}^{*} denotes the optimal order/production quantity with economic and environmental criteria. A simple sensitivity of Q_{ee}^{*} with respect to Q^{*} yields

$$\frac{Q_{ee}^{*}}{Q^{*}} = \sqrt{\frac{Kh+fh}{Kh+gK}} \tag{4.6}$$

and the following set of relationships hold:

(i) $\quad Q_{ee}^{*} = Q^{*} \Leftrightarrow \frac{K}{h} = \frac{f}{g}$ (4.7)

(ii) $\quad Q_{ee}^{*} > Q^{*} \Leftrightarrow \frac{K}{h} < \frac{f}{g}$ (4.8)

(iii) $$Q_{ee}^* < Q^* \Leftrightarrow \frac{K}{h} > \frac{f}{g} \quad (4.9)$$

Hence, the optimal order/production quantity is governed by the trade-off between replenishment and inventory holding costs with the only change of added environmental cost components. The refined optimal order/production quantity may be larger or smaller than the EOQ as it might be equal to it as well depending on the values of the cost components.

Eq. (4.4) resembles the usual EOQ apart from f and g. If these added parameters are incorporated into K and h, then Eq. (4.4) reduces to EOQ exactly. Otherwise, one of the cases in Eq. (4.7), (4.8) or (4.9) applies. The unit inventory holding cost, h, incorporates the opportunity cost of the capital committed in addition to the real costs of inventory holding. However, such an argument is clearly not valid for g. Hence, g might be smaller than h in most practical situations. On the other hand, fixed environmental impacts are induced at all stages of the production, transportation, and order processing activities. Hence f might be larger than K. Therefore, Eq. (4.8) is more likely to be realized when the added environmental impact is considered; i.e. $Q_{ee}^* > Q^*$.

The direct accounting approach is an optional one and left to the discretion of the managers of the organization, i.e. organizations may or may not calculate total cost by using the environmental cost components. However, the above analysis shows that there is value for the organization in investigating the sources of emissions and the related costs.

4.2.2.2. Carbon Tax Model

Organizations may be given incentive to account for the environmental costs through an externally applied carbon tax by the regulatory agencies. A simple tax schedule is a linear one; i.e. organizations pay an amount of p money-units for each unit of carbon emitted. However, other tax schedules including convex/progressive, concave/regressive, non-linear, piecewise linear, or staircase may also be applied as well. The linear tax schedule is considered in this chapter. The refined model with a linear tax schedule is as follows:

$$C(\mathrm{Q}) = \frac{K+pf+(c+pv)Q}{Q/\lambda} + (h+pg)\frac{Q}{2} = \frac{(K+pf)\lambda}{Q} + \lambda(c+pv) + \frac{(h+pg)Q}{2} \qquad (4.10)$$

and by a similar analysis as in the EOQ model, the optimal order/production quantity is found as

$$Q_{ee}^{*} = \sqrt{\frac{2(K+pf)\lambda}{(h+pg)}} \qquad (4.11)$$

which yields the following optimal cost

$$C(Q_{ee}^{*}) = \frac{(K+pf)\lambda}{\sqrt{\frac{2(K+pf)\lambda}{(h+pg)}}} + \lambda(c+pv) + \frac{(h+pg)\sqrt{\frac{2(K+pf)\lambda}{(h+pg)}}}{2}$$

$$= \lambda(c+pv) + \sqrt{2(K+pf)\lambda(h+pg)} \qquad (4.12)$$

Note that f, v, and g now directly denote the amount of emissions in the preceding analysis. Multiplying them with the tax rate p again transforms the emissions into costs in monetary units. Incorporating a linear tax schedule is similar to the direct accounting of the environmental costs except for f and g being replaced by pf and pg. When a sensitivity analysis of Q_{ee}^{*} with respect to Q^{*} is conducted, the same conditions may easily be obtained as in the direct accounting (Eq. 4.6-4.9) setting, independent of the tax rate p. In other words, the tax rate, p, in a linear tax schedule does not have an impact on the optimal policy; i.e. the order/production quantity in this setting. However, it affects the total average cost as seen in Eq. (4.12). Hence, taxing carbon emissions gives incentive to identify emission sources, estimate the emission parameters and curb the emissions to achieve lower operating cost. Therefore, applying a carbon tax schedule suitable with the macroeconomic policy of a country is a useful tool for the regulatory agencies.

4.2.2.3. Direct Cap Model

Letting f, v, and g directly denote the emission amounts due to their respective activities is another approach, as applied in modeling the carbon tax setting. This approach also facilitates estimating the values of these environmental parameters. In this subsection, this approach is considered for the analysis. For a more complete discussion on the sources of carbon emissions in inventory control, one can refer to Penman and Stock [101], Stock [102], Stock et al. [103] and Sundarakani et al [104].

The model in Eq. (4.3) and the preceding analysis in the direct accounting section ignore the total impact on environment caused by replenishment and inventory holding, since direct accounting for environmental costs does not give the organization an initiative to curb the emissions. Furthermore, not all organizations consider these costs willingly. This may not be true in case of a carbon tax imposed by the regulatory agencies where tax increases the monetary costs and the organizations are enforced to consider their environmental impact, as a consequence (see discussion on the carbon tax above).

An alternative modeling scheme is the one where a direct cap on environmental footprint is imposed either by the regulatory agencies or by the public awareness such that customers are seeking for more environmentally friendly products. In other words, the demand for the products may depend on the emission levels of the organization during the supply of its products to the customers.

Assume that there is an upper limit on the amount of GHG emissions, denoted by ζ, as in the case of the countries signed the Kyoto Protocol [105]. Assume further that the above environmental cost parameters (f, v, g) now denote the amount of emissions due to their respective activities mentioned before. Since the EOQ model is based on a single cycle and since the cycles are identical, ζ may also be assumed to be an upper bound on the average amount of GHG emissions per cycle (inducing a cap per unit product is another way of modeling, which would be used for gathering customer attention by carbon labeling the product; see Brenton et al. [106]; Edwards-Jones et al. [107]; see also Section §4.3.2.3 for more details in carbon labeling). Therefore, the refined problem becomes

$$minimize\ C(\mathrm{Q}) = \frac{K\lambda}{Q} + \lambda c + \frac{hQ}{2} \tag{4.13}$$

$$subject\ to$$

$$\frac{f+vQ}{Q/\lambda} + g\,{Q}/{2} \leq \zeta \tag{4.14}$$

$$Q \geq 0 \tag{4.15}$$

This new model resembles the resource constrained EOQ model where a traditional case is to incorporate a linear constraint on the available warehouse space [7]. However in the above case, the constraint is nonlinear. Optimal policy is to order/produce the standard optimal of the EOQ model if it satisfies the constraint in Eq. (4.14). In this case, the optimal cost is the usual EOQ optimal given by,

$$C(\mathrm{Q}^{*}) = \frac{K\lambda}{\sqrt{2K\lambda/h}} + \lambda c + \frac{h\sqrt{2K\lambda/h}}{2} = \lambda c + \sqrt{2K\lambda h} \tag{4.16}$$

and the emission amount becomes

$$EM(\mathrm{Q}^*) = \frac{f\lambda}{\sqrt{2K\lambda/h}} + \lambda v + \frac{g\sqrt{2K\lambda/h}}{2} \tag{4.17}$$

Otherwise, the constraint is binding at optimality and the optimal order/production quantity to the above problem is found by solving the quadratic equation,

$$\frac{f\lambda}{Q} + \lambda v + \frac{gQ}{2} = \zeta \tag{4.18}$$

which yields

$$Q_{ee}^* = \frac{\zeta - \lambda v \pm \sqrt{(\lambda v - \zeta)^2 - 2g\lambda f}}{g} \tag{4.19}$$

and $EM(\mathrm{Q}_{\mathrm{ee}}^*) = \zeta$. Similarly, the optimal total cost may be found by plugging Q_{ee}^* into Eq. (4.13).

Note that any order quantity should be a nonnegative real value to be valid. However, Eq. (4.18) may not have a real root or have two distinct or identical roots, depending on the parameters. If it has real roots, either one or both of the roots may be negative. Hence, the optimal policy is governed by the relationship among environmental and economic parameters of the organization.

If the objective is to minimize purely the emissions, the optimal order/production quantity would be,

$$Q_e^* = \sqrt{\frac{2f\lambda}{g}} \tag{4.20}$$

and apparently, Q_{ee}^{*} is in between Q_{e}^{*} and Q^{*} provided that $\frac{K}{h} \neq \frac{f}{g}$.

4.2.2.4. Cap and Trade Model

Another important mechanism to curb the emissions is the carbon trading markets, simply called as cap and trade. In this setting, companies emitting less than the allowed cap are rewarded whereas those over emitters are penalized. This penalty and reward mechanism is achieved via a carbon trading market. Companies emitting lower than the cap sell their allowances, which stand for the difference between their actual emissions and the effective carbon cap; whereas those emitting more than the cap buy such allowances. Therefore, the caps are not strict but encouraging in a cap and trade system. Such markets have already been developed in EU and US and the participation of the companies in the system is mandatory [108, 109]. This market trades significant volumes now, and has a potential to grow up further [108].

Let the assumptions of the direct cap system hold along with the model parameters. Since the environmental parameters in the direct cap system denote the emission amounts due to their respective activities, emissions are accounted directly in the cap and trade system as in the direct cap system. Assume further that p now denotes the price of the carbon which is fixed and externally set by the market mechanism. Let s^{+} denote the amount of allowances sold by the organization and s^{-} denote the amount of allowances bought by the organization. Note that only one of these trading variables may be positive; i.e. the organization either buys or sells allowances. The optimal order/production quantity and the amount of allowances either sold or bought by the organization are found by solving the following mixed integer nonlinear program:

$$minimize\ C(\mathrm{Q}) = \frac{K\lambda}{Q} + \lambda c + \frac{hQ}{2} + p(s^- - s^+) \tag{4.21}$$

$$subject\ to$$

$$\frac{f+vQ}{Q/_{\lambda}} + g\,{}^{Q}/_{2} - s^- + s^+ \leq \zeta \tag{4.22}$$

$$s^- \leq y_1 M \tag{4.23}$$

$$s^+ \leq y_2 \zeta \tag{4.24}$$

$$y_1 + y_2 = 1 \tag{4.25}$$

$$Q, s^+, s^- \geq 0 \tag{4.26}$$

$$y_1, y_2 \in \{0,1\} \tag{4.27}$$

where M is a large positive number. The optimal cost and the emissions may also be obtained by solving the above model. Note that under the above model with a nonnegative carbon price, there are three options for the organization: (i) organization buys allowances if there is not a feasible Q satisfying Eq. (4.14), (ii) neither buys nor sells allowances if there is a feasible Q satisfying Eq. (4.14) at equality, (iii) and sells allowances if the constraint is satisfied but is not tight.

In this system, one important parameter is the carbon price, which appears to vary between 0 and 30 euro-cents per ton in the EU ETS [110]. This price is an exogenous system parameter determined by the market mechanism and assumed to be fixed in the above model. An alternative and intuitive scenario is the case where carbon price is dependent on the carbon cap. If the cap is tighter, the price of the allowance should obviously be higher. Therefore, one can assume an inversely proportional relation between p and ζ as such:

$$b = p + a\zeta \tag{4.28}$$

where a and b are assumed to be nonnegative scalars without loss of generality. The above model can be readjusted to incorporate such a relationship by plugging in $p = b - a\zeta$.

If regulatory agencies regulate the trading market by setting the carbon price, a macroeconomic view is needed as in the carbon tax model.

4.2.2.5. Carbon Offsets Model

The final environmental management mechanism discussed in this chapter is carbon offsets which stand for emission reducing investments. These investments may be in the form of energy efficient equipment and facilities, renewable energy resources, energy saving programs, carbon capturing and sequestration (CCS) systems, to name a few. The organization pays a price for the offset in return for reduced carbon footprint due to the increased technology and environmentally friendly resources.

Let the assumptions of the cap and trade system hold except for p now denoting the unit price of the offsets and s^- denoting the amount of offset purchased by the organization. It is assumed that the offset directly relax the carbon emission constraint and does not reduce the values of emission parameters although this might be the case and modeled as well. The optimal order/production quantity and the amount of offset purchased may be found by solving the following nonlinear program:

$$minimize\ C(Q) = \frac{K\lambda}{Q} + \lambda c + \frac{hQ}{2} + ps^- \qquad (4.29)$$

$$subject\ to$$

$$\frac{f+vQ}{Q/\lambda} + g\,Q/2 - s^- \leq \zeta \qquad (4.30)$$

$$Q, s^- \geq 0 \qquad (4.31)$$

The optimal cost and emissions may also be obtained by solving the above nonlinear programming problem. However, it is important to note that buying offsets is reasonable only in the case that there is no feasible Q satisfying Eq. (4.14). In such a case, it is mandatory to buy offsets to be able to maintain the operations due to the cap exercised.

The model for carbon offsets is similar to the model for cap and trade mechanism except for the allowances sold (s^+) in the cap and trade system. As in the cap and trade system, the emission amounts are directly accounted without converting them into monetary units. Moreover, a similar relationship between the offset price, p, and the carbon cap, ζ, may also be considered as in the cap and trade system. Instead of a fixed price, p may be inversely proportional to the carbon cap ζ.

Purchasing offsets is optional for the organization although it is mandatory to participate in the cap and trade system. It may be the case that the market demands cleaner products with cleaner technology and energy. In such a case, carbon offsetting becomes obligatory in a sense for the organization to ensure competitive advantage. Nevertheless, this situation enables the organization to carbon-label its products and charge relatively larger prices to those environmentally sensitive customers. Let r_1 denote the price charged to usual customers and r_2 denote the price charged to environmentally sensitive customers when the organization purchases some offsets ($r_2 \geq r_1 \geq c$). Then, the joint pricing and ordering/production model for the standard case is as follows:

$$minimize\ C(\mathrm{Q}) = \frac{K\lambda}{Q} + \lambda(c - r_1) + \frac{hQ}{2} \tag{4.32}$$

$$subject\ to$$

$$\frac{f + vQ}{Q/\lambda} + g\, Q/2 \leq M \tag{4.33}$$

$$Q \geq 0 \tag{4.34}$$

where M is a sufficiently large nonnegative carbon cap enabling a feasible Q satisfying Eq. (4.33). On the other hand, the model with offsets can be formulated as follows:

$$minimize\ C(\mathrm{Q}) = \frac{K\lambda}{Q} + \lambda(c - r_2) + \frac{hQ}{2} + ps^- \tag{4.35}$$

$$subject\ to$$

$$\frac{f+vQ}{Q/\lambda} + g\,{}^{Q}\!/_{2} - s^- \leq \zeta \tag{4.36}$$

$$Q, s^- \geq 0 \tag{4.37}$$

where ζ is sufficiently tighter which does not allow a feasible Q satisfying Eq. (4.14).

A numerical comparison of the above two models as can be seen in §4.3.2.3 reveals the extent to which organizations may charge a relatively higher price for more environmentally friendly supply of products using carbon offsets and tighter carbon caps to those environmentally sensitive customers. This is not valid, of course, in markets where customers are non-sensitive to environmental friendliness.

4.2.3. EOQ Model with Social Consideration

The CSR literature has been the primary area of investigation in terms of incorporating social criteria of sustainability. There is a vast body of literature on this subject; however, a literature review conducted in this area reveals that there are no studies concerned directly with the modeling of CSR aspects in supply chain and operations management problems in the open literature. When seeking appropriate supply chain metrics, SCOR model is the classical reference [90]. However, it does not provide any social metrics for supply chain modeling. The sustainable supply chain management literature also lacks social aspects as mentioned previously in the literature review section [1]. As a result, there is no straight forward metric available to use in modeling the social criteria. On the other hand, ILO provides labor standards from which one can extract social metrics to be used in modeling the social criteria. Therefore, the analysis relies on the labor standards put forth by ILO.

According to ILO; there must be a legal upper limit on the working hours of employees [82-83]. On the other hand, the available man-hours is inevitably exhausted by the operations. Therefore, in order to assess the social performance of an organization, the amount of man-hours required to perform the operations can be used as a valid metric. Hence, the analysis accounts for the required man-hours in modeling the social criterion. Direct accounting and direct cap approaches are employed.

4.2.3.1. Direct Accounting Model

The following parameters are used: m denote the fixed amount of man-hours required due to setups, order processing or transportation, n denote the variable amount of man-hours required due to the production and related activities, and l denote the man-hours required due to the inventory holding as a result of material handling and warehousing activities. By using the labor cost accounting, the cost of labor per man-hour can be easily obtained. Multiplication of the above man-hour requirement parameters with this cost factor yields the corresponding man-hour cost parameters of each activity. Let m, n, and l also denote their respective cost correspondents. Assume further that the total available man-hours during a cycle is denoted by W.

Using a similar aggregation of costs as in deriving Q_{ee}^*, we can derive Q_{se}^*, the optimal order/production quantity with social and economic criteria, as

$$Q_{se}^* = \sqrt{\frac{2(K+m)\lambda}{(h+l)}} \tag{4.38}$$

and the corresponding optimal cost as

$$C(Q_{se}^{*}) = \frac{(K+m)\lambda}{\sqrt{\frac{2(K+m)\lambda}{(h+l)}}} + \lambda(c+n) + \frac{(h+l)\sqrt{\frac{2(K+m)\lambda}{(h+l)}}}{2}$$

$$= \lambda(c+n) + \sqrt{2(K+m)\lambda(h+l)} \qquad (4.39)$$

Furthermore, the following relationships hold:

(i) $Q_{se}^{*} = Q^{*} \Leftrightarrow \frac{K}{h} = \frac{m}{l}$ (4.40)

(ii) $Q_{se}^{*} > Q^{*} \Leftrightarrow \frac{K}{h} < \frac{m}{l}$ (4.41)

(iii) $Q_{se}^{*} < Q^{*} \Leftrightarrow \frac{K}{h} > \frac{m}{l}$ (4.42)

The values of m, n, and l rely on the abilities of the employees and the design of the work environment. One can argue that n and l are getting smaller due to automation in production environments whereas m is most likely to be stable as a global trend. However, when they are assumed to represent their cost correspondents, they differ significantly between the developed and developing/under-developed countries. Hence, the above equations (4.40-4.42) explain why under-developed countries exercise low quality mass production whereas the developed countries produce quality products in relatively higher lots. This also lays the foundation for mass customization in the developed countries where customization is achieved in a mass production setting.

4.2.3.2. Direct Cap Model

Alternatively, since there is a legal upper limit on working hours and not all companies account for social costs willingly, the constrained-EOQ logic might also be employed and the problem might be formulated as follows:

$$minimize\ C(\mathrm{Q}) = \frac{K\lambda}{Q} + \lambda c + \frac{hQ}{2} \tag{4.43}$$

$$subject\ to$$

$$\frac{m+nQ}{Q/_{\lambda}} + l\,{}^{Q}/_{2} \leq W \tag{4.44}$$

$$Q \geq 0 \tag{4.45}$$

If the standard EOQ optimal satisfies the constraint in Eq. (4.44), it is still optimal for the above model. Then, the optimal cost is again the usual EOQ optimal given by $C(\mathrm{Q}^*) = \lambda c + \sqrt{2K\lambda h}$ whereas the required man-hours is obtained by,

$$RM(\mathrm{Q}^*) = \frac{m\lambda}{\sqrt{2K\lambda/_{h}}} + \lambda n + \frac{l\sqrt{2K\lambda/_{h}}}{2} \tag{4.46}$$

Otherwise, the constraint is binding at optimality and the optimal order/production quantity to the above problem is found by solving the quadratic equation,

$$\frac{m\lambda}{Q} + \lambda n + \frac{lQ}{2} = W \tag{4.47}$$

which yields

$$Q^*_{se} = \frac{W-\lambda n \pm \sqrt{(\lambda n - W)^2 - 2l\lambda m}}{l} \tag{4.48}$$

and $RM(\mathrm{Q}^*_{\mathrm{se}}) = W$. Similarly, the optimal total cost may be found by plugging Q^*_{se} into Eq. (4.43). The existence of a feasible Q^*_{se} depends on the values of the parameters of the above model as discussed previously for Q^*_{ee}.

If the objective is to minimize purely the man-hours, the optimal order/production quantity would be,

$$Q_s^* = \sqrt{\frac{2m\lambda}{l}} \tag{4.49}$$

and apparently, Q_{se}^* is in between Q_s^* and Q^* provided that $\frac{K}{h} \neq \frac{m}{l}$.

4.2.4. EOQ Model with Triple Bottom Line (TBL) Accounting

In this part, the case where the three pillars of sustainability are analyzed simultaneously is considered. The three pillars are modeled using the direct accounting and direct cap modeling approaches, since these approaches are common for both the environmental and the social criteria. However, different modeling approaches may also be picked for environmental and social pillars like using cap and trade model for carbon footprint and direct cap modeling for man-hours as well. The economic, environmental and social parameters are assumed to be same as in the previous sections.

4.2.4.1. Direct Accounting Model

By using the direct accounting approach, one can easily find out Q_{ees}^*, the optimal order/production quantity with economic, environmental, and social criteria as

$$Q_{ees}^* = \sqrt{\frac{2(K+f+m)\lambda}{(h+g+l)}} \tag{4.50}$$

with $C(Q_{ees}^*)$ as

$$C(Q_{ees}^*) = \frac{(K+f+m)\lambda}{\sqrt{\frac{2(K+f+m)\lambda}{(h+g+l)}}} + \lambda(c+v+n) + \frac{(h+g+l)\sqrt{\frac{2(K+f+m)\lambda}{(h+g+l)}}}{2}$$

$$= \lambda(c+v+n) + \sqrt{2(K+f+m)\lambda(h+g+l)} \qquad (4.51)$$

and deduce the following:

(i) $Q_{ees}^* = Q^* \Leftrightarrow \frac{K}{h} = \frac{f+m}{g+l}$ (4.52)

(ii) $Q_{ees}^* > Q^* \Leftrightarrow \frac{K}{h} < \frac{f+m}{g+l}$ (4.53)

(iii) $Q_{ees}^* < Q^* \Leftrightarrow \frac{K}{h} > \frac{f+m}{g+l}$ (4.54)

4.2.4.2. Direct Cap Model

The optimal order/production quantity may also be found using the direct cap modeling approach as the solution of the following nonlinear program:

$$minimize\ C(\mathrm{Q}) = \frac{K\lambda}{Q} + \lambda c + \frac{hQ}{2} \qquad (4.55)$$

$$subject\ to$$

$$\frac{f+vQ}{Q/_{\lambda}} + g\,{}^{Q}/_{2} \leq \zeta \qquad (4.56)$$

$$\frac{m+nQ}{Q/_{\lambda}} + l\,{}^{Q}/_{2} \leq W \qquad (4.57)$$

$$Q \geq 0 \qquad (4.58)$$

If the standard EOQ optimal satisfies the above constraints, then it is still optimal. Otherwise one of the constraints is binding at optimality and either $Q_{ees}^* = Q_{ee}^*$ or $Q_{ees}^* =$

Q_{se}^{*} provided that there is a feasible solution to the above model. The resulting optimal emission amounts and the required man-hours may also be obtained by plugging Q_{ees}^{*} into Eq. (4.56) and (4.57).

4.3. Numerical Analysis of the Revised Models

In this section, numerical experiments are presented that are conducted for the analysis of the revised models in §4.2. In particular, the following are investigated numerically: (i) the optimal policy and the resulting performance measures of the unconstrained models and (ii) the sensitivity of the optimal policy and total cost with respect to changes in the exogenous model parameters of the constrained models; i.e. the emissions cap, ζ; the carbon/offset price, p; and the man-hours cap, W. Table A.1 provides the data used throughout the experiments. The solutions are obtained using the default NLP and MINLP solvers of GAMS using default solver options [111, 112, 113].

4.3.1. Analysis with the Unconstrained Models

First, the optimal policy and the resulting performance measures of the unconstrained models are investigated.

Table 4.1 Optimal Pure Policies and Resulting Performance Measures

Models	*Lot Size*	*Cost*	*Emissions*	*Required Man-hours*
Standard (Pure Cost)	44.72	**689.44**	339.44	245.84
Pure Emissions	77.46	703.28	**327.46**	278.11
Pure Working Hours	7.07	889.91	677.80	**214.14**

Table 4.1 suggests that one should order/produce in the amount of $Q^{*} = 44.72$ units if the objective is purely to minimize the economic costs. In return, a total cost in the amount of $C(Q^{*}) = 689.44$ monetary-units would be incurred. Furthermore, ordering/producing 44.72 units would lead to an emissions amount of $EM(Q^{*}) = 339.44$ units and requires

$RM(Q^*) = 245.84$ units of man-hours. On the other hand, the order/production quantity would be in the amount of $Q_e^* = 77.45$ units with a total cost of $C(Q_e^*) = 703.28$ monetary-units if the objective is to minimize purely the emissions. With this environmental policy, the emission amount is reduced by %3.5; to an amount of $EM(Q_e^*) = 327.45$ units whereas required man-hours increase by 13.12%; to an amount of $RM(Q_e^*) = 278.11$ units. Similarly, the lot size would be $Q_s^* = 7.07$ units with a total cost of $C(Q_s^*) = 889.91$ units if the objective is to minimize purely the required man-hours. With this social policy, the emissions amount is almost doubled with an amount of $EM(Q_s^*) = 677.80$ units whereas the required man-hours is reduced by 12.89%; to an amount of $RM(Q_s^*) = 214.14$ units. Table 4.1 numerically presents the extreme values that the policy and resulting performance measures might take.

Table 4.2 Optimal Policy and Performance Measures for Unconstrained Models

Models	*Lot Size*	*Cost*	*Emissions*	*Required Man-hours*
Direct Emissions Acc.	57.74	1023.21	**330.83**	258.60
Carbon Tax	69.69	2337.85	**327.89**	270.41
Direct Man-hours Acc.	32.02	928.06	359.71	**233.58**
Direct TBL Acc.	44.94	**1274.72**	**339.22**	**246.06**

As seen in Table 4.2, the direct emissions accounting and carbon tax models suggest a lot size (Q_{ee}^*) which is larger than the standard EOQ optimal; since $\frac{K}{h} < \frac{f}{g}$. Moreover, the resulting cost ($C(Q_{ee}^*)$) and required man-hours ($RM(Q_{ee}^*)$) are higher in return for reduced emissions ($EM(Q_{ee}^*)$) with respect to the standard model. On the other hand, the direct man-hours accounting model suggests a lot size (Q_{se}^*) which is smaller than the standard EOQ optimal; since $\frac{K}{h} > \frac{m}{l}$, which leads to a reduction in the required man-hours ($RM(Q_{se}^*)$) whereas an increase in cost ($C(Q_{se}^*)$) and emissions ($EM(Q_{se}^*)$). Finally, direct TBL accounting suggests a lot size (Q_{ees}^*) close to the standard EOQ optimal (since $\frac{K}{h} \sim \frac{f+m}{g+l}$) and in between the values proposed individually by the unconstrained environmental and social models so as to balance the trade-off between these two additional criteria. Note also that the resulting performance measures proposed by the TBL accounting model – $EM(Q^*_{ees})$ and $RM(Q^*_{ees})$ – are also close to the ones proposed by the standard model except the total cost $C(Q^*_{ees})$, which is higher due to the change in calculating the total cost (see Eq. (4.51)).

4.3.2. Analysis with the Constrained Models

In this subsection, the sensitivity of the optimal policy and total cost with respect to changes in the exogenous model parameters of the constrained models are investigated. In particular, the analysis of the policy and cost under varying values of the emissions cap, ζ, the carbon/offset price, p, and the man-hours cap, W are presented.

4.3.2.1. Carbon Cap Model

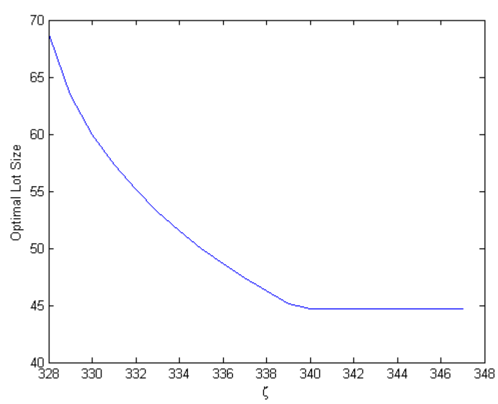


Figure 4.1 Lot Size - Carbon Cap

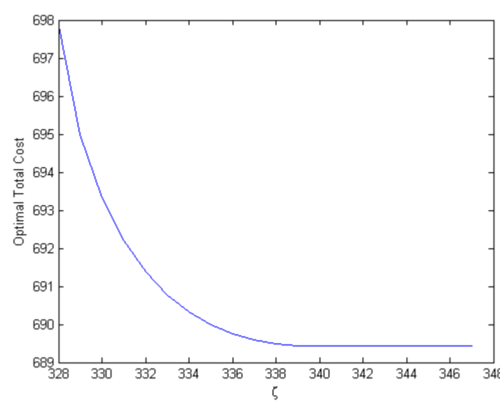


Figure 4.2 Total Cost - Carbon Cap

Figures 4.1 and 4.2 show how optimal lot size and the resulting total cost changes as the emission cap is relaxed in the direct emissions cap model. Note that for $\zeta < EM(Q^*_e)$, the model is infeasible. The optimal production lot size and the resulting optimal total cost decreases as the cap is relaxed. However, since the constraint is nonbinding for $\zeta > EM(Q^*)$, the standard optimal production lot size is feasible and optimal beyond such values of ζ. Therefore, no change in the policy and total cost is observed for the values of the emissions cap beyond this threshold value. Using these figures enables the decision-maker to address a certain level of emissions by implementing the corresponding optimal production lot size and assess the resulting optimal total cost.

4.3.2.2. Cap and Trade Model

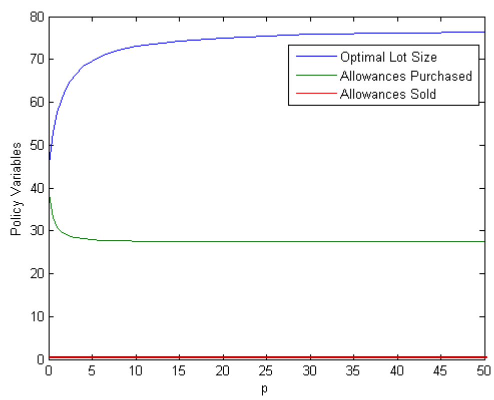


Figure 4.3 Policy - Carbon Price

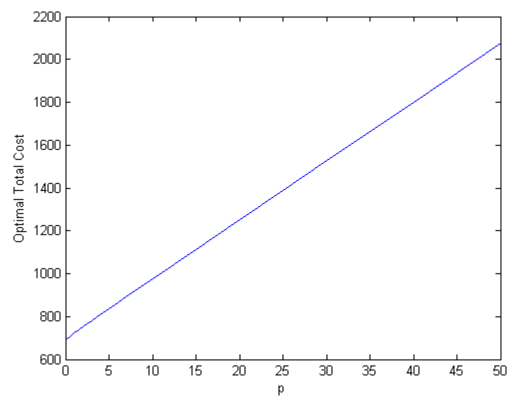


Figure 4.4 Total Cost - Carbon Price

Figures 4.3 and 4.4 show that organizations buy allowances whenever $p \geq 0$ and $\zeta < EM(Q_e^*)$ $(\zeta = 300)$. For $p = 0$, the policy is reduced to ordering/producing Q^*, since buying allowances becomes cost-free in this extreme case. In other words, $p = 0$ is equal to carbon cap constraint being inactive whatever the value of ζ is. As p increases, the policy tends to move towards ordering/producing Q_e^* with higher total cost while the amount of allowances bought is reduced gradually to the value of $EM(Q_e^*) - \zeta$. It is assumed that p is externally set by the regulatory agencies or the market mechanism. In this case, all organizations decide and operate under the given price.

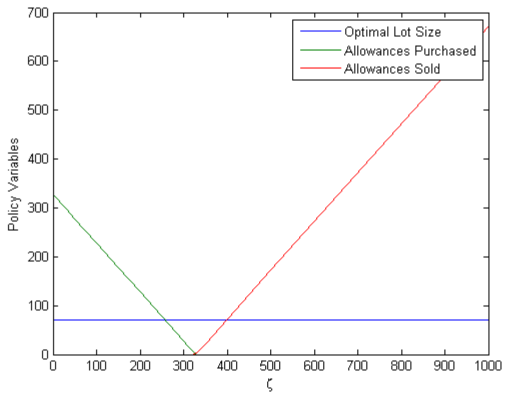


Figure 4.5 Policy - Carbon Cap

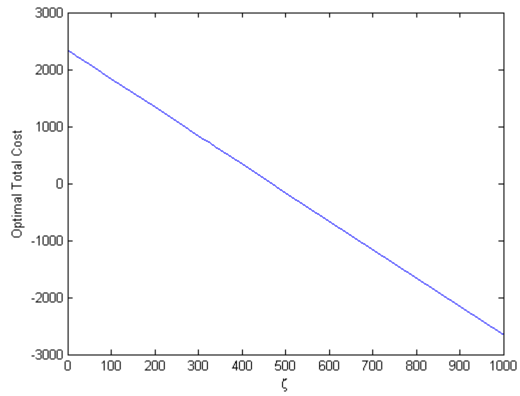


Figure 4.6 Total Cost - Carbon Cap

Figures 4.5 and 4.6 suggest that varying the carbon cap while carbon price is fixed ($p = 5$) does not have an impact on the optimal order/production quantity. Conversely, varying the price affects the policy, as seen in Figure 4.3. Intuitively, one would expect that when $\zeta > EM(Q^*)$, the policy should be reduced to ordering/producing Q^* (as in Figure 4.11). However, for such values of ζ, the organization makes money and reduces costs further by selling allowances in a cap and trade system, which is the main difference when compared to the carbon offset mechanism.

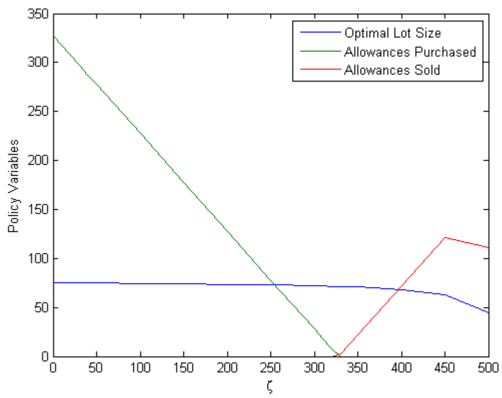


Figure 4.7 Policy - Cap-dependent Price

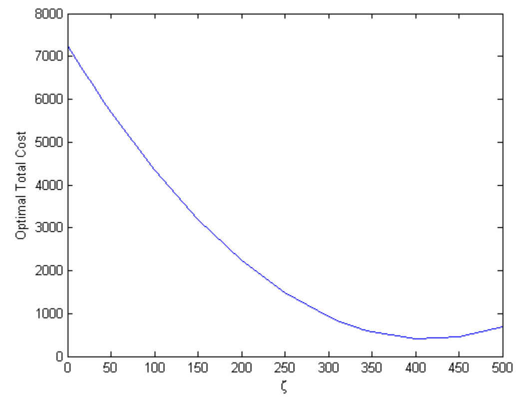


Figure 4.8 Total Cost - Cap-dependent Price

When the market price of the carbon is dependent on the cap $(20 = p + 0.04\zeta)$ exercised by the regulatory agencies or by the market mechanism like customer preferences, the effect of varying the carbon cap and price is experienced jointly. Figures 4.7 and 4.8 are similar to Figures 4.5 and 4.6 except for the policy being changed as well as higher costs being observed for smaller values of ζ due to higher carbon prices. Note how $C(Q)$ is diminished as ζ gets larger. Note also that in a cap and trade system, organizations buy allowances until ζ is relaxed sufficiently (i.e. $\zeta \geq EM(Q_e^*)$) and sells allowances then onwards.

4.3.2.3. Carbon Offsets Model

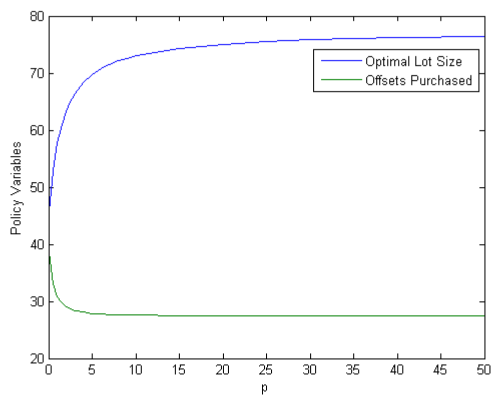


Figure 4.9 Policy - Offset Price

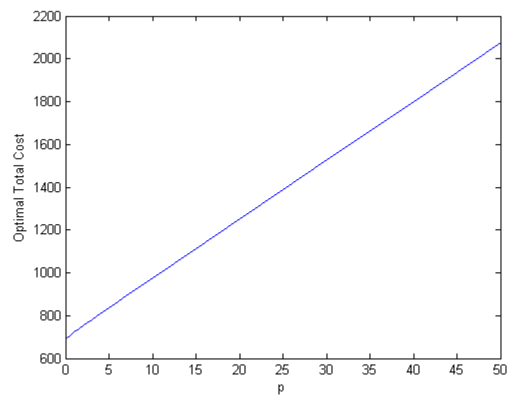


Figure 4.10 Total Cost - Offset Price

Figures 4.9 and 4.10 are exactly equivalent to Figures 4.3 and 4.4 except for the s^+ data series, which is not valid for carbon offset model; since nothing is sold in a carbon offset setting. This shows that when $\zeta < EM(Q_e^*)$ $(\zeta = 300)$, both systems respond to changes in p in the same manner; although p denotes carbon price in the cap and trade system whereas it denotes the offset price in the carbon offset mechanism. As price increases, the amount of offset purchased, s^-, decreases whereas order/production quantity increases, similar to the cap and trade system except for s^- denoting carbon allowances purchased in a cap and trade system.

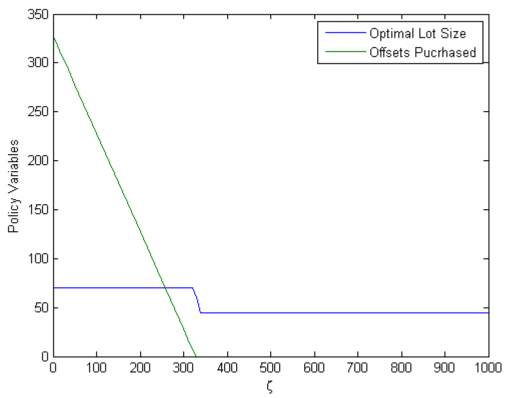


Figure 4.11 Policy - Carbon Cap

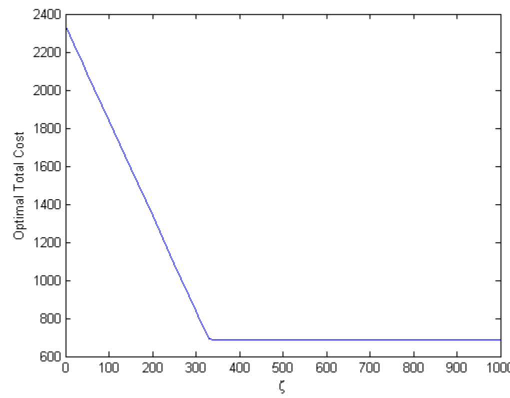


Figure 4.12 Total Cost - Carbon Cap

Figures 4.11 and 4.12 are also similar to Figures 4.5 and 4.6 except for the s^+ series, which is not valid for carbon offset model. This shows that when $\zeta < EM(Q_e^*)$, both systems respond to changes in ζ in the same manner given a fixed offset price, p ($p = 5$). However, when $\zeta > EM(Q_e^*)$, no offsets are being purchased and the policy is gradually reduced to ordering/producing Q^* as $\zeta > EM(Q^*)$. Furthermore, $C(Q)$ becomes stable as $\zeta \geq EM(Q^*)$. Therefore, the offset system gives incentive to curb the emissions only if $\zeta < EM(Q_e^*)$.

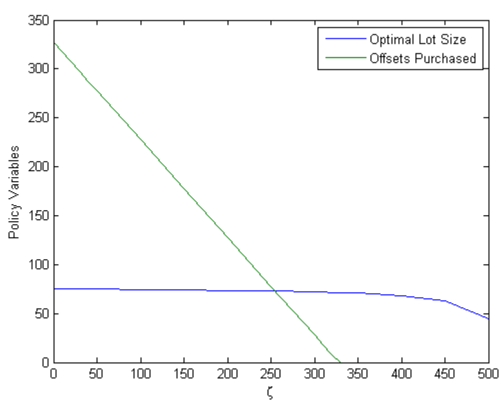


Figure 4.13 Policy - Cap-dependent Price

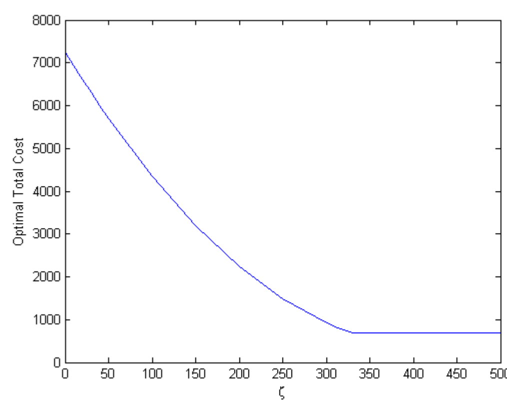


Figure 4.14 Total Cost - Cap-dependent Price

When the offset price is dependent on the cap $(20 = p + 0.04\zeta)$ exercised by the regulatory agencies or by the market mechanism like customer preferences, the effects of varying the carbon cap and offset price changes are experienced jointly. Figures 4.13 and 4.14 are exactly equivalent to Figures 4.7 and 4.8 except for the s^+ series in the offset system. As a result, the same policy with same cost structure is observed as in Figures 4.7 and 4.8 for $\zeta \geq EM(Q_e^*)$.

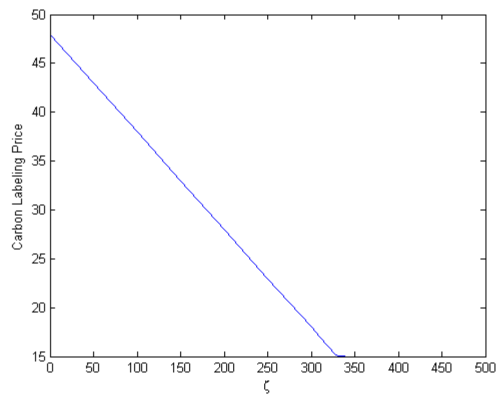


Figure 4.15 Product Price: Carbon Labeling

Finally, the extent to which organizations may carbon-label their products is tested. For $\zeta \geq EM(Q^*)$, there is no need for offsetting and hence carbon labeling is not valid for such caps. However, when the cap is tighter, then the price of the product should increase to achieve the cost value attained when $\zeta > EM(Q^*)$ compared with the case where $r_1 = 15$ and $p = 5$. In order to lower the emissions 10 units (i.e. ζ >329); for example, the carbon labeling price r_2 should equal to 15.11 (see Figure 4.15).

4.3.2.4. Man-hours Cap Model

Similar to Figures 4.1 and 4.2, Figures 4.16 and 4.17 show how the optimal lot size and the resulting total cost changes as the man-hours cap is relaxed in the direct man-hours cap model. Note that for $W < RM(Q_s^*)$, the model is infeasible. The optimal production lot size increases and the resulting optimal total cost decreases as the cap is relaxed. However, since the constraint is nonbinding for $W > RM(Q^*)$, the standard optimal production lot size is feasible and optimal beyond such values of W. Therefore, no change in the policy and the total cost is observed for the values of the man-hours cap beyond this threshold value. Using these figures enables the decision-maker to address a certain level of man-hours and assess the resulting optimal total cost by implementing the corresponding optimal production lot size.

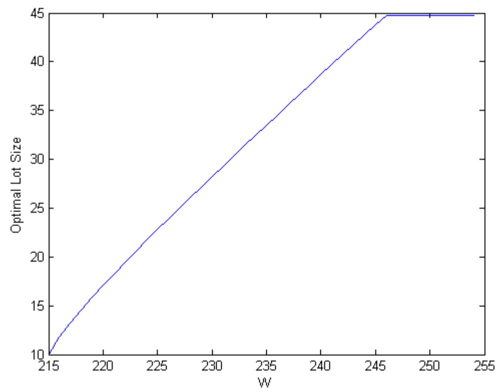


Figure 4.16 Lot Size - Man-hours Cap

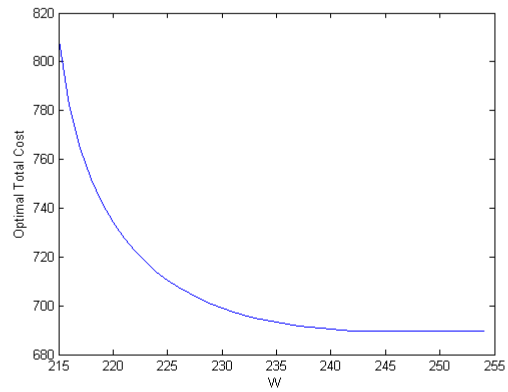


Figure 4.17 Total Cost - Man-hours Cap

4.3.2.5. Triple Bottom Line Accounting Model

Finally, the feasibility of the TBL accounting model for varying values of the emission cap, ζ, and the man-hours cap, W is investigated. In particular, the (W, ζ) pairs for which the TBL accounting model is feasible are searched. The experiments for the feasibility space result in the following figure (Figure 4.18):

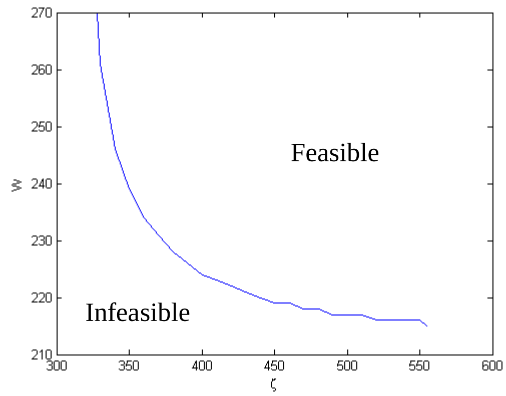


Figure 4.18 Feasible Parameters Space for the TBL Accounting Model

For a given emission cap, ζ, the graph show the corresponding minimum value for the man-hours limit, W and therefore the required man-hours. Similarly, for a given man-hours limit, W, the graph provide the minimum value of the emission cap, ζ and therefore the emissions. In the above figure, the upper right part of the graph above the line denotes the feasibility space of the TBL accounting model. For instance, implementing a production lot size which would emit 350 units of GHG would require 239 units of man-hours and vice versa. Note also that for relatively smaller values of the emission cap, the resulting required minimum level of man-hours increase geometrically. Using this figure, one can quantitatively address the environmental and social criteria simultaneously by choosing a certain balance between the emissions and man-hours levels.

4.4. Managerial Insights

In this section, a summary of the managerial insights based on the analysis given in previous sections is presented:

i. Incorporating sustainability into standard operational decision-making processes has an impact on the operating policies of organizations.

The analysis performed in this chapter demonstrates how environmental and social concerns can be incorporated into a standard operational decision-making model for inventory control. Since the optimal order/production quantity becomes a function of all the economic, social and environmental parameters (see §4.2.4.1 Eq. (4.50) and §4.2.4.2), the cost structure is also affected by this revised model (see §4.2.4.1 Eq. (4.51)). Therefore, there are important differences in the policies and the resulting costs when the triple bottom line accounting of sustainability is considered.

ii. Organizations should estimate environmental and social parameters in order to achieve sustainability.

Estimating environmental and social parameters is a necessity for the organizations to comply with the emerging legislative restrictions and market requirements. In order to operate sustainably, organizations should consider their environmental and social impacts in addition to economic factors. For this reason, managers need to identify the sources of these impact factors and estimate the parameters regarding these additional criteria in order to be able to model and assess environmental and social impacts of their organizations (see §4.2.2.1, §4.2.2.3, and §4.2.3.1).

iii. Regulatory agencies' intervention is the key to achieve sustainability until market awareness is established.

Regulatory agencies should work to increase market awareness on decision-making strategies that considers sustainability (see §4.2.2.4, §4.2.2.5, §4.3.2.2 and

§4.3.2.3). Such a practice does not only favor customers but also the organizations and the whole economy in the long term. However, regulatory agencies should put in place tax schedules and caps until the natural market mechanism is established (see §4.2.2.2, §4.2.2.3, §4.2.3.2 and §4.2.4.2).

iv. Exercising caps on emissions (working hours) is the key to strictly curb emissions (working hours).

The analysis show that mechanisms involving direct cost accounting and tax schedules (see §4.2.2.1, §4.2.2.2, §4.2.3.1 and §4.2.4.1) give organizations incentive to investigate sources of environmental and social costs; however do not provide them with a rigid obligation to consider these added dimensions of sustainability. On the other hand, mechanisms involving a cap (direct cap, cap and trade, and carbon offset models; see §4.2.2.3, §4.2.2.4, §4.2.2.5, §4.2.3.2, and §4.2.4.2) steer the organizations to adjust their policies accordingly. Therefore, a strict control of emissions (working hours) is possible only when caps are exercised by the regulatory agencies.

v. Organizations should find ways to improve not only the economic cost parameters but also the environmental and social cost parameters.

The analysis with the direct accounting approach shows that the revised optimal cost is always larger than the standard EOQ optimal even when the policy remains as the EOQ optimal order/production quantity (see Eq. (4.5), (4.39), and (4.51)). This suggests that organizations should improve their environmental and social impact parameters in addition to the economic ones. However, discussing these improvement opportunities is in the scope of another study, hence left aside.

4.5. Conclusions

Sustainability in supply chain management is an emerging requirement for a better business practice. In achieving sustainability, decision makers should adopt environmental and social considerations as well as the traditional economic objectives. This chapter attempts to address the issue from an operations management perspective. A simple and widely used inventory control model; namely the EOQ model, is utilized and the standard model is revised with additional environmental and social criteria. Alternative model formulations for a number of different settings are proposed and useful and practical results are derived analytically and numerically for decision and policy makers.

This chapter also serves as a reference point illustrating alternative environmental and social management approaches and their modeling apart from revising a classical model of an operational issue in supply chain management. As depicted, alternative modeling schemes are available for different approaches.

Chapter 5

Application to the Newsvendor Model

5.1. Introduction

The newsvendor problem is one of the fundamental inventory control problems in supply chain and operations management. The problem refers to the determination of the order quantity of a perishable item with a limited selling season; i.e. items have little or no value at the end of the season. Moreover, the demand for the items is uncertain; this is why the problem is also known as the single period stochastic inventory problem.

The newsvendor problem is important due to the fact that the problem setting arises in a number of real life applications. For this reason, the stochastic inventory theory based on the newsvendor model has a vast literature (see [114, 115]). Furthermore, the standard newsvendor model is extended to cover a number of different settings such as risk, shortages, multiple products or locations, to name a few. One can refer to Ozler et al. [116], Mileff and Nehez [117], Choi and Chiu [118], Chen and Chuang [119] and the references in these papers for such extended newsvendor formulations among many others.

In order to model the newsvendor problem, a standard mathematical programming formulation is utilized. This model characterizes the optimal ordering policy with the typical objective of maximizing the expected value of the total profit. However, this standard model is a pure economical model.

In order to achieve sustainability, additional environmental and social criteria along with the conventional economics must be considered. These criteria are commonly called the "three pillars" or the "triple bottom line" of sustainability [3].

In this chapter, the standard newsvendor model is revised to incorporate sustainability considerations. The problem of a manufacturer who must take a decision on the optimal production lot size in the presence of additional environmental and social considerations is investigated. The revised models are analyzed in order to obtain insights. The analysis shows how these additional criteria can be used in conjunction with the traditional cost accounting in order to address sustainability in the newsvendor problem.

5.2. Model Formulations and Analysis

5.2.1. The Standard Newsvendor Model

The newsvendor model can be interpreted from the perspective of a manufacturer that produces perishable items. The random customer demand for the items is denoted by D and $F_D(.)$ denotes the cumulative distribution function which is known, stationary and continuous. In this context, the manufacturer incurs a fixed cost of K money-units due to setups, a variable cost of c money-units per item due to the actual production, and a cost of h money-units per item unsold and left in the inventory. In return, the manufacturer charges a price of r money-units for the items. The production lot size is modeled by Q.

In this setting, the objective is to maximize the total profit, π, which is given by;

$$\pi = r\,min(Q, D) - K - cQ - h(Q - D)^+ \qquad (5.1)$$

where $(Q - D)^+ = \max\,(0, Q - D)$. Since Eq. (5.1) involves a random variable, a common approach is to maximize the expected profit, $E[\pi]$, which follows as,

$$E[\pi] = r\,E[\min\,(Q, D)] - K - cQ - h\,E[(Q - D)^{+}] \qquad (5.2)$$

Eq. (5.2) can be rewritten as,

$$E[\pi] = r\,E[D] - r\,E[(D - Q)^{+}] - K - cQ - h\,E[(Q - D)^{+}]$$

that is equivalent to,

$$E[\pi] = r\int_{0}^{+\propto} x\,f_D(x)dx - r\int_{Q}^{+\propto}(x - Q)f_D(x)dx - K - cQ - h\int_{0}^{Q}(Q - x)f_D(x)dx$$
(5.3)

by letting $\min(D, Q) = D - (D - Q)^{+}$. Finding the optimal Q maximizing $E[\pi]$ requires checking the first and second order conditions. The first order condition on Q yields,

$$\frac{d\pi}{dQ} = r\big(1 - F_D(Q)\big) - c - h\,F_D(Q) = 0 \qquad (5.4)$$

and the second order condition,

$$\frac{d^2\pi}{dQ^2} \leq 0\ \forall Q \in [0, \infty) \qquad (5.5)$$

ensures that the first order condition is sufficient for optimality. Therefore, the optimal production lot size, Q^{*}, satisfies,

$$Q^{*} = F_D^{-1}\left(\frac{r-c}{r+h}\right) \qquad (5.6)$$

assuming that F_D is strictly increasing, thus having an inverse. Note that the case where the fixed cost, K, is sufficiently large that $E[\pi] < 0$ and hence $Q^* = 0$ is simply ignored here. This assumption also holds for the rest of the analysis.

5.2.2. Newsvendor Model with Environmental Consideration

In this section, the above model, referred to as the "standard" model in the rest of the article, is revised to encompass environmental considerations. In particular, the following are analyzed: (i) the case where there is a strict emissions cap, (ii) the case where there is emissions tax (iii) and finally the combination of the former two cases, i.e. a cap and tax setting.

5.2.2.1. Emissions Cap Model

There is a formal restriction on emissions (as in the countries that accepted Kyoto Protocol, see [65]) imposed by the market or the regulatory agencies (e.g. government). The emission cap is represented with ξ and f denotes the fixed amount of emissions due to setups, v denotes the variable amount of emissions due to the actual production, and g denotes the amount of emissions due to the processing of the unsold items and inventory holding. Then, the following constrained stochastic program (see [120]) is obtained:

$$max\ E[\pi] = r\int_0^{+\propto} x\, f_D(x)dx - r\int_Q^{+\propto}(x - Q)f_D(x)dx - K - cQ - h\int_0^Q(Q - x)f_D(x)dx \quad (5.7)$$

$s.t.$

$$f + vQ + g\int_0^Q(Q - x)f_D(x)dx \ \leq \xi \quad (5.8)$$

$$Q \geq 0 \quad (5.9)$$

Proposition 1. Given a feasible solution to the model with an emission cap, the optimal production lot size is:

(i) $Q^* = F_D^{-1}\left(\frac{r-c}{r+h}\right)$ units, if $vQ^* + g\int_0^{Q^*}(Q^* - x)f_D(x)dx \le \xi - f$

(ii) Q_{ee}^* units, otherwise, where Q_{ee}^* satisfies $vQ_{ee}^* + g\int_0^{Q_{ee}^*}(Q_{ee}^* - x)f_D(x)dx = \xi - f$

Proof. (i) If $vQ^* + g\int_0^{Q^*}(Q^* - x)f_D(x)dx \le \xi - f$, then $Q^* = F_D^{-1}\left(\frac{r-c}{r+h}\right)$ is feasible. Since it is also optimal for the standard model, it is optimal for the above stochastic program. (ii) If $vQ^* + g\int_0^{Q^*}(Q^* - x)f_D(x)dx > \xi - f$, then the constraint in Eq. (5.8) is binding at the optimal solution. Therefore, the optimal production lot size, denoted by Q_{ee}^* is obtained by solving the equation $vQ_{ee}^* + g\int_0^{Q_{ee}^*}(Q_{ee}^* - x)f_D(x)dx = \xi - f$ ■

Proposition 1 suggests that the optimal production lot size in the presence of a strict emission cap is a function of the financial parameters, (r, c, h) except for the fixed cost, K, the environmental parameters (f, v, g, ξ), and the demand distribution, $F_D(.)$.

5.2.2.2. Emissions Tax Model

In this setting, $f, v,$ and g denote the respective emission amounts as in the previous section except when there is no strict cap on emissions. Instead, the manufacturer pays t money-units for each unit of emissions. In other words, a linear emission tax schedule applies to the manufacturer. Then, the revised formulation is as follows:

$$max\ E[\pi] = r\int_0^{+\propto} x\, f_D(x)dx - r\int_Q^{+\propto}(x-Q)f_D(x)dx - (K+tf) - (c+tv)Q -$$
$$(h+tg)\int_0^Q (Q-x)f_D(x)dx \qquad (5.10)$$

$s.t.$

$$Q \geq 0 \qquad (5.11)$$

Proposition 2. The optimal production lot size with an emission tax is $Q_{ee}^* = F_D^{-1}\left(\frac{r-c-tv}{r+h+tg}\right)$ units and the following set of relationships hold:

(i) $Q_{ee}^* = Q^* \Leftrightarrow \frac{-v}{g} = \frac{r-c}{r+h}$

(ii) $Q_{ee}^* > Q^* \Leftrightarrow \frac{-v}{g} > \frac{r-c}{r+h}$

(iii) $Q_{ee}^* < Q^* \Leftrightarrow \frac{-v}{g} < \frac{r-c}{r+h}$

Furthermore, since the only realizable case among the above relationships is (iii), the revised optimal production lot size under a linear emission tax schedule, Q_{ee}^*, is always less than the standard optimal, Q^*, independent of the tax rate, t.

Proof. Inserting $c = c + tv$ and $h = h + tg$ in the standard model and by a similar derivation, the optimal production lot size is found as $Q_{ee}^* = F_D^{-1}\left(\frac{r-c-tv}{r+h+tg}\right)$. (i) (⇒) Assume that $Q_{ee}^* = Q^*$, $F_D(Q_{ee}^*) = \frac{r-c-tv}{r+h+tg} = \frac{r-c}{r+h} = F_D(Q^*)$ and this implies that $\frac{-v}{g} = \frac{r-c}{r+h}$ (⇐) Can be derived similarly as in (⇒) (ii), (iii) Using the fact that F_D is a monotone increasing function, can be derived as in part (i) ■

Proposition 2 suggests that the production lot size under a linear emission tax schedule along with the standard economic considerations is a function of the financial parameters, (r, c, h), the environmental parameters, (v, g), the demand distribution, $F_D(.)$, and the linear tax rate, t. On the other hand, the fixed costs f and K do not affect the policy as in the standard setting.

5.2.2.3. Cap and Tax Model

When a tax schedule applies to the manufacturer for its emissions, there is still a maximum allowable amount on emissions released. The following constrained stochastic program formulates the lot sizing problem of the manufacturer:

$$max\ E[\pi] = r\int_0^{+\propto} x\, f_D(x)dx - r\int_Q^{+\propto}(x-Q)f_D(x)dx - (K+tf) - (c+tv)Q - (h+tg)\int_0^Q (Q-x)f_D(x)dx \quad (5.12)$$

$s.t.$

$$f + vQ + g\int_0^Q (Q-x)f_D(x)dx \ \le \xi \quad (5.13)$$

$$Q \ge 0 \quad (5.14)$$

Proposition 3. Given a feasible solution to the model with an emission cap and tax, the optimal production lot size is:

(i) $Q_{ee}^* = F_D^{-1}\left(\frac{r-c-tv}{r+h+tg}\right)$ units, if $vQ_{ee}^* + g\int_0^{Q_{ee}^*}(Q_{ee}^* - x)f_D(x)dx \ \le \xi - f$

(ii) Q_{ee}^* units, otherwise, where Q_{ee}^* satisfies $vQ_{ee}^* + g\int_0^{Q_{ee}^*}(Q_{ee}^* - x)f_D(x)dx = \xi - f$

Proof. (i) Assume that Eq. (5.13) is relaxed and insert $c = c + tv$ and $h = h + tg$ in the standard model. Then, by a similar derivation, the optimal production lot size is found as $Q_{ee}^* = F_D^{-1}\left(\frac{r-c-tv}{r+h+tg}\right)$. If $v\, Q_{ee}^* + g \int_0^{Q_{ee}^*}(\, Q_{ee}^* - x) f_D(x) dx\ \leq \xi - f$, then $Q_{ee}^* = F_D^{-1}\left(\frac{r-c-tv}{r+h+tg}\right)$ is feasible and hence optimal for the above stochastic program. (ii) If $v\, Q_{ee}^* + g \int_0^{Q_{ee}^*}(\, Q_{ee}^* - x) f_D(x) dx\ > \xi - f$, $Q_{ee}^* = F_D^{-1}\left(\frac{r-c-tv}{r+h+tg}\right)$ is not feasible. In this case, the constraint in Eq. (5.13) is binding at the optimal solution. Therefore, the optimal production lot size is found by solving the stochastic equation $vQ_{ee}^* + g \int_0^{Q_{ee}^*}(Q_{ee}^* - x) f_D(x) dx\ = \xi - f$ ■

Proposition 3 suggests that the optimal production lot size in the presence of both a strict emission cap and emission tax is a function of the financial parameters, (r, c, h), the environmental parameters, (f, v, g, ξ), the demand distribution, $F_D(.)$, and the tax rate, t.

5.2.3. Newsvendor Model with Social Consideration

In this section, the standard model is revised to encompass social considerations in the newsvendor problem. In particular, the following are analyzed: (i) the case where there is a target customer service level, (ii) the case where there is a penalty on lost sales, (iii) and finally the combination of the former two cases, i.e. penalty and target.

5.2.3.1. Service Level Target Model

Since the customer demand is random and may not be perfectly matched by the supply process in the standard newsvendor setting, providing sufficient service level to the customer is critical. This is due to the fact that customers might suffer from their demand being unsatisfied in a physical manner in certain cases. This situation emerges when the timely possession of the demanded product is critical and backlogging is not an option for the customer. Products related to customer's physical health and safety (e.g. medical products or certain drugs which should be used on a continuous basis by the patients) constitute an example to this situation. Therefore, provision of a certain service level is not only economically desirable for the company but might also be socially crucial for the customers. A standard way of formulating customer satisfaction is to consider the fill rate, which is given by,

$$\frac{E[sales]}{E[demand]} = \frac{E[\min(Q,D)]}{E[D]} \tag{5.15}$$

and imposing a lower bound, α, which is called the desired/target service level, on this quantity. The value of α depends on the industry/market in which the company operates. Using a simple interchange $[\min(D,Q) = D - (D-Q)^+]$, the model with the target service level constraint can be written as follows:

$$max\ E[\pi] = r\int_0^{+\infty} x\, f_D(x)dx - r\int_Q^{+\infty}(x-Q)f_D(x)dx - K - cQ - h\int_0^{Q}(Q-x)f_D(x)dx$$

(5.16)

$s.t.$

$$\frac{\int_Q^{+\infty}(x-Q)f_D(x)dx}{\int_0^{+\infty} x f_D(x)dx} \le (1-\alpha) \tag{5.17}$$

$$Q \ge 0 \tag{5.18}$$

Proposition 4. Given a feasible solution to the model with a target service level, the optimal production lot size is:

(i) $Q^* = F_D^{-1}\left(\frac{r-c}{r+h}\right)$ units, if $\frac{\int_{Q^*}^{+\infty}(x-Q^*)f_D(x)dx}{\int_0^{+\infty} x f_D(x)dx} \leq (1-\alpha)$

(ii) Q_{se}^* units, otherwise, where Q_{se}^* satisfies

$\int_{Q_{se}^*}^{+\infty}(x - Q_{se}^*)f_D(x)dx = (1-\alpha)\int_0^{+\infty} x\, f_D(x)dx$

The proof of Proposition 4 is similar to the proof of Proposition 1. Therefore, the proof is omitted here.

Proposition 4 suggests that the optimal production lot size in the presence of a service level target is a function of the financial (r, c, h) parameters, the target service level, α, and the demand distribution $F_D(.)$.

5.2.3.2. Lost Sales Penalty Model

Instead of a service level target, the manufacturer may incur a penalty, p, for each unit of lost sales due to the actual sales loss and the loss of customer goodwill/loyalty. Then, the revised formulation is as follows:

$$max\ E[\pi] = r\int_0^{+\infty} x\, f_D(x)dx - (r+p)\int_Q^{+\infty}(x-Q)f_D(x)dx - K - cQ - h\int_0^Q (Q-x)f_D(x)dx \quad (5.19)$$

$s.t.$

$$Q \geq 0 \quad (5.20)$$

Proposition 5. The optimal production lot size with a lost sales penalty is $Q_{se}^* = F_D^{-1}\left(\frac{r+p-c}{r+p+h}\right)$ units and the following set of relationships hold:

(i) $Q_{se}^* = Q^* \Leftrightarrow h = -c$

(ii) $Q_{se}^* > Q^* \Leftrightarrow h > -c$

(iii) $Q_{se}^* < Q^* \Leftrightarrow h < -c$

Furthermore, since the only realizable case among the above relationships is (ii), the revised optimal production lot size under a lost sales penalty, Q_{se}^*, is always greater than the standard optimal, Q^*, independent of the penalty cost, p.

Proposition 5 suggests that that the production lot size under lost sales penalty along with the standard economic considerations is a function of the financial parameters, (r, c, h), the demand distribution, $F_D(.)$, and the penalty cost, p. On the other hand, the fixed cost, K, does not affect the policy as in the standard setting. The proof of Proposition 5 is similar to the proof of Proposition 2, therefore omitted.

A similar characterization of the optimal lot size under a lost sales penalty can be found in Nahmias [7]. Pasternack [121] also utilizes the newsvendor model with lost sales and loss of customer goodwill costs and obtains a similar relationship. Proposition 5 extends the former studies with a sensitivity of the revised optimal with respect to the standard optimal.

5.2.3.3. Penalty and Target Model

Finally assume that the manufacturer incurs a lost sales penalty for each unit of sales loss; however, there is also the service level target imposed by the market/industry. Then, the following model formulates the lot sizing problem of the manufacturer:

$$max\ E[\pi] = r \int_0^{+\propto} x\, f_D(x)dx - (r+p) \int_Q^{+\propto} (x-Q) f_D(x)dx - K - cQ - h \int_0^{Q} (Q-x) f_D(x)dx \quad (5.21)$$

$s.t.$

$$\frac{\int_Q^{+\propto} (x-Q) f_D(x)dx}{\int_0^{+\propto} x f_D(x)dx} \leq (1-\alpha) \quad (5.22)$$

$$Q \geq 0 \quad (5.23)$$

Proposition 6. Given a feasible solution to the model with a target service level and lost sales penalty, the optimal production lot size is:

(i) $Q_{se}^{*} = F_D^{-1}\left(\frac{r+p-c}{r+p+h}\right)$ units, if $\frac{\int_{Q_{se}^{*}}^{+\propto} (x-Q_{se}^{*}) f_D(x)dx}{\int_0^{+\propto} x f_D(x)dx} \leq (1-\alpha)$

(ii) Q_{se}^{*} units, otherwise, where Q_{se}^{*} satisfies
$\int_{Q_{se}^{*}}^{+\propto} (x-Q_{se}^{*}) f_D(x)dx = (1-\alpha) \int_0^{+\propto} x\, f_D(x)dx$

Proposition 6 suggests that the optimal production lot size in the presence of a service level target and lost sales penalty is a function of the financial parameters, (r, c, h), the service level target, α, the penalty cost, p, and the demand distribution $F_D(.)$.The proof of Proposition 6 is similar to the proof of Proposition 3, therefore omitted.

5.2.4. Newsvendor Model with Triple Bottom Line Accounting

The environmental and social criteria mentioned above can be considered simultaneously by the manufacturer in addition to the economic criterion. In particular, the manufacturer incurs emission tax and lost sales penalty where there are also the emission cap and the service level target. When all the economic, environmental, and social parameters are given as in the previous sections, the following constrained stochastic program models the revised problem with TBL accounting:

$$max\ E[\pi] = r\int_0^{+\propto} x\, f_D(x)dx - (r+p)\int_Q^{+\propto}(x-Q)f_D(x)dx - (K+tf) - (c+tv)Q - (h+tg)\int_0^{Q}(Q-x)f_D(x)dx \qquad (5.24)$$

$s.t.$

$$f + vQ + g\int_0^{Q}(Q-x)f_D(x)dx \ \leq \xi \qquad (5.25)$$

$$\frac{\int_Q^{+\propto}(x-Q)f_D(x)dx}{\int_0^{+\propto} x f_D(x)dx} \leq (1-\alpha) \qquad (5.26)$$

$$Q \geq 0 \qquad (5.27)$$

Proposition 7. Given a feasible solution to the model with TBL accounting, the optimal production lot size is:

(i) $Q_{ees}^{*} = F_D^{-1}\left(\frac{r+p-c-tv}{r+p+h+tg}\right)$ units, if $\frac{\int_{Q_{ees}^{*}}^{+\propto}(x-Q_{ees}^{*})f_D(x)dx}{\int_0^{+\propto} x f_D(x)dx} \leq (1-\alpha)$ and $vQ_{ees}^{*} + g\int_0^{Q_{ees}^{*}}(Q_{ees}^{*}-x)f_D(x)dx \ \leq \xi - f$. In this case, the following holds:

(a) $Q_{ees}^{*} = Q^{*} \Leftrightarrow\ -rv + hp - hv = rg - cp - cg$
(b) $Q_{ees}^{*} > Q^{*} \Leftrightarrow\ -rv + hp - hv > rg - cp - cg$
(c) $Q_{ees}^{*} < Q^{*} \Leftrightarrow -rv + hp - hv < rg - cp - cg$

(ii) Q_{ees}^{*} units, otherwise, where Q_{ees}^{*} satisfies either $\int_{Q_{ees}^{*}}^{+\propto}(x-Q_{ees}^{*})f_D(x)dx = (1-\alpha)\int_0^{+\propto} x\, f_D(x)dx$ or $vQ_{ees}^{*} + g\int_0^{Q_{ees}^{*}}(Q_{ees}^{*}-x)f_D(x)dx = \xi - f$

Proof. (i) Assume that Eq. (5.25-5.26) are relaxed and insert $r = r + p$, $c = c + tv$, and $h = h + tg$ in the standard model. Then, by a similar derivation, the optimal production lot size is found as $Q_{ees}^{*} = F_D^{-1}\left(\frac{r+p-c-tv}{r+p+h+tg}\right)$. If $\frac{\int_{Q_{ees}^{*}}^{+\propto}(x-Q_{ees}^{*})f_D(x)dx}{\int_0^{+\propto} x f_D(x)dx} \leq (1-\alpha)$ and $vQ_{ees}^{*} + g\int_0^{Q_{ees}^{*}}(Q_{ees}^{*} - x)f_D(x)dx \leq \xi - f$, then $Q_{ees}^{*} = F_D^{-1}\left(\frac{r+p-c-tv}{r+p+h+tg}\right)$ is feasible and hence optimal for the above stochastic program. (a) (⇒) Assume that $Q_{ees}^{*} = Q^{*}$, $F_D(\,Q_{ees}^{*}) = \frac{r+p-c-tv}{r+p+h+tg} = \frac{r-c}{r+h} = F_D(Q^{*})$ and this implies that $-rv + hp - hv = rg - cp - cg$ (⇐) Can be derived similarly as in (⇒) (b), (c) Using the fact that F_D is a monotone increasing function, can be derived similarly as in part (a)

(ii) If $vQ_{ees}^{*} + g\int_0^{Q_{ees}^{*}}(\,Q_{ees}^{*} - x)f_D(x)dx > \xi - f$ or $\frac{\int_{Q_{ees}^{*}}^{+\propto}(x-Q_{ees}^{*})f_D(x)dx}{\int_0^{+\propto} x f_D(x)dx} > (1-\alpha)$, $Q_{ees}^{*} = F_D^{-1}\left(\frac{r+p-c-tv}{r+p+h+tg}\right)$ is not feasible. In this case, the violated constraint (either Eq. (5.25) or Eq. (5.26)) is binding at the optimal solution. Therefore, the optimal production lot size is found by solving either of the stochastic equations $vQ_{ees}^{*} + g\int_0^{Q_{ees}^{*}}(Q_{ees}^{*} - x)f_D(x)dx = \xi - f$ or $\int_{Q_{ees}^{*}}^{+\propto}(x - Q_{ees}^{*})f_D(x)dx = (1-\alpha)\int_0^{+\propto} x\, f_D(x)dx$ ■

Table 5.1 lists the parameters that affect the optimal lot size for each model discussed in this section.

Table 5.1 Policy-effective Parameters of the Revised Models

Model	**Parameters**		
	Economic	*Environmental*	*Social*
Standard	$r, c, h, F_D(.)$		
Emissions Cap	$r, c, h, F_D(.)$	f, v, g, ξ	
Emissions Tax	$r, c, h, F_D(.)$	v, g, t	
Cap and Tax	$r, c, h, F_D(.)$	f, v, g, ξ, t	
Target Service Level	$r, c, h, F_D(.)$		α
Penalty on Lost Sales	$r, c, h, F_D(.)$		p
Penalty and Target	$r, c, h, F_D(.)$		α, p
TBL Accounting	$r, c, h, F_D(.)$	f, v, g, ξ, t	α, p

5.3. Numerical Analysis of the Revised Models

In this section, numerical analysis of the revised models presented in section §5.2 is conducted in order to obtain additional insights from the revised models. Throughout the analysis, it is assumed that the random demand is (i) uniformly distributed over the interval $[0, L]$, (ii) exponentially distributed with rate λ, (iii) and normally distributed with mean, μ, and standard deviation, σ. The data for the parameters used in the analysis is shown in Table C.1 in Appendix C.

First, the optimal lot sizes based on the standard model and its unconstrained revisions are investigated. Then, the effects of limits, ξ and α, on the optimal policy and expected profit are analyzed using the constrained revisions of the standard model. Finally, the feasibility of the TBL accounting model with respect to these limits is investigated.

5.3.1. Analysis with the Unconstrained Models

The optimal lot sizes are found for each unconstrained model by using the corresponding parameter values given in Table C.1. Three continuous probability distributions for the random demand are investigated and the distribution parameters are chosen such that they have equal means $\left(\frac{L}{2} = \frac{1}{\lambda} = \mu = 100, \text{see Table C.1}\right)$. The optimal lot sizes are given in Table 5.2:

Table 5.2 Optimal Lot Size Values for Unconstrained Models

Model	**Distribution**		
	Uniform	*Exponential*	*Normal*
Standard	129.41	104.15	109.43
Emission Tax	84.21	54.65	95.02
Lost Sales Penalty	147.83	134.37	116.02
Tax and Penalty	112.00	82.10	103.77

As seen in Table 5.2, the standard model suggests a production lot size which is larger than the mean demand for all three demand distributions. However, the model with emission tax suggests producing smaller quantities when compared to the standard model due to the environmental impact. On the other hand, the model with lost sales penalty suggests an even higher lot size than the standard model due to the social impact. Finally, the model with both an emission tax and lost sales penalty leads to a lot size between the values proposed individually by the emission tax and lost sales penalty models so as to balance the trade-off between the environmental and social criteria.

5.3.2. Analysis with the Constrained Models

The effect of the limits, namely ξ and α, on the optimal policy and expected profit is investigated using the constrained revisions of the standard model. Moreover, the feasibility space for the TBL accounting model with respect to these limits is presented.

Note that in order to analyze the constrained models, one needs expressions for the expected lost sales, $E[(D-Q)^{+}]$ and expected overstock, $E[(Q-D)^{+}]$ for each demand distribution (see the derivations for the uniform and exponential distributions in Appendix B). The corresponding quantities are shown in Table 5.3.

Table 5.3 Expected Overstock and Lost Sales

Model	**Distribution**		
	Uniform	*Exponential*	*Normal*
$E[(Q-D)^{+}]$	$\frac{Q^2}{2L}$	$\frac{\lambda Q + e^{-\lambda Q} - 1}{\lambda}$	$(Q-\mu)\Phi(z) + \sigma f_Z(z)$
$E[(D-Q)^{+}]$	$\frac{L^2 + Q^2 - 2QL}{2L}$	$\frac{e^{-\lambda Q}}{\lambda}$	$(\mu - Q)\big(1-\Phi(z)\big) + \sigma f_Z(z)$

The constrained models can be reformulated by replacing $E[(D-Q)^{+}]$ and $E[(Q-D)^{+}]$ with the corresponding quantities given in Table 5.3. These reformulated models can be found in Appendix D. The constrained models with uniform and exponential distributions are then solved using GAMS and its default nonlinear programming solver CONOPT with the default options. For the normal distribution, Excel Solver and the built-in functions for $\Phi(z)$ and $f_Z(z)$ are used [113, 111, 122]. The key insights from the analysis are summarized in the following subsections.

5.3.2.1. Emission Cap Model

Figures 5.1 to 5.6 show how optimal lot size and the resulting expected optimal profit changes as the emission cap (ξ) is relaxed. In particular, the optimal production lot size increases almost linearly as this cap increases. In return, the optimal expected profit also increases. In other words, the tighter the cap, the less the production and profit whatever the demand distribution is. However, when the cap exceeds a certain threshold, the profit function reaches an asymptote and increasing values of ξ does not affect the policy and profit. This is due to the fact that the emission cap constraint becomes nonbinding and standard optimal production lot size is feasible beyond such threshold value of ξ.

Uniform Distribution

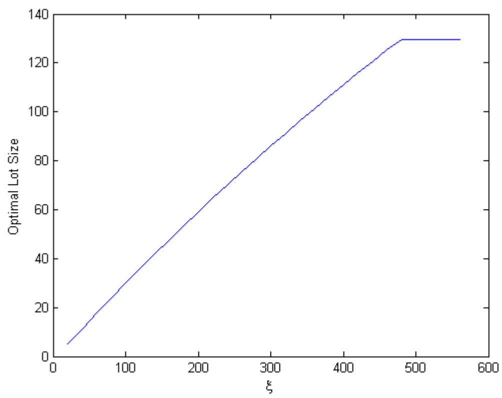


Figure 5.1 Lot Size – Emission Cap

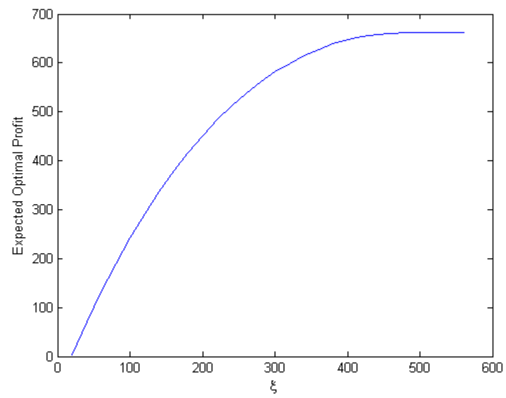


Figure 5.2 Expected Profit – Emission Cap

Exponential Distribution

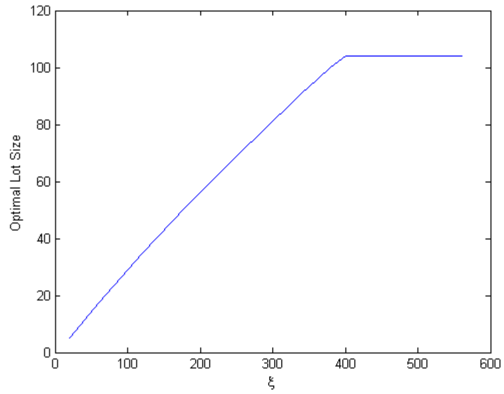


Figure 5.3 Lot Size – Emission Cap

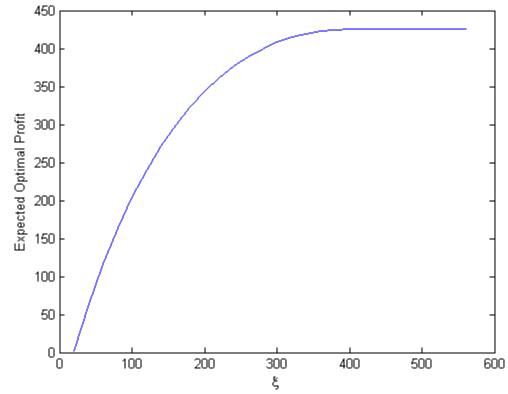


Figure 5.4 Expected Profit – Emission Cap

Normal Distribution

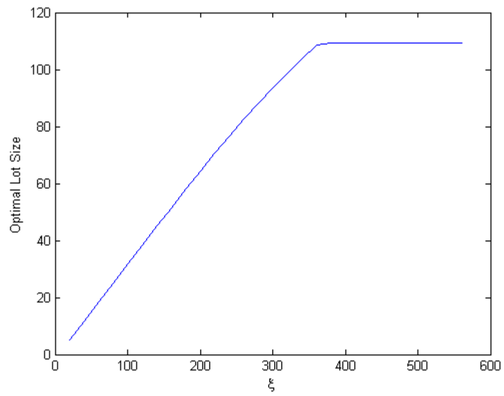


Figure 5.5 Lot Size – Emission Cap

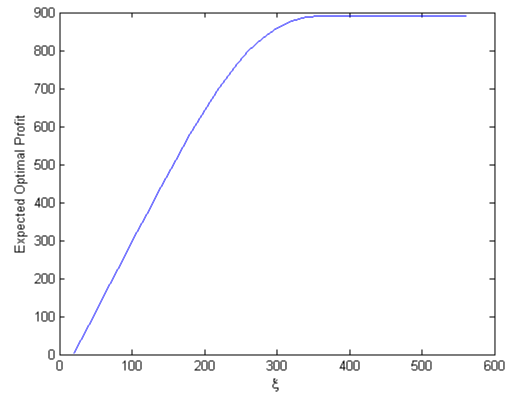


Figure 5.6 Expected Profit – Emission Cap

This threshold value also stands for the level of GHG emissions when the standard optimal production lot size is implemented. Note this value for uniformly distributed demand is 480, for exponentially distributed demand it is 400, and for normally distributed demand it is 380 (note that 20 emission-units increments are used in the optimization runs). Using these figures, the decision-maker can address a certain emissions level by selecting the corresponding optimal production lot size and assess the resulting expected optimal profit.

5.3.2.2. Service Level Target Model

Figures 5.7 to 5.12 show the profile of the optimal lot size and the resulting expected optimal profit changes as the target service level (α) increases. In particular, the optimal production lot size increases as the service level target increases. In return, the optimal expected profit decreases. In other words, the higher the service level, the more the production and less the profit whatever the demand distribution is. However, when the target falls below a certain threshold, it does not affect the policy and profit. This is due to the fact that the service level target constraint becomes nonbinding and standard optimal production lot size is feasible beyond such values of α.

This threshold value also stands for the customer service level when the standard optimal production lot size is implemented. Note that the threshold value for uniformly distributed demand is 85%, for exponentially distributed demand it is 60%, and for normally distributed demand it is 90% (note that 5% increments are used). Using these figures, the decision-maker can address a certain service level by selecting the corresponding optimal production lot size and assess the resulting expected optimal profit.

Uniform Distribution

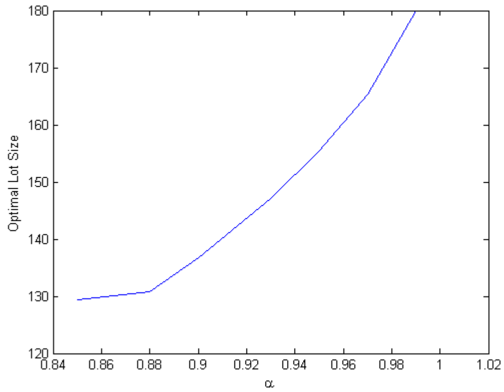


Figure 5.7 Lot Size – Service Level Target

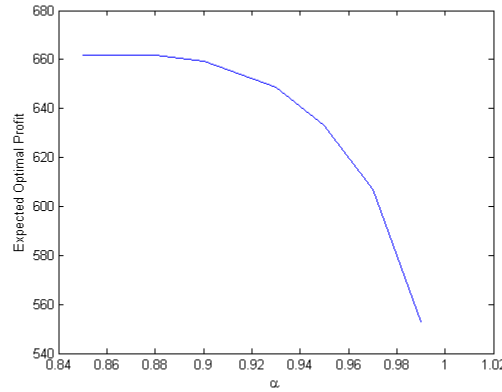


Figure 5.8 Expected Profit – Service Level Target

Exponential Distribution

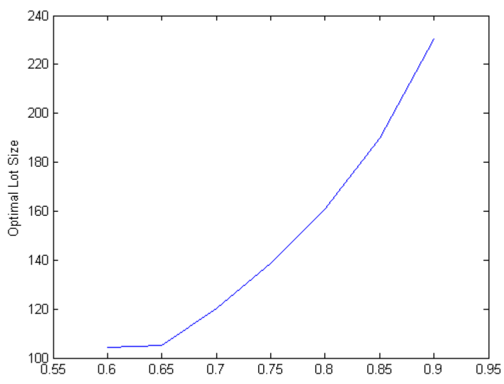


Figure 5.9 Lot Size - Service Level Target

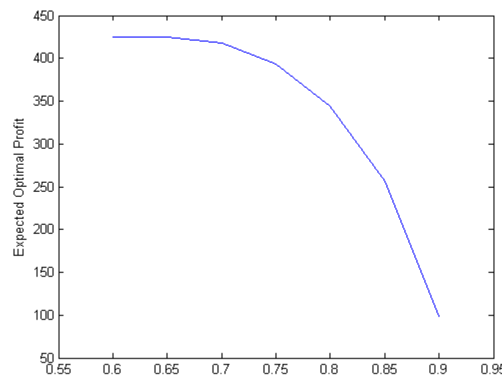


Figure 5.10 Expected Profit - Service Level Target

Normal Distribution

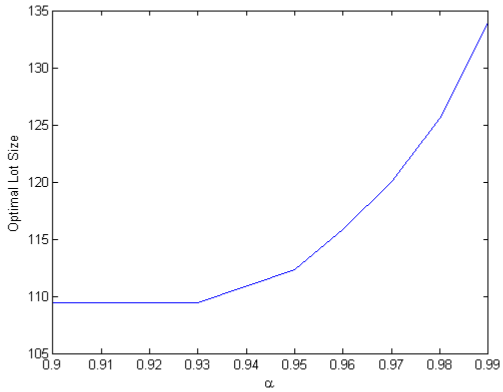


Figure 5.11 Lot Size - Service Level Target

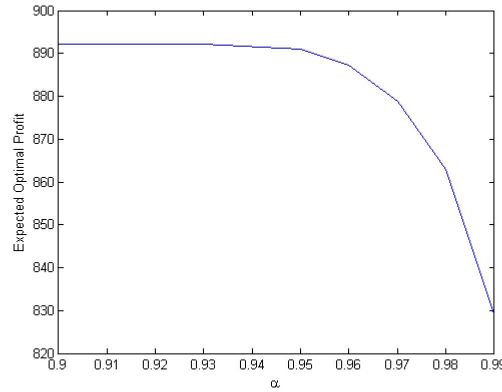


Figure 5.12 Expected Profit – Service Level Target

5.3.2.3. Triple Bottom Line Accounting Model

Finally, the feasibility of the TBL accounting model for varying values of the emission cap, ξ, and the service level target, α is investigated. In particular, the (α, ξ) pairs for which the TBL accounting model is feasible are searched. The experiments with uniform, exponential and normal demand distributions result in the following figures (Figures 5.13 to 5.15) for the feasibility space.

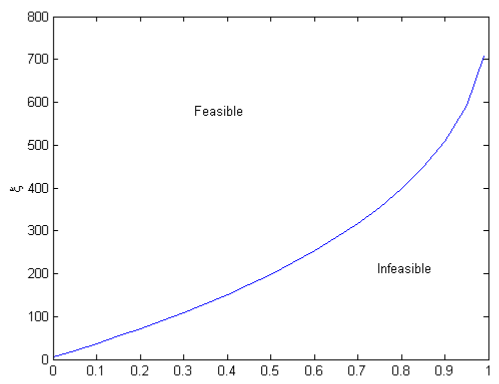


Figure 5.13 Feasibility Space: Uniform Dist.

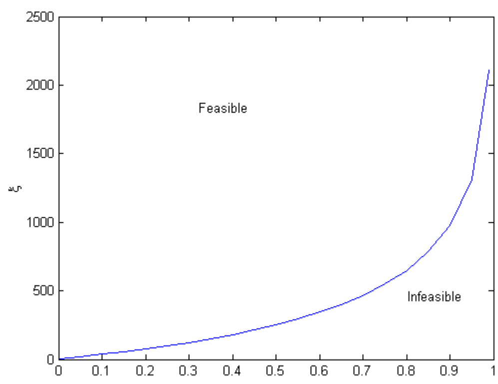


Figure 5.14 Feasibility Space: Exponential Dist.

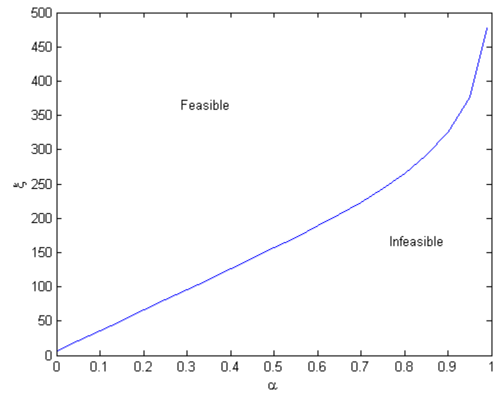


Figure 5.15 Feasibility Space: Normal Dist.

For a given service level target α, the graphs show the corresponding minimum value for the emission cap, ξ, and therefore the emissions. Similarly, for a given emission cap, ξ, these profiles provide the maximum value of the service level target and therefore the service level. In each of these figures above, the upper half of the graph above the line denotes the feasibility space of the TBL accounting model. For instance, implementing a production lot size which would provide a 90% service level leads to a minimum of 325 units emissions when the demand is normally distributed.

Note that for the same level of service, the minimum amount of emissions with exponential demand is greater than the level with uniform distributions which is also greater than the level with the normal distribution. In particular, for the above example with 90% service level, the minimum with uniform distribution is 509 units and 977 units with the exponential distribution. Note also that for values of the service level beyond 80%, the minimum level of emissions increase geometrically. Using these figures, one can obtain a quantitative understanding of environmental and social criteria should be addressed simultaneously by selecting a certain balance between the emissions and service level under an estimated demand distribution.

5.4. Conclusions

In this chapter, the newsvendor problem from the perspective of a manufacturer is considered and the standard newsvendor model is revised with additional environmental and social criteria to incorporate sustainability considerations. First, the optimal policy for the revised models is analytically characterized. The analysis reveals that the lot sizing decisions must be made after careful analysis of the model parameters and their combined effect on the decision criteria. Following that, numerical experiments are conducted to illustrate the analytical findings and obtain additional insights. For the unconstrained models, it is observed that the model with emission tax suggests producing smaller quantities whereas the model with lost sales penalty suggests producing larger quantities when compared with the standard model. On the other hand, the model with both an emission tax and lost sales penalty leads to a lot size between the values proposed individually by the emission tax and lost sales penalty models so as to balance the trade-off between the environmental and social criteria. For the constrained models, the optimal production lot size decreases as the emission cap decreases whereas it increases as the service level target increases. In return, the optimal expected profit decreases for both cases and these patterns hold up to certain threshold values. Finally, the feasibility of the constrained triple bottom line accounting model with respect to the limits, namely the emission cap and service level target, is investigated and the paired values of these limits for the experimental setting which makes the model feasible are quantitatively found out. Furthermore, these paired values can also be interpreted as the minimum achievable emissions level for a given service level or as the maximum achievable service level for a given emissions level.

In the analysis, it is assumed that the demand distribution is continuous and three main probability distributions for the random demand are investigated throughout the numerical analysis. The central limit theorem justifies the normal assumption assuming that the actual demand is the sum of many individual demand sources. Moreover, if smaller values for the demand are much more likely than larger values, the exponential distribution might be a good approximation. Finally, although it might be wild to assume that each possible value of the demand is equally likely, analyzing the case of a uniform distribution is still helpful for the reason of comparison and completeness.

The approach used in this chapter shows how sustainability criteria can be appended to traditional cost accounting in supply chain and operations management based on the newsvendor problem. Using such revised models in decision-making enables the quantitative assessment and control of the sustainability performance of the companies as well as their financial performance.

Chapter 6

Application to the Aggregate Planning Model

6.1. Introduction

Aggregate planning is the determination of production, inventory, and capacity levels at each period with the objective of minimizing total cost over the entire planning horizon that consists of T periods. In general, the planning horizon, T, ranges from 3 to 18 months depending on the particular problem.

The decision maker first estimates aggregate cost components including labor costs, capacity changing costs, production costs, inventory holding costs, stock-out and backlogging costs, and subcontracting costs in order to deduce an aggregate plan. The estimation of these costs is not an easy task; however, it is a prerequisite to aggregate planning.

Apart from the cost components, other factors including the demand forecast, D_t, for each period, t; the number of working days in each period, labor hours required per item of production, and the initial inventory, backlog and workforce levels are required to devise the aggregate plan. Once all these inputs are determined, the aggregate planning problem can be formulated as a mathematical program and solved. The resulting plan should then be disaggregated to form the Master Production Schedule and obtain the Materials Requirement Plan [7]. In other words, the aggregate planning is a prerequisite for many operations including production planning, scheduling, and inventory management.

The decision maker not only reveals information on production, inventory, and capacity levels but also on the required capital, machinery, equipment and warehouse space, sourcing decisions and supplier purchase levels, customer service levels, and product pricing by deducing the aggregate plan. As a result, aggregate planning is a fundamental step in the entire supply chain and operations management.

The traditional mathematical program which is used to devise the aggregate plan is purely an economical model. However, the emerging requirement of sustainability suggests that additional environmental and social criteria along with economical criterion, which are called the "three pillars" or the "triple bottom line" of sustainability, should be considered [3]. Hence, in order to achieve sustainability in supply chain and operations management, the decision maker should incorporate these three pillars of sustainability simultaneously into the decision-making process.

In this chapter, the methodological approach to incorporate sustainability considerations in the aggregate planning problem is presented. The standard mathematical programming formulation of the aggregate planning problem is revised to account for additional environmental and social criteria. The revised models are then analyzed to obtain insights. The analysis shows how environmental and social criteria can be appended to traditional cost accounting in order to address sustainability in supply chain and operations management based on the aggregate planning problem.

6.2. Model Formulations

6.2.1. The Standard Aggregate Planning Model

In this section, the standard mathematical programming formulation of the aggregate planning problem is presented:

$$min\, z = \sum_{i=1}^{T} hn_t c_L W_t + c_H H_t + c_F F_t + c_M P_t + c_O O_t + c_I I_t + c_B B_t + c_S S_t \quad (6.1)$$

$s.t.$

$$P_t \leq K n_t W_t + O_t \qquad \forall t \in \{1, \dots, T\} \quad (6.2)$$

$$W_t + F_t = W_{t-1} + H_t \qquad \forall t \in \{1, \dots, T\} \quad (6.3)$$

$$I_t + B_{t-1} + D_t = P_t + S_t + B_t + I_{t-1} \qquad \forall t \in \{1, \dots, T\} \quad (6.4)$$

$$O_t \leq K n_t W_t \qquad \forall t \in \{1, \dots, T\} \quad (6.5)$$

$$W_t, H_t, F_t \in \{Z^+ \cup \{0\}\} \qquad \forall t \in \{1, \dots, T\} \quad (6.6)$$

$$P_t, O_t, I_t, B_t, S_t \geq 0 \qquad \forall t \in \{1, \dots, T\} \quad (6.7)$$

$$W_0 = W_{init} \quad (6.8)$$

$$I_0 = I_{init} \quad (6.9)$$

$$B_0 = B_{init} \quad (6.10)$$

Eq. (6.1) denotes the objective function which is the sum of all possible cost components resulting from the aggregate plan and therefore to be minimized at optimality. Eq. (6.2) sets the capacity constraint based on regular and overtime production. Eq. (6.3) balances workforce size where hiring and firing is included. Eq. (6.4) balances the inventory levels as a function of production, subcontracting and backlogging. Eq. (6.5) serves as a logical constraint imposing that both regular and overtime production does not take place in the absence of a positive workforce size. This constraint can also be modified to serve for social factors, as discussed in section §6.2.3.2. Eq. (6.6) and (6.7) denote the integrality and non-negativity of the decision variables respectively. Variables denoting the number of workers (W_t, H_t and F_t) should have integer values at optimality, which is expressed by constraint (6.6) in the above model. Furthermore, the rest of the variables ($P_t, O_t, U_t, I_t, B_t, S_t$) may have integer values in a discontinuous industrial setting. In such a case, constraint in Eq. (6.7) may be eliminated and instead, constraint in Eq. (6.6) should be modified to capture the integrality of the rest of the variables. However, it is assumed that these variables are continuous in this chapter. Finally, Eq. (6.8), (6.9), and (6.10) sets the initial conditions for workforce, inventory, and backlog levels, respectively.

The above model can be solved to optimality by using a standard linear programming (LP) solver by temporarily relaxing constraint in Eq. (6.6). Following that, the integrality of W_t, H_t and F_t can be achieved via a rounding routine. However, this procedure does not guarantee the optimality and even the feasibility of the actual mixed-integer solution.

An alternative approach is to keep constraint in Eq. (6.6) and solve the above mixed-integer linear program (MILP). Since the aggregate plan assumes a moderate planning horizon, the program can still be solved to optimality with a standard MILP solver as in this chapter. Note also for the logic of a feasible and optimal aggregate plan, $H_t F_t = 0$ and $I_t B_t = 0 \ \ \forall t \in \{1, \dots, T\}$ should hold. Adding these additional constraints to the MILP formulation yields an MINLP. However, these conditions are automatically satisfied in a linear program due to its properties.

6.2.2. Aggregate Planning Model with Environmental Considerations

In this section, the standard aggregate planning model is revised to account for the carbon footprint and energy consumption of the organization: these two factors constitute the majority of the environmental affects resulting from aggregate planning.

6.2.2.1. Carbon Footprint

Carbon footprint refers to the set of greenhouse gases including carbon dioxide released by an organization [74]. Typically, these greenhouse gases are inevitably released due to the operations [29]. As a result, in order to assess the environmental performance of an organization, the amount of GHG emissions is commonly used in the green/environmentally friendly supply chain and operations management literature (see [29] and the references therein).

Assume that there is a cap, ε_C, on the amount of GHG emissions released by the organization during the entire planning horizon, as in the case of Kyoto Protocol [105]. Let $c_I^{'}$ denote the amount of GHG emissions due to inventory holding (e.g. due to material handling), $c_P^{'}$ denote the amount of GHG emissions due to regular time production (e.g. due to manufacturing), and $c_S^{'}$ denote the amount of GHG emissions due to subcontracting (e.g. due to transportation). Then, the following constraint should be added to the standard aggregate planning model:

$$\sum_{i=1}^{T} c_I^{'} I_t + c_P^{'} P_t + c_S^{'} S_t \leq \varepsilon_C \tag{6.11}$$

6.2.2.2. Energy Consumption

One of the fundamental considerations in terms of the environmental impact is to manage the energy used by the organization. Energy, particularly in the form of electricity, is a fundamental entity that is consumed in most industrial operations [67, 75, 76]. Assume that there is a cap, ε_E, on the amount of electricity used by the organization during the entire planning horizon. Let $c_I^{''}$ denote the amount of electricity used due to inventory holding (e.g. due to refrigeration), $c_P^{''}$ denote the amount of electricity used due to regular time production (e.g. due to manufacturing), $c_O^{''}$ denote the incremental amount of electricity used due to overtime production (e.g. due to extra lighting). Then, the following constraint should be added to the standard model:

$$\sum_{i=1}^{T} c_I^{''} I_t + c_P^{''} P_t + c_O^{''} O_t \leq \varepsilon_E \tag{6.12}$$

Estimating the aggregate carbon footprint and energy consumption parameters (those used in Eq. (6.11) and (6.12)) might be difficult like estimating the standard aggregate economic cost parameters. However, emerging market awareness and legislative restrictions enforce organizations to take action in terms of monitoring and assessment of their carbon footprint and energy consumption [123].

6.2.3. Aggregate Planning Model with Social Considerations

In this section, the standard aggregate planning model is revised to account for the employee job security and morale-motivation, employee health and work-family balance, and customer service level.

6.2.3.1. Employee Job Security and Morale-Motivation

The standard aggregate plan may suggest hiring and firing of employees at some periods to adjust capacity, which is called as a chase strategy. This is observed especially in make to order/pull production systems where a high service level with a minimum inventory is aimed. This in return requires regular changes in capacity, which eliminates job security of the employees, impairs their morale-motivation and leads to voluntary retention [124].

The level strategy, on the other hand, is observed in make to stock/push production systems where a stable level of capacity is maintained with a stable level of output. Therefore, inventory is built up in a level strategy where workforce turnover rate is minimum in contrast to a chase strategy. As a result, the level strategy is much more preferable for the employees when compared to a chase strategy. Regular changes in the workforce should be kept at the minimum although this might be economically desirable.

When there is an upper bound on the total number of hiring and firing of employees during the entire planning horizon, indicated by S_{lim}, the following constraint should be added to the standard aggregate planning model to account for employee job security and morale-motivation:

$$\sum_{i=1}^{T} H_t + F_t \leq S_{lim} \qquad (6.13)$$

Furthermore, an upper bound on the number of employees fired at each period of the planning horizon (L_{lim}) may also be imposed by adding the following constraint:

$$F_t \leq L_{lim} \qquad \forall t \in \{1, \dots, T\} \qquad (6.14)$$

The upper bounds, S_{lim} and L_{lim}, can be obtained from predetermined standards put forth by the labor unions or the government. These limits may be expressed as a percentage of the available workforce, as well.

6.2.3.2. Employee Health and Work-Family Balance

The standard aggregate plan also allows overtime work for employees, which is called a time flexibility strategy. This strategy utilizes overtime working in peak periods of demand provided that there is excess capacity. It is similar to the chase strategy in terms of providing high service levels with minimum inventory. On the other hand, it is similar to level strategy in terms of having a stable capacity. However, overtime working has physical and psychological strain on employee health [125, 126]. Moreover, extended number of hours worked damages the social life and work-family balance of the employees [127]. For these reasons, overtime working is limited by labor rights.

Let O_{lim} be the daily limit of overtime hours for each worker; then, modifying Eq. (6.5) models the limit on overtime production:

$$O_t \leq \frac{K n_t W_t}{h} O_{lim} \qquad \forall t \in \{1, \dots, T\} \qquad (6.15)$$

Ideally, overtime working should completely be eliminated from the aggregate plan; i.e. a zero-overtime policy should be adopted. One can achieve this by setting $O_{lim} = 0$ which modifies Eq. (6.15) as follows:

$$O_t = 0 \qquad \forall t \in \{1, \dots, T\} \qquad (6.16)$$

6.2.3.3. Customer Demand Satisfaction

The standard aggregate planning formulation assumes the possibility of stock-outs. When the production is not sufficient to meet the demand, the items stocked out might be backlogged in a manufacturing setting. The items in the consequent periods are then first used to satisfy the backlogged demand of the previous period.

The standard model charges a cost, c_B, to backlogging which may cover the cost of lost sales and the additional cost for the loss of customer goodwill. However, although it may be affordable to backlog, it is undesirable for the customer. This is due to the fact that customers might suffer from their demand being unsatisfied in a physical manner in certain cases. This situation emerges when the timely possession of the demanded product is critical and backlogging is not an option for the customer. Products related to customer's physical health and safety (e.g. medical products or certain drugs which should be used on a continuous basis by the patients) constitute an example to this situation. Therefore, provision of a certain service level is not only economically desirable for the company but might also be socially crucial for the customers and a minimum service level should be attained at each period. Let α be the desired service level as the fraction of the demand satisfied at each period (e.g. 0.95). Then, the following constraint models the customer service level criterion:

$$B_t \leq (1 - \alpha) D_t \qquad \forall t \in \{1, \dots, T\} \qquad (6.17)$$

6.2.4. Aggregate Planning Model with Triple Bottom Line Accounting

In this section, an aggregate planning formulation which accounts for the above environmental and social criteria simultaneously is presented. The following MILP formulation captures environmental consciousness and social responsibility in addition to the conventional economics:

$$min\, z = \sum_{i=1}^{T} hn_t c_L W_t + c_H H_t + c_F F_t + c_M P_t + c_O O_t + c_I I_t + c_B B_t + c_S S_t \tag{6.18}$$

$s.t.$

$$P_t \leq K n_t W_t + O_t \quad \forall t \in \{1, \dots, T\} \tag{6.19}$$

$$W_t + F_t = W_{t-1} + H_t \quad \forall t \in \{1, \dots, T\} \tag{6.20}$$

$$I_t + B_{t-1} + D_t = P_t + S_t + B_t + I_{t-1} \quad \forall t \in \{1, \dots, T\} \tag{6.21}$$

$$O_t \leq \frac{K n_t W_t}{h} O_{lim} \quad \forall t \in \{1, \dots, T\} \tag{6.22}$$

$$\sum_{i=1}^{T} c_I^{'} I_t + c_P^{'} P_t + c_O^{'} O_t + c_S^{'} S_t \leq \varepsilon_C \tag{6.23}$$

$$\sum_{i=1}^{T} c_I^{''} I_t + c_P^{''} P_t + c_O^{''} O_t \leq \varepsilon_E \tag{6.24}$$

$$\sum_{i=1}^{T} H_t + F_t \leq S_{lim} \tag{6.25}$$

$$F_t \leq L_{lim} \quad \forall t \in \{1, \dots, T\} \tag{6.26}$$

$$B_t \leq (1 - \alpha) D_t \quad \forall t \in \{1, \dots, T\} \tag{6.27}$$

$$W_t, H_t, F_t \in \{Z^+ \cup \{0\}\} \quad \forall t \in \{1, \dots, T\} \tag{6.28}$$

$$P_t, O_t, I_t, B_t, S_t \geq 0 \quad \forall t \in \{1, \dots, T\} \tag{6.29}$$

$$W_0 = W_{init} \tag{6.30}$$

$$I_0 = I_{init} \tag{6.31}$$

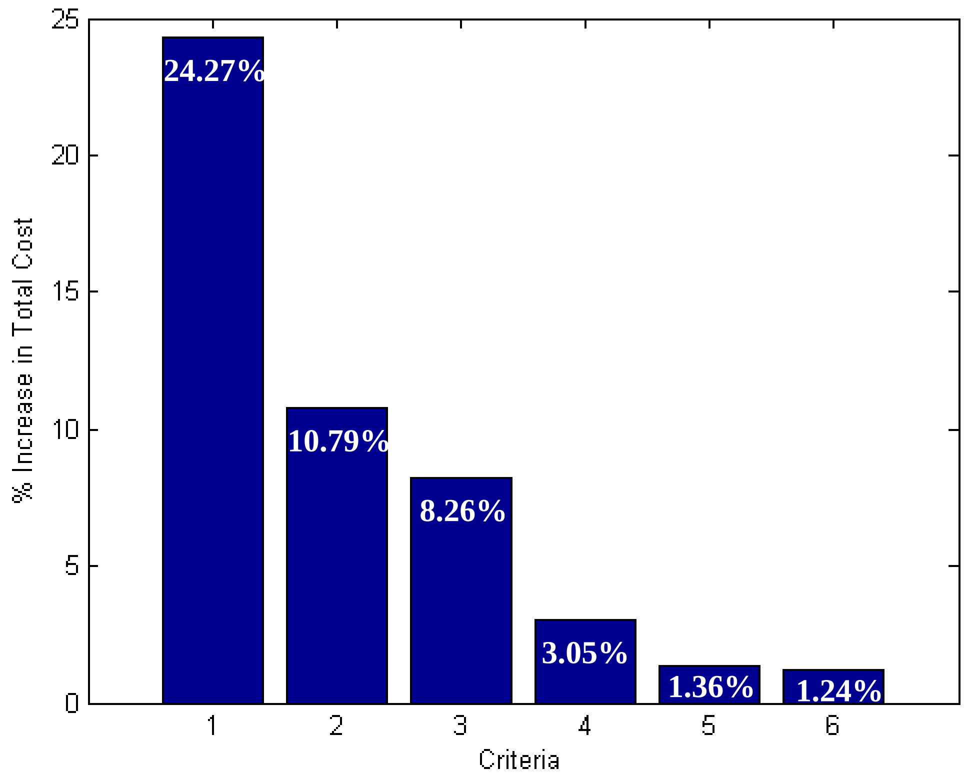
$$B_0 = B_{init} \tag{6.32}$$

Depending on the model parameters, the above formulation may lead to one of the typical aggregate planning strategies - chase, level or time flexibility. However, a combination of these three strategies may be observed throughout the planning horizon, which might be called a mixed or a *sustainable* strategy in this context.

6.3. Numerical Analysis of the Revised Models

In this section, a numerical analysis of the models presented in §6.2 is conducted. The data used in the experiments as well as its interpretation are presented in Appendix E. The solutions to the models are obtained using CPLEX – the default MILP solver of GAMS – using default options except the optimality gap [113, 128]. In particular, in order to achieve the proven optimal solutions, the relative optimality gap for the MILP is set equal to 0 throughout the analysis. For each revised model, the revised policy and its interpretation can be found in Appendix F.

The major result of the experiment; i.e. the effects of the additional criteria on total cost, is presented in Figure 6.1. Results of the numerical example shows that social management adds more cost to the triple bottom line accounting, compared to environmental management.



1: Triple Bottom Line Accounting 2: Job Security and Morale-Motivation 3: Customer Service Level 4: Health and Work-family Balance 5: Energy Usage 6: Carbon Cap

Figure 6.1 Effect of different criteria on total cost

In particular, the carbon cap criterion increases the total cost by 1.24% whereas energy usage criterion increases by 1.36%. In other words, one can achieve a certain level of emissions and energy consumption in return for a minor increase in total cost. Although these two criteria targets different environmental issues resulting from diverse operational activities (as mentioned in sections §6.2.2.1 and §6.2.2.2 and discussed in Appendix F), they lead to almost the same increase in total cost.

On the other hand, considering the job security and morale-motivation of the employees which yields 10.79% increase in the total cost, customer service level which leads to 8.26%

increase in the total cost, and health and work-family balance of the employees which leads to 3.05% increase in the total cost might be much more difficult to implement due their amplified effects on the total cost.

Finally, incorporating all of the above criteria simultaneously to exercise TBL accounting yields the largest deviation from the current operation both in terms of the optimal policy (See Table F.7 in Appendix F) and the total cost (24.27%). If, for instance, the tolerable increase in total cost is 5%, then the managers or policy makers may simply adopt controls on overtime working as well as GHG emissions and electricity consumption.

6.3.1. Sensitivity of Cost with respect to Varying Values of Exogenous Parameters

In this section, a sensitivity analysis of the total cost against important system parameters is conducted. In particular, the effects of changing the values of the model parameters which are exogenously determined are investigate.

i. GHG Emissions Cap (ε_C)

Figure 6.2 shows that the total cost is extremely sensitive for the values of ε_C below 10 emission-units. The GHG emissions constraint is not binding for the values of ε_C over 140 emission-units. In between, the cost is robust with respect to changes in the GHG emissions cap.

When the GHG emissions constraint is applied in the presence of all other environmental and social constraints, Figure 6.3 is obtained. Note that the MILP is infeasible for the values of ε_C below 20 emission-units. On the other hand, the constraint becomes redundant for the values of ε_C over 120 emission-units. In between, the cost linearly increases as ε_C is reduced.

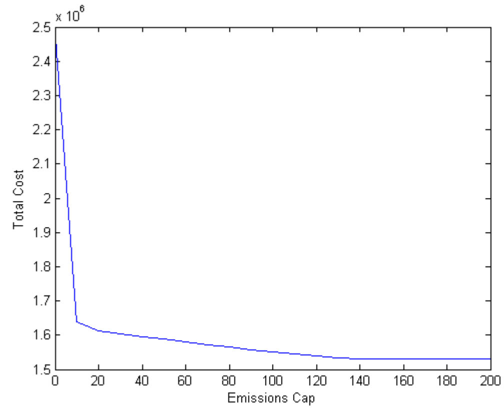


Figure 6.2 Total Cost - Emissions Cap

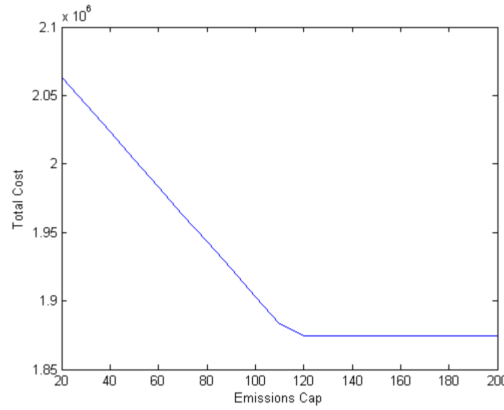


Figure 6.3 Total Cost - Emissions Cap in TBL Acc.

ii. Energy Consumption Cap (ε_E)

Figure 6.4 shows that the cost is insensitive to values of ε_E above 3000 electricity-units. On the other hand, the cost linearly increases as ε_E decreases below 3000 electricity-units.

A similar pattern holds when all other environmental and social constraints are present (Figure 6.5) except for the fact that the energy consumption constraint is not binding for the values of ε_E over 2000 electricity-units.

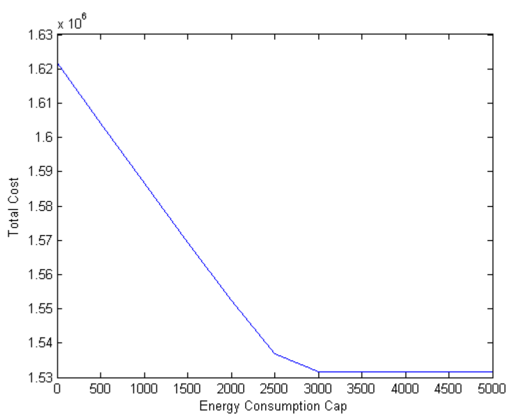


Figure 6.4 Total Cost - Energy Cap

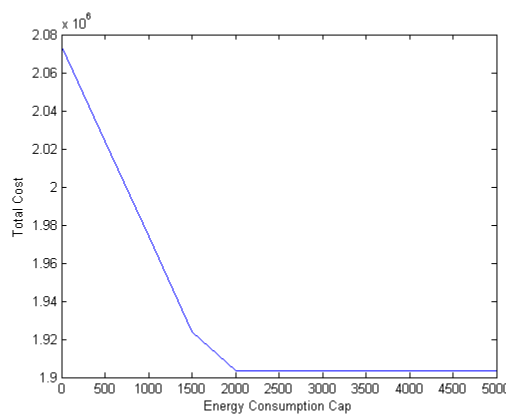


Figure 6.5 Total Cost - Energy Cap in TBL Acc.

iii. Smoothing Limit (S_{lim})

Figure 6.6 shows that the total cost increases for tighter values of smoothing limit (S_{lim}) and stabilizes for the values of S_{lim} over 12 workers. Note that the layoff limit constraint is binding for such values of S_{lim}, with $L_{lim} = 2$ for each period.

A similar pattern for total cost with respect to the changes in the values of S_{lim} is observed when other environmental and social constraints are also present (Figure 6.7).

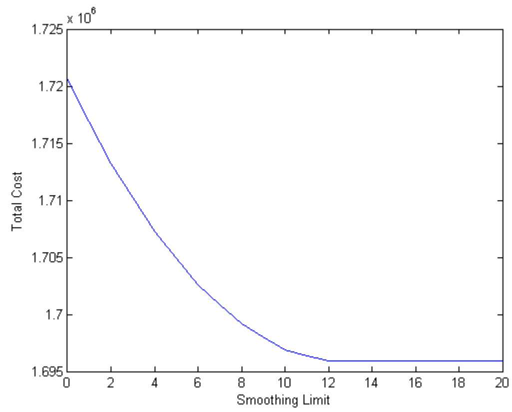


Figure 6.6 Total Cost – Smoothing Limit

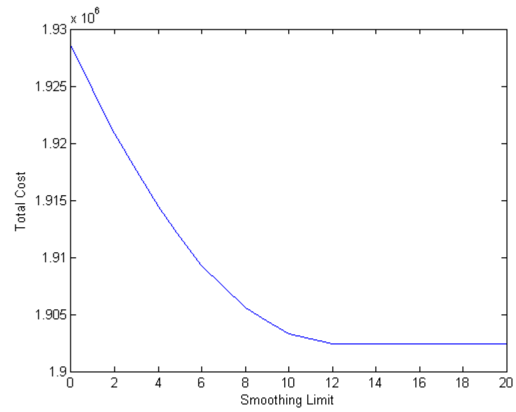


Figure 6.7 Total Cost - Smoothing Limit in TBL Acc.

iv. Layoff Limit (L_{lim})

Figure 6.8 shows that the total cost increases for tighter values of the layoff limit (L_{lim}) and stabilizes for the values of L_{lim} over 10 workers. Note that the smoothing limit constraint is binding for such values of L_{lim}, with $S_{lim} = 10$ for the entire horizon with $T = 6$.

A similar pattern for total cost with respect to the changes in the values of L_{lim} is observed when other environmental and social constraints are also present (Figure 6.9).

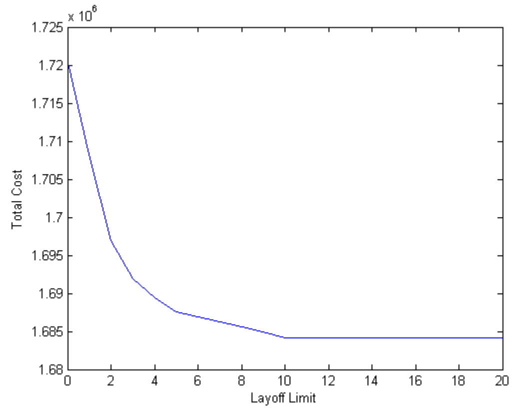


Figure 6.8 Total Cost - Layoff Limit

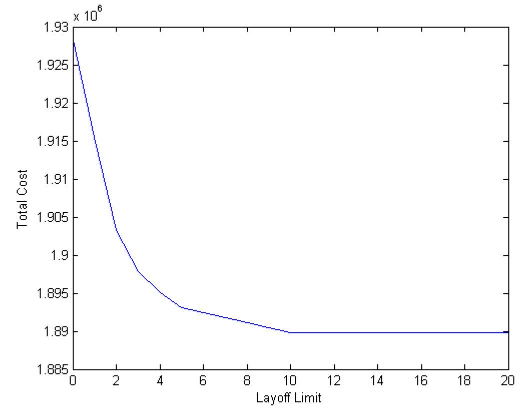


Figure 6.9 Total Cost - Layoff Limit in TBL Acc.

v. Overtime Limit (O_{lim})

Figure 6.10 shows that as overtime limit (O_{lim}) is relaxed, the cost decreases slightly. On the other hand, the total cost is completely insensitive to changes in the values of O_{lim} when the rest of the environmental and social constraints are also present in the formulation (Figure 6.11). This is due to the fact that the optimal policy with TBL Accounting does not utilize overtime production (see Table F.7). The overtime limit constraint becomes non-binding in this case and hence the value of the overtime limit does not have an effect on the total cost when other environmental and social constraints are also present in the formulation.

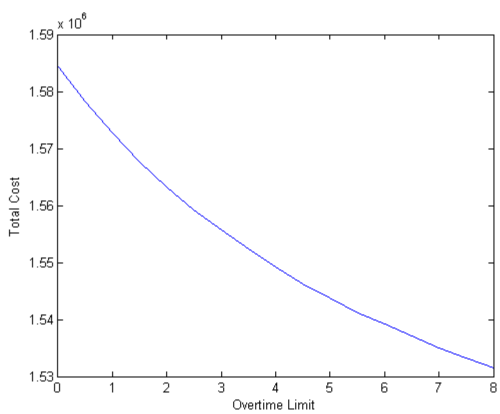


Figure 6.10 Total Cost - Overtime Limit

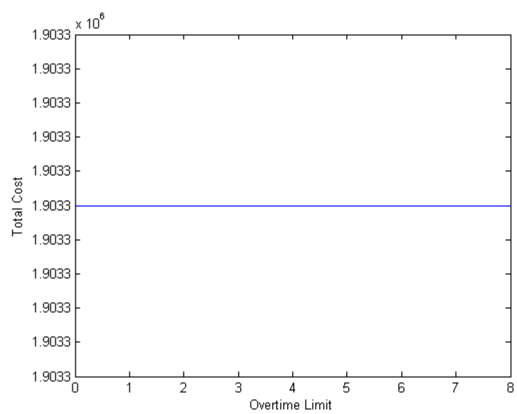


Figure 6.11 Total Cost - Overtime Limit in TBL Acc.

vi. Target Customer Service Level (α)

Figure 6.12 shows that a linear increase in cost is observed with increasing values of the target customer service level. A similar pattern holds when the rest of the environmental and social constraints are also present (Figure 6.13).

These figures (Figure 6.12 and 6.13) show the values of the service level for which a particular cost position is achieved under the presence of an additional service level constraint and TBL accounting. Similarly, the previous figures also provide a quantitative assessment of the total cost with respect to the changing values of the critical system parameters that reflect sustainability considerations.

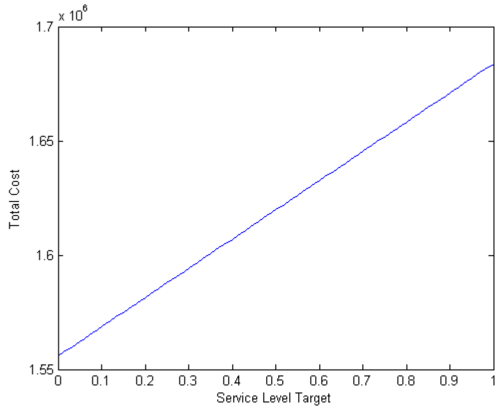


Figure 6.12 Total Cost - Service Level Target

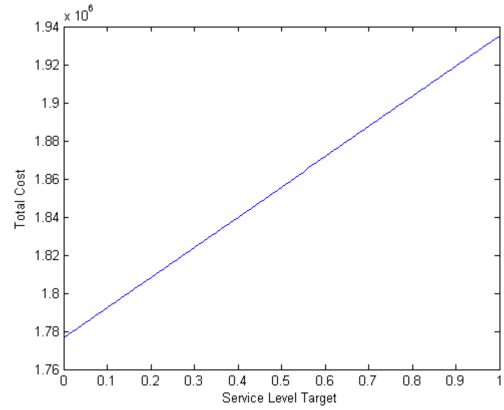


Figure 6.13 Total Cost - Service Level Target in TBL Acc.

6.4. Conclusions

In this chapter, the traditional mathematical programming formulation of the aggregate planning problem is revised by incorporating environmental and social considerations in the form of functional constraints. The numerical experiments propose that the optimal plan is subject to substantial changes when these considerations are embedded. Therefore, managers should reconsider their planning decisions in the light of sustainability. In particular, controlling environmental damage impairs social responsibility, whereas acting socially responsibly impairs the environmental footprint. The TBL accounting, on the other hand, suggests a balanced plan where both of these concerns are met in return for a considerable increase in the total economic cost. Moreover, the social criteria seem to have a bigger effect on costs than some of the most important environmental criteria have. Finally, the effects of these additional criteria seem to be additive, leading to the effect of TBL accounting. This suggests that environmental and social concerns can be managed independent of each other. Finally, it is observed that the optimal total cost might be highly sensitive to changes in exogenous model parameters. However, TBL accounting smoothes out the marginal effects of some of these parameters on total cost.

The approach used in this chapter shows how sustainability criteria can be appended to traditional cost accounting in supply chain and operations management. Using such revised models in decision-making enables the quantitative assessment and control of the sustainability performance of the companies as well as their financial performance.

Chapter 7

Application to the Facility Location Model

7.1. Introduction

Network design is a strategic decision-making problem in supply chain and operations management. Among various decisions that affect the design of the supply network, the determination of the number and location of the facilities including the manufacturing plants, warehouses, distribution centers, and retailers - known as the *facility location* problem - is fundamental. The facility location problem is important due to the fact that several other decisions follow the solution of the facility location problem. Capacity/demand allocation, sourcing, production and distribution planning are examples of such decisions.

The standard mathematical programming formulation of the facility location problem considers only the financial aspects of these decisions. In particular, the model aims to minimize the total financial cost resulting from the fixed costs of construction and the variable costs of supplying the customers.

On the other hand, additional environmental and social criteria along with the conventional economics should be considered in order to achieve sustainability. These criteria are commonly called the “three pillars” or the “triple bottom line” of sustainability [3]. Melo et al. [131] provides a thorough picture of the literature on the facility location problem and its extensions, including the ones with environmental concerns.

In this chapter, the standard facility location model is revised to consider additional environmental and social factors. Numerical analysis of this revised model is conducted to observe the characteristics of the optimal network design problem under sustainability considerations.

7.2. Model Formulations

7.2.1. The Standard Facility Location Model

The following is a standard mathematical programming model of the facility location problem among many alternative formulations [132]:

$$minimize\ z_{cost} = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij}\, x_{ij} + \sum_{j=1}^{n} f_j y_j \tag{7.1}$$

$subject\ to$

$$\sum_{i=1}^{m} x_{ij} \le m\, y_j \qquad j = 1, \ldots, n \tag{7.2}$$

$$\sum_{j=1}^{n} x_{ij} = 1 \qquad i = 1, \ldots, m \tag{7.3}$$

$$x_{ij} \ge 0 \qquad \forall i, j \tag{7.4}$$

$$y_j \in \{0,1\} \qquad \forall j \tag{7.5}$$

In this chapter, the above formulation is chosen as the standard model considering the fact that it does not require a predetermined upper bound on the number of facilities to be built or the facility capacities. This formulation is also referred to as the deterministic, static, uncapacitated facility/warehouse location problem (UFP/UWLP) or the simple plant location problem (SPLP) [133, 134, 135]. Although there are special cases for which the problem is polynomial-time solvable [136], the problem is known to be an NP-hard combinatorial optimization problem [134].

The solution of the above model not only provides the optimal number and location of the facilities to be built up but also the allocation of their capacities to customer demands. Therefore, the above formulation can also be categorized under the location-allocation models [137]. Furthermore, given the actual demand information of each customer, the solution of the model also prescribes the required sizes/capacities of each of the facility that is to be opened.

The only assumption of the above model is to have the possible facility sites predetermined. However, this assumption is realistic in the sense that such locations are almost always preset by geographical factors and legal restrictions.

In terms of the factors affecting the facility location decisions, the above formulation implicitly accounts for the distances among the demand and supply points and the related cost of transportation reflected by the model parameter, c_{ij}. Note that the estimation of c_{ij} requires a fixed network topology and mode of transportation. On the other hand, other factors including the climate conditions, available labor force and wages, power sources and the related construction costs are reflected by model parameter, f_j [86]. However, a complete treatment of the facility location problem requires the incorporation of environmental and social aspects from sustainability perspective in the decision-making process as discussed in the following subsections.

7.2.2. Facility Location Model with Environmental Considerations

The decisions involved in the facility location problem have a number of environmental effects that include primarily the impacts generated during the actual construction of the facilities and the transportation of the goods from the facilities to the customers. These impacts consist of the following: (i) greenhouse gas (GHG) emissions and (ii) solid and liquid waste generation.

7.2.2.1. Carbon Footprint

Greenhouse gases are released mainly during the transportation of the goods from facilities to the demand points. Assume that g_t denotes the amount of emissions released per unit transportation cost. Then, $g_t c_{ij}$ denote the emissions released when all demand of customer *i* is fulfilled by a facility at site *j*. Eq. (7.6) models the minimization of the GHG emissions:

$$minimize\ z_{emissions} = \sum_{i=1}^{m} \sum_{j=1}^{n} g_t c_{ij} x_{ij} \tag{7.6}$$

7.2.2.2. Waste Generation

Apart from GHG emissions which pollute the atmosphere and lead to the greenhouse effect, waste is generated in solid and liquid form mainly during the construction of the facilities and pollutes the environment; particularly the soil and the water resources. Due to the geographical characteristics of the potential sites, the soil and water contamination potentials vary. Assume that w_j denotes the waste released to the environment when a facility is built at site j. Eq. (7.7) models the waste minimization.

$$minimize\ z_{waste} = \sum_{j=1}^{n} w_j y_j \tag{7.7}$$

7.2.3. Facility Location Model with Social Considerations

The facility location decisions also have important social effects similar to the environmental ones that include the impacts due to the actual construction of the facilities, the operation of the facilities, and the transportation of the goods from the facilities to the customers. These impacts consist of the following: (i) employment and regional development and (ii) customer satisfaction.

7.2.3.1. Employment and Regional Development

The construction and operation of the facility as well as the transportation of the goods create employment opportunities and contribute to the development of the particular region. Assume that u_j denotes the social utility gained when a facility is built at site j. In estimating u_j, macroeconomic indicators such as unemployment/underdevelopment rates or specific tax incentive/reduction rates for the potential regions are used [84, 85]. Eq. (7.8) models the maximization of social development.

$$maximize\ z_{development} = \sum_{i=1}^{m} \sum_{j=1}^{n} u_j x_{ij} \qquad (7.8)$$

7.2.3.2. Customer Demand Satisfaction

The other social impact is the satisfaction of customer demand (see discussion in Chapters 3, 5 and 6) which is generated by the allocation of facility capacities to customer demands. The standard model captures this constraint in Eq. (7.3) by imposing that all demand coming from each customer should be fulfilled by a subset of facilities. It is left as a constraint instead of modeling it as an additional objective.

7.2.4. Facility Location Model with Triple Bottom Line Accounting

The triple bottom line accounting of sustainability must consider all pillars of sustainability simultaneously. In other words, the objective incorporates the minimization of cost, emissions and waste while social development is maximized. In order to express a vector of objectives that is to be minimized, the negative of the social development objective, $z_{development}$ is minimized. As a result, the following multi-objective mixed-integer linear programming formulation is used to model the triple bottom line accounting of sustainability in facility location decisions.

$$minimize\ \bar{z} = \{z_{cost}, z_{emissions}, z_{waste}, -z_{development}\} \quad (7.9)$$

$subject\ to$

$$\sum_{i=1}^{m} x_{ij} \leq m\, y_j \qquad j = 1, \dots, n \quad (7.10)$$

$$\sum_{j=1}^{n} x_{ij} = 1 \qquad i = 1, \dots, m \quad (7.11)$$

$$x_{ij} \geq 0 \qquad \forall i, j \quad (7.12)$$

$$y_j \in \{0,1\} \qquad \forall j \quad (7.13)$$

7.3. Numerical Analysis of the Revised Models

The model in §7.2.4 includes a multi-objective mixed-integer optimization problem. One of the approaches to solve this problem is to use the weighted sum method and convert the vector objective, $\bar{z}$, into a single objective, z, by multiplying each objective, z_i, with a priori preference factor - called the *weight* - λ_i; that is, $z = \sum_i \lambda_i z_i$ [138]. This approach guarantees that the optimal solution is efficient provided that each weight, λ_i, is positive. Moreover, if the objectives and the feasible set are all convex, each new assignment of weights results in a new efficient solution and hence all the efficient set can theoretically be obtained by changing the weights [139].

In order to analyze the facility location problem with TBL accounting considerations, the weighted sum method is employed. Positive weights are assigned that reflect the preferences of the decision-maker to each of the objectives in a systematic manner so as to observe the optimal network design under various preferences on the economic, environmental and social objectives. Furthermore, weights are assigned such that $\sum_i \lambda_i = 1$, although this is not mandatory to obtain an efficient solution. The resulting composite objective is as follows:

$$minimize\ \lambda_{\text{cost}} z_{cost} + \lambda_{\text{emissions}} z_{emissions} + \lambda_{\text{waste}} z_{waste} + \lambda_{\text{development}} z_{development}$$

(7.14)

The resulting model is a mixed-integer linear program (MILP) with a single objective. Note that the environmental pillar itself consists of two sub-objectives. The resulting MILP model is solved by assigning weights such that one objective is preferred or strictly preferred over the other(s) or they are treated as equally important. The following cases are investigated: (i) cost and emissions, (ii) cost and waste, (iii) cost, emission and waste; (iv) cost and development, and finally (v) the triple bottom line accounting where all objectives are considered simultaneously with positive weights given. This approach leads to 29 different combinations of the weights each time investigating another set of preferences over the economic, environmental and social objectives.

The approach is illustrated on a network topology consisting of 10 different demand sources/customers and 10 potential sites for the facilities to be built as schematically represented in the following figure (Figure 7.1). The relative optimality gap of the MILP is set equal to 0; hence, the proceeding network configurations are guaranteed to be optimal.

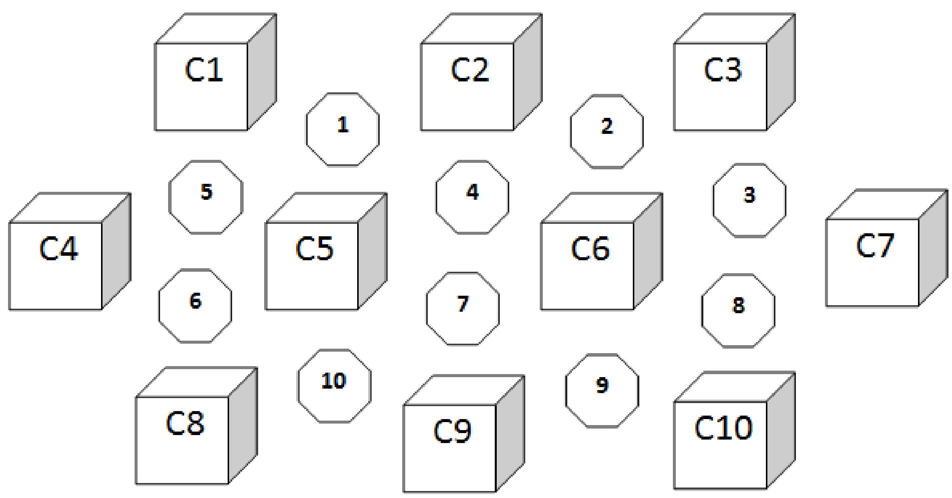


Figure 7.1 Schematic representation of the network

The values for f_j, w_j, and u_j are depicted in the following figure (Figure 7.2). Note that in order to preserve the negativity of the development objective, $z_{development}$, the values of the parameter u_j are replaced by $-u_j$ throughout the computations; however, results are reported using its original nonnegative values. The data for the transportation costs, c_{ij}, and the emissions factor, g_t can be found in Appendix G.

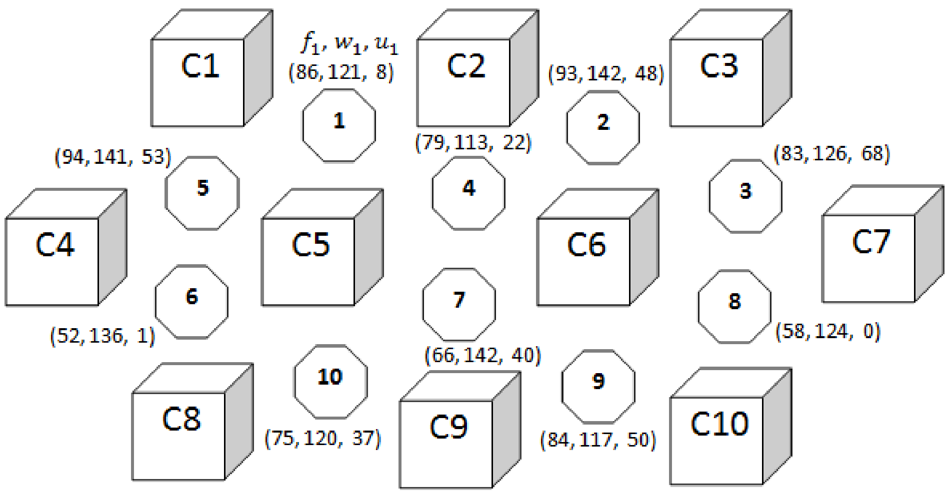
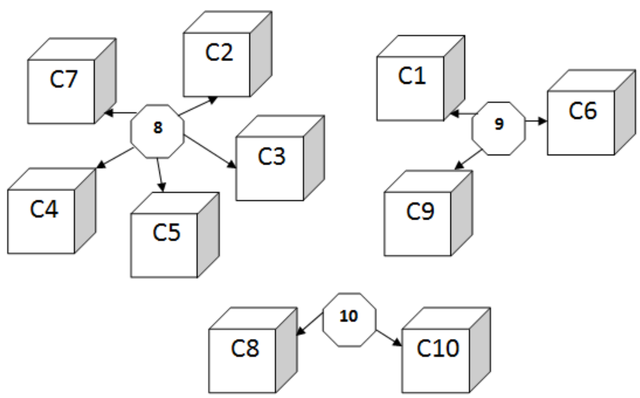


Figure 7.2 The values of f_j, w_j and u_j over the network

Some interesting variations in the optimal solutions are observed when changing preference factors are used in solving the standard model that includes purely the economical factors and the weighted sum facility location model. In particular, out of these 29 scenarios, 13 different network configurations are observed; i.e. the standard configuration together with 12 new configurations under environmental and social criteria.

7.3.1. Solution of the Standard Model

The solution of the standard model suggests that a total of three facilities should be built at sites 8, 9 and 10. As stated in §7.2.1, both the standard and the weighted sum MILP models also propose the allocation of each facility's capacity to customer demands. In particular, Eq. (7.3) in the standard formulation suggests that all of the demand of each customer should be satisfied by a subset of the facilities. For the standard model, the allocation of the site capacities to customer demands is shown in the following figure (Figure 7.3). Note that for each customer there is only one sourcing facility, whereas a sourcing facility can supply multiple demand locations. This is expected for the MILP formulation [133, 135]. All demand coming from a single customer is actually satisfied by a single facility. However, a facility may serve more than one customer. This also holds for the weighted sum MILP model and can be observed in the rest of the allocation figures in Appendix H.



$\lambda_{\text{cost}} = 1\ \lambda_{\text{emissions}} = 0\ \lambda_{\text{waste}} = 0\ \lambda_{\text{development}} = 0$
$z_{cost} = 1768\ \ z_{emissions} = 4653\ z_{waste} = 361\ \ z_{development} = 224$

Figure 7.3 Solution of the standard model

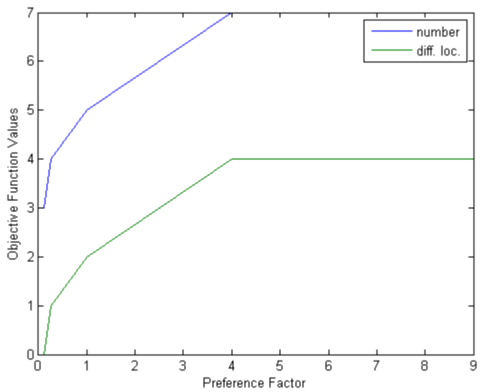
The allocation information also reveals another important decision which is the sizes/capacities of the facilities. Assuming, for example, that the demand of each customer is *D* units, the relative required capacity of each facility can be obtained by considering the number of customers served by each open facility. The standard model, for example, prescribes that a $5D$ capacity facility at Site 8, a $3D$ capacity facility at Site 9 and a $2D$ capacity facility at Site 10 should be opened (Figure 7.3). Note that it is possible to determine the exact sizes of the facilities or a more accurate capacity plan by using the actual demand information or the demand forecast when available. However, since x_{ij} represents the fraction of demand satisfied for each customer (see Table G.1), the demand information is not required to obtain the optimal solution.

The optimal solution of the standard model results in a total cost of 1768 money-units, total emissions of 4653 emission-units, total waste of 361 waste-units, and a social utility of 224 units.

7.3.2. Analysis with Economic and Environmental Considerations

7.3.2.1. Cost and Emissions Model

When the emissions objective is given weight in combination with the cost objective, the model suggests a solution with higher total cost and lower emissions when compared with the standard model. This is achieved by increasing the number of facilities to be opened. As a result, new locations are selected from the possible sites for these additional facilities (specific configurations can be found in Appendix H, figures H.1 to H.5). Figure 7.4 and 7.5 below show these trends with exact numerical values. The x axis of these figures denotes the *preference factor*, which is defined as the ratio of the weight of the entering objective to the weight of the cost objective in this chapter. For example, a preference factor of 0.11 suggests that the cost weight is 0.9 and the emissions weight is 0.1 in this case (note the weights is assumed to add up to 1). In other words, the emissions objective is given 11% importance relative to the cost objective.



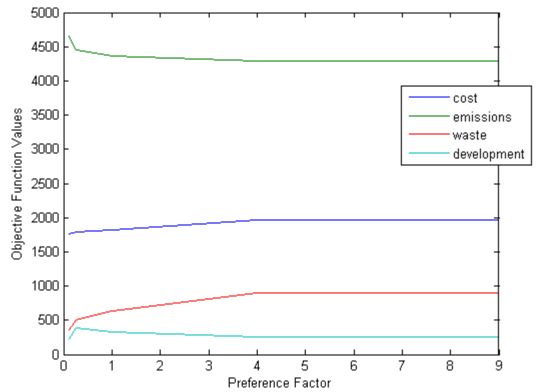


Figure 7.4 The number of facilities and different location **Figure 7.5** The objective function values

Note also that the waste objective is worsened as the number of facilities selected increases. On the other hand, development objective is improved with respect to the standard model solution and achieves its best value when the emissions preference factor is 0.25. In other words, although these two objectives are not in consideration for this case, they are also affected by the solution determined by the other objectives. Furthermore, the social objective improved when emissions are considered although the solution has a worsened performance on the other environmental component – the waste.

7.3.2.2. Cost and Waste Model

When the waste objective is given weight in combination with the cost objective, the model suggests a solution with higher total cost and lower waste when compared with the standard model. This is achieved by decreasing the number of facilities selected. No new location is selected from the possible sites, contrary to the case of emissions described above. The specific configurations can be found in Appendix H (Figures H.6 to H.10).

Note also that the emissions objective worsens as the number of facilities selected decreases. On the other hand, the value of the development objective does not exhibit a trend but instead varies depending on the optimal number and location of the facilities selected. In other words, although these two objectives are not in consideration for this case, they are also affected by the solution determined by the other objectives. Furthermore, the solution has a worse performance on the other environmental component – the emissions – when waste is considered. Figure 7.6 and 7.7 below show these trends.

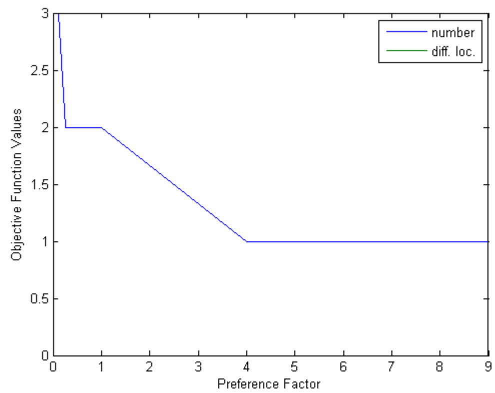


Figure 7.6 The number of facilities and different locations

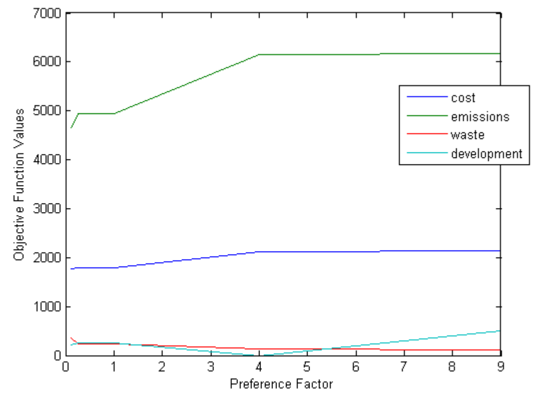


Figure 7.7 The objective function values

7.3.2.3. Cost, Emissions and Waste Model

When both components of the environmental objective; i.e. the emissions and waste objectives, are given weight in combination with the cost objective, the model suggests a solution with higher total cost for all sets of preferences. On the other hand, emissions are reduced in return for higher total waste for the cases where emission weight dominates waste weight or they are equal. The only case where waste is reduced in return for higher emissions is the case where the weight of the waste dominates the weight of the emissions. Furthermore, there is no set of weights where cost is notably increased in return for a reduction both in the emissions and waste. The reason is although these two represent environmental components, they are in direct conflict with each other. In particular, an increased number of facilities increases the waste while it reduces emissions and vice versa. Note also that the development objective is improved in all sets of preferences even though it is not directly considered in this setting. Table 7.1 shows the exact numerical values of the performance measures. The specific configurations can be found in Appendix H (Figures H.11 to H.17).

Table 7.1 Performance Measures Under Cost, Emissions and Waste

Weights	Cost	Emissions	Waste	Development	Number of Facilities	Number of Different Locations
0.8 / 0.1 / 0.1 / 0	1768	4653	361	224	3	0
0.5 / 0.25 / 0.25 / 0	1795	4452	502	386	4	1
0.5 / 0.1 / 0.4 / 0	1789	4941	241	250	2	0
0.5 / 0.4 / 0.1 / 0	1818	4365	638	334	5	2
0.2 / 0.4 / 0.4 / 0	1795	4452	502	386	4	1
0.8 / 0.1 / 0.7 / 0	1789	4941	241	250	2	0
0.8 / 0.7 / 0.1 / 0	1894	4314	780	345	6	3
Average	**1806.86**	**4588.29**	**466.43**	**310.71**	**3.71**	**1.00**

Compared with the standard model, the above scenarios (Table 7.1) on the average lead to 2.20% increase in cost, 1.39% reduction in emissions, 29.30% increase in waste and 38.71% increase in development. This is achieved by an average of 3.71 facilities (23.81% facilities more than the standard model solution) and selecting one different location when compared with the standard model solution.

7.3.3. Analysis with Economic and Social Considerations

When the employment and regional development objective is given weight in combination with the cost objective, the model suggests a solution with higher total cost and higher social utility compared to the standard model. However, since the value of this objective is affected by both the construction of facilities and the transportation of goods to the customers, the optimal number and location of the facilities to be opened change depending on the preference factor. When the development preference factor is 1 and 9, the number of facilities is reduced whereas it is same as the standard solution for the rest of the preference factors. Moreover, except for the preference factor of 0.11, at least one alternative location is selected even if the number of facilities to be opened is the same as the standard solution. The specific configurations can be found in Appendix H (Figures H.18 to H.22).

Note also that the emissions objective worsens for all levels of development preference as the number of facilities selected decreases. Furthermore, the waste objective is worsened except for the development preference factors of 0.11, 0.25 and 4 and improved for the preference factors of 1 and 9. In other words, although these two environmental objectives are not in consideration for this case, they are also affected by the solution determined by the economic and social objectives. Figure 7.8 and 7.9 below show these trends.

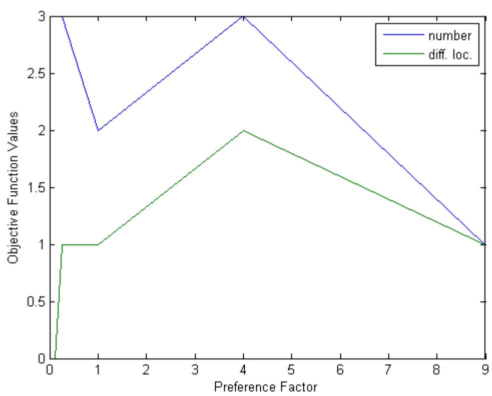


Figure 7.8 The number of facilities and different locations

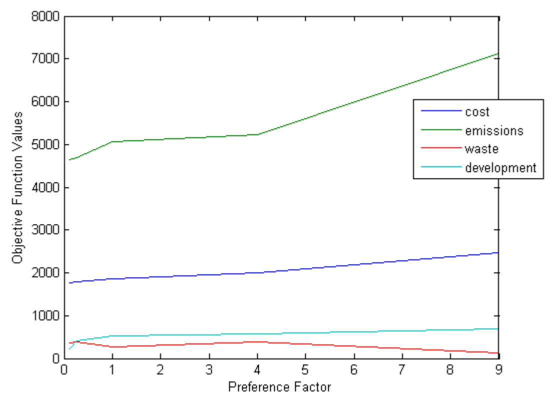


Figure 7.9 The objective function values

The following figure (Figure 7.10) summarizes the individual gains as a percentage on the additional emission, waste and development objectives with respect to the increases in cost. The percentage deviations are calculated using the objective function values in the solution proposed by the standard model and when the preference factor is highest in the numerical experiments; i.e. when it is 9 (0.1 weight for the cost and 0.9 weight for the other objective). On the environmental front, 11.54% loss in cost gives 7.8% gain in emissions, whereas 21.04% loss in cost gives 67.59% gain in waste. On the social front, a much significant impact is observed with greater loss in cost. 39% increase in cost gives 203.57% gain in the employment and regional development objective.

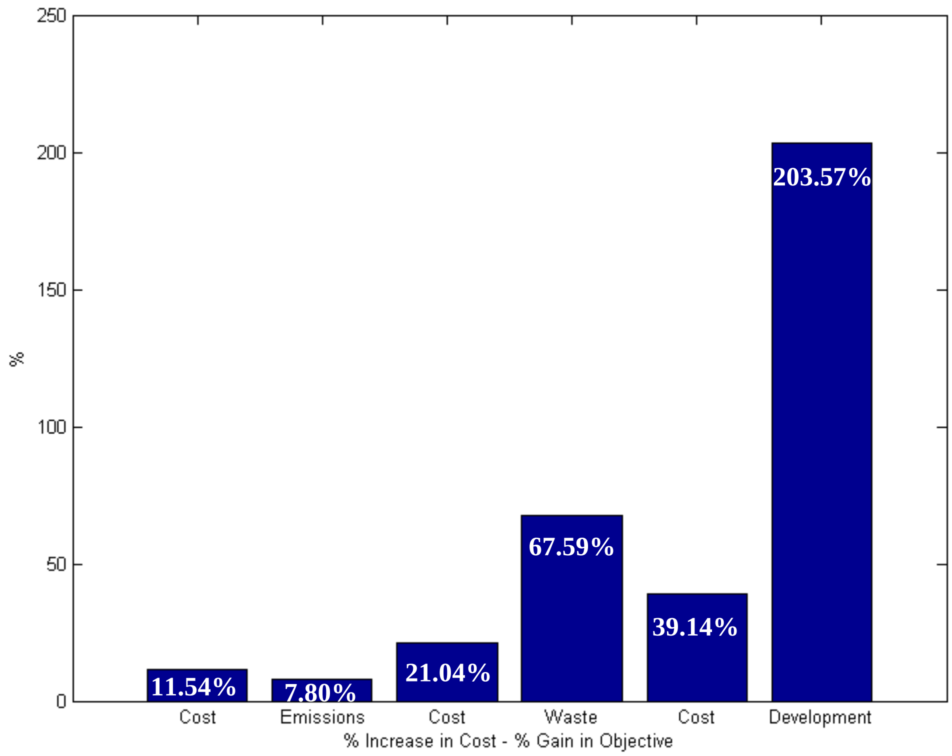


Figure 7.10 The gains in environmental and social objectives with respect to the losses in cost

7.3.4. Analysis with Triple Bottom Line Accounting

When the economic, environmental and social objectives are given weights simultaneously, the model suggests a solution with higher total cost for all sets of preferences. Emissions are reduced in return for higher total waste for the cases where emission weight dominates waste weight or when they are equal. The only exception is for the case where they have equal weights of 0.1 and development weight dominates the rest. In this case, both the emissions and waste are higher than the standard model solution. The only case where waste is reduced in return for higher emissions is the case where the weight of the waste dominates the weight of the emissions. On the other hand, the development objective is improved in all sets of preferences. Table 7.2 shows the exact numerical values for the performance measures. The specific configurations for each combination of weights can be found in Appendix H (Figures H.23 to H.28).

Table 7.2 Performance Measures Under TBL Accounting

Weights	Cost	Emissions	Waste	Development	Number of Facilities	Number of Different Locations
0.6 / 0.1 / 0.1 / 0.2	1795	4452	502	386	4	1
0.33 / 0.165 / 0.165 / 0.33	1795	4452	502	386	4	1
0.2 / 0.3 / 0.3 / 0.2	1795	4452	502	386	4	1
0.2 / 0.1 / 0.5 / 0.2	1869	5073	258	518	2	1
0.2 / 0.5 / 0.1 / 0.2	1818	4365	638	334	5	2
0.2 / 0.1 / 0.1 / 0.6	1909	4944	384	548	3	2
Average	**1830.17**	**4623.00**	**464.33**	**426.33**	**3.67**	**1.33**

Compared with the standard model, the above scenarios (Table 7.2) on the average lead to 3.52% increase in cost, 0.64% reduction in emissions, 28.62% increase in waste and 90.33% increase in development. This is achieved by an average of 3.67 facilities (22.22% facilities more than the standard model solution) and selecting 1.33 different location when compared with the standard model solution.

Depending on the actual preferences of the decision-maker, a solution can be obtained by adjusting the weights of economic, environmental and social objectives simultaneously using the weighted sum facility location model proposed in this chapter. With some loss in the cost objective as depicted above, gaining from the environmental and social objectives and therefore achieving a balance among the three pillars of sustainability is possible in the supply chain network design problem.

7.4. Conclusions

In this chapter, the network design problem is considered on the basis of a standard facility location model and this model is revised to incorporate sustainability considerations. The standard model used in this chapter prescribes the optimal number and locations of the facilities to be built up as well as the allocation of their capacity to demand sources and their relative required sizes. The solution is based on the trade-off between the fixed costs of locating a facility at a particular site and the variable costs of satisfying the demand by transporting the goods to the customers. On the other hand, when the model is revised to account for sustainability, this trade-off is reshaped by the balance among the economic, environmental, and social factors.

A numerical analysis of this revised model is conducted to observe the optimal network design under sustainability considerations. The numerical experiments show that the optimal network configuration changes fundamentally when such considerations are present. In particular, out of the 28 additional scenarios investigated, only four of them resulted in the same solution as the standard model suggests. Furthermore, the rest of these 24 scenarios are comprised of 12 different network configurations with at least a difference in the number, location or allocation of the facilities. Depending on these changes, the cost and the environmental and social performance measures are affected as well.

On the environmental front, the model reduces the emissions by suggesting an increased number of facilities and different locations when compared to the standard model in return for an increase in cost and waste. On the other hand, it reduces waste by suggesting a decreased number of facilities and no new locations with respect to the standard model in return for an increase in cost and emissions. On the social front, the model increases the employment and regional development in return for an increase in cost either by opening up more new facilities or by increasing the facility capacity. Depending on the particular rates, the model also suggests location changes. Finally, the average of the triple bottom line accounting scenarios suggests a network with an increased number of facilities and different locations with an increase in cost, reduction in emissions, increase in waste and increase in the employment and regional development.

The analysis shows how sustainability considerations can be embedded into the traditional cost accounting in the supply chain network design problem based on the facility location formulation. Depending on the preferences of the decision-maker, a sustainable supply chain network design might be achieved which favors the additional environmental and social pillars of sustainability with relatively minor increases in cost.

Chapter 8

CONCLUSIONS

In this chapter, the contributions and main observations of the study are outlined along with a discussion on the implications and future opportunities.

8.1. Contributions of the Thesis

Sustainability and its interpretation in supply chain management is an emerging requirement that decision-makers have to deal with. In this thesis, a methodological approach to achieve sustainability in managing supply chain systems is introduced and applications of the proposed method on three fundamental decision-making problems from three decision-making levels are presented. The proposed approach is based on the revision of standard mathematical programming (optimization) models of classical supply chain and operations management problems with environmental and social factors and the analysis of these revised models. Hence, it is a quantitative framework with a theoretical background in modeling and analysis of sustainable supply chain systems. Furthermore, it incorporates the economic, environmental and social dimensions of sustainability simultaneously. Therefore, this study is a first step aimed at filling the gaps in the open sustainable supply chain and operations management literature as discussed in Chapter 2 (see Table 2.1 in Chapter 2 and Table 8.1 below). Besides, the introduction of the environmental and social considerations and metrics to quantify these considerations (Chapter 3) as well as the formulation of the revised mathematical programming models (Chapters 4-7) are the secondary contributions of the study that are accomplished during the implementation of the proposed approach.

Table 8.1 Contributions of the Thesis

Papers	Problem Considered	Base Model	Economic Pillar	Environmental Pillar	Social Pillar	Conceptual Framework
Arslan and Turkay (2011) (Chapter 7)	**Network Design**	**Uncapacitated Facility Location**	**Yes**	**Yes**	**Yes**	**Yes (Chapter 3)**
Arslan and Turkay (2011) (Chapter 6)	**Production Planning**	**Aggregate Planning**	**Yes**	**Yes**	**Yes**	**Yes (Chapter 3)**
Arslan and Turkay (2011) (Chapter 5)	**Inventory Control**	**Newsvendor**	**Yes**	**Yes**	**Yes**	**Yes (Chapter 3)**
Hua et al (2011)	Inventory Control	Economic Order Quantity	Yes	Yes	N/A	N/A
Benjaafar et al (2010)	Inventory Control	Deterministic Lot Sizing	Yes	Yes	N/A	N/A
Hoen et al (2010)	Transportation Planning	Newsvendor	Yes	Yes	N/A	N/A
Bouchery et al (2010)	Inventory Control	Economic Order Quantity	Yes	Yes	Yes	N/A
Lee et al (2010)	Network Design	Deterministic and Stochastic Programming	Yes	Yes	N/A	N/A
Chaabane et al (2010)	Network Design	Mixed Integer Linear Programming	Yes	Yes	N/A	Yes
Arslan and Turkay (2010) (Chapter 4)	**Inventory Control**	**Economic Order Quantity**	**Yes**	**Yes**	**Yes**	**Yes (Chapter 3)**
Bonney and Jaber (2009)	Inventory Control	Economic Order Quantity	Yes	Yes	N/A	N/A
Bauer et al (2009)	Transportation Planning	Multi-commodity Capacitated Network Flow	Yes	Yes	N/A	N/A
Kim et al (2009)	Transportation Planning	Bi-criteria Linear Programming	Yes	Yes	N/A	N/A
Neto et al (2008)	Network Design	Multi-objective Programming	Yes	Yes	N/A	Yes
Erkut et al (2008)	Network Design	Multi-criteria Location-allocation	Yes	Yes	N/A	N/A
Letmathe and Balakrishnan (2005)	Production Planning	Linear and Mixed Integer Programming	Yes	Yes	N/A	N/A
Manikas and Godfrey (2000)	Inventory Control	Newsvendor	Yes	Yes	N/A	N/A
Penkuhn et al (1997)	Production Planning	Constrained Nonlinear Programming	Yes	Yes	N/A	N/A

N/A: *Not Available*

8.2. Main Observations and Implications

Chapters 4 and 5 are both devoted to the analysis of an operational decision-making problem, namely the inventory control problem and the EOQ and newsvendor models from the inventory control literature. The main distinction between these two models is the fact that the EOQ model models a known demand scenario whereas the newsvendor model assumes that the demand is uncertain. In both of these models, the decision-maker decides on the optimal order/production quantity in the presence of pure-economical objectives; i.e. minimizing cost or maximizing profit. Instead of this pure-economical comprehension, a number of different settings are considered where additional environmental and social criteria are integrated to these standard models. It is observed that the optimal ordering/production policy changes substantially along with an increase in cost or decrease in profit in return for environmental and social gains.

Chapter 6 is devoted to the analysis of a tactical decision-making problem, namely the production planning problem and the aggregate planning model from the production planning literature. In the aggregate planning model, the decision-maker deduces an optimal production plan that is comprised of the production, inventory and capacity levels for a finite and medium-term planning horizon with the objective of minimizing total cost. This standard formulation is revised with additional environmental and social criteria instead of this pure-economical comprehension. The numerical experiments show that the optimal plan changes substantially when such considerations are present. Moreover, although cost increases in return for environmental and social benefits, addressing environmental criteria considered in the aggregate planning model is much cheaper than addressing social criteria.

Finally, Chapter 7 is devoted to the analysis of a strategic decision-making problem, namely the network design problem and the facility location model from the network design literature. In the facility location model, the decision-maker decides on the optimal number and location of the facilities to be built given a set of potential sites with the objective of minimizing total cost. Instead, this pure-economical model is revised with additional environmental and social criteria. The numerical experiments show that the optimal network configuration changes fundamentally when such considerations are embedded. This change is observed either in the number, locations, capacities or the allocations of the facilities or in a collection of these four attributes.

This study can be considered as a partial revision of classical supply chain and operations management problems with the triple bottom line accounting. The analysis of the revised models presented in Chapters 4-7 suggests that, by adjusting the optimal policy accordingly, environmental and social gains can be achieved in return for an economic loss. The magnitudes of these gains and losses depend on the criteria targeted in addition to the particular context reflected by the model parameters. Furthermore, the analysis also shows that certain legislations or incentives should be placed by the regulatory agencies or market mechanisms in order to enforce the adoption of the proposed approach in decision-making. This is due to the fact that the managers and policy makers tend to retain the conventional pure-economical approach in making decisions to avoid the economic loss and instead deal with the environmental and social impacts of their pure-economical decisions by taking corrective actions. However, since it is hard to reverse these impacts as these impacts might also be irreversible in some cases, taking such actions is not even always possible. Therefore, this second approach is not viable and an alternative to the proposed approach in this study.

The development of training programs for industrial specialists that shows the benefits and method of sustainable decision-making is an important step to establish an interface between the outputs of this research and the industrial application. In this way, the potential resistance against considering these environmental and social impacts as explained above might be eliminated. In connection, due to the widespread use of the enterprise resource planning (ERP) software by the organizations, the development of environmentally and socially revised optimization modules for ERP software is another opportunity for the entrepreneur industrial engineer.

8.3. Limitations and Future Work

Further extensions are numerous. In chapter 4, the standard EOQ setting is considered with a single item at a single location with no backlogging, constant lead times, and an unlimited supply. These assumptions may be relaxed to account for multiple items at multiple locations with planned backorders, variable lead times, and a finite production rate. It is of course possible to include traditional extensions of the EOQ model in the above models such as quantity discounts, imperfect quality, and resource constraints like warehouse space. Furthermore, other forms of cost-accounting such as net present value (NPV) calculation instead of considering the average total cost may also be utilized. In Chapter 4, the situation of a single organization is analyzed. Considering multiple organizations and echelons in the chain and analyzing the terms of coordination among supply chain members with these added environmental and social criteria might reveal new insights for sustainable supply chain management. New types of contracts may also be designed which coordinates the chain *sustainably*. Lastly, an interesting and possibly more complex problem in the cap and trade system in Chapter 4 is the one where organizations decide on the price of the allowances. A proper treatment of such a problem would require a game theoretic analysis.

An extension to Chapter 5 is to consider multiple items and analyze their joint lot sizing decisions with sustainability considerations. The revised policy under other demand distributions can also be analyzed as well. In Chapter 5, the lot sizing problem of a single manufacturer is considered. Analyzing the case where there are multiple parties along the supply chain either competing or collaborating under sustainability considerations is another important direction for further investigation. Finally, similar environmental and social considerations can be incorporated into the newsvendor setting for applications in service systems.

For Chapter 6, a dynamic structure in parameter estimation might be used which is convenient to assume for most industrial settings. Apparently, such a modification would require a dynamic solution procedure as well. In Chapter 6, a single decision maker's planning decision is considered. An extension is to consider collaboration among supply chain parties and conditions of coordination, similar to Chapters 4 and 5.

In Chapter 7, the analysis is based on the uncapacitated facility location model. In contrary, a capacitated facility location model might also be used. The maximum number of facilities to be opened might also be assumed to be fixed as well. Moreover, the problem of placing additional facilities into an already existing network might also be investigated under sustainability considerations.

Apart from these specific extensions above, there are also some general directions of future work. Other supply chain and operations management problems (as mentioned in Chapter 3) can be revised and analyzed using the approach proposed in this study. Thus, a complete revision of classical supply chain and operations management by triple bottom line accounting can be achieved.

For these problems and corresponding models (including the ones in Chapters 4-7), other environmental and social criteria that would fit into the problem context may be considered and analyzed as well. Although the ones identified for the problems addressed in this thesis span the general considerations and metrics, others can be found based on specific problem contexts.

A limitation of this thesis is about the numerical experiments which lack real data. In other words, all of the data employed in numerical experiments are hypothetical. This is due to the fact that environmental and social parameter estimates are not available within the companies and estimating them requires conducting field studies. Therefore, conducting field studies to estimate the economic, environmental and social parameters of the revised models is another future direction. Thus, the models can be numerically analyzed with real data and specific insights can be derived based on specific sectors and companies.

BIBLIOGRAPHY

[1] S. Seuring and M. Muller, From a literature review to a conceptual framework for sustainable supply chain management, Journal of Cleaner Production, 16 (2008), 1699-1710.

[2] J. Elkington, Towards the sustainable corporation: win-win-win business strategies for sustainable development, California Management Review, 36(2) (1994), 90-100.

[3] J. Elkington, Cannibals with forks: the triple bottom line of 21st century business, Oxford: Capstone, (2002).

[4] WCED (World Commission on Environment and Development), Our common future, Oxford University Press, (1987).

[5] R.B. Handfield and E.L. Nichols, Introduction to supply chain management, Prentice-Hall, (1999).

[6] R.S. Russell and B.W. Taylor, Operations management, Pearson Education Inc., (2003).

[7] S. Nahmias, Production and operations analysis, McGraw-Hill, (2009).

[8] F.R. Jacobs and R.B. Chase, Operations and supply management: the core, McGraw-Hill, (2010).

[9] L.M. Corbett, Sustainable operations management: a typological approach, Journal of Industrial Engineering and Management, 2(1) (2009), 10-30.

[10] C.J. Corbett and R.D. Klassen, Extending the horizons: environmental excellence as key to improving operations, Manufacturing and Service Operations Management, 8(1) (2006), 5-22.

[11] C.J. Corbett and P.R. Kleindorfer, Environmental management and operations management: introduction to part 1 (manufacturing and eco-logistics), Production and Operations Management, 10 (2001a), 107-111.

[12] C.J. Corbett and P.R. Kleindorfer, Environmental management and operations management: introduction to part 2 (integrating operations and environmental management systems), Production and Operations Management, 10 (2001b), 225-227.

[13] M.C. Gupta, Environmental management and its impact on the operations function, International Journal of Operations and Production Management, 15(8) (1995), 34-51.

[14] S.M. Gupta and A.J.D. Lambert, Environment conscious manufacturing, CRC Press, (2009).

[15] P.R. Kleindorfer, K. Singhal and L.N.V. Wassenhove, Sustainable operations management, Production and Operations Management, 14(4) (2005), 482-492.

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

[17] P. Sasikumar and G. Kannan, Issues in reverse supply chain, part 3: classification and simple analysis, International Journal of Sustainable Engineering, 2 (2009), 2-27.

[18] S.K. Srivastava, Green supply-chain management: a state-of-the-art literature review, International Journal of Management Reviews, 9 (2007), 53-80.

[19] B.M. Beamon, Designing the green supply chain, Logistics Inf. Mgmt., 12 (4) (1999), 332-342.

[20] P. Boulanger and T. Brechet, Models for policy-making in sustainable development: the state of the art and perspectives for research, Ecological Economics, 55 (2005), 337-350.

[21] M. Fleischmann, J.M. Bloemhof-Ruwaard, R. Dekker, E. van der Laan, J.A.E.E. van Nunen and L.N. van Wassenhove, Quantitative models for reverse logistics: a review, Eur. J. Oper. Res., 103 (1997), 1-17.

[22] R. Handfield, R. Sroufe and S. Walton, Integrating environmental management and supply chain strategies, Bus. Strat. Env., 14 (2005), 1-19.

[23] W.B. Jones, C.R. Cassady and R.O. Bowden, Developing a standard definition of intermodal transportation, Transport. Law J., 27 (2000), 345-355.

[24] K. Kim, I. Song, J. Kim and B. Jeong, Supply planning model for remanufacturing system in reverse logistics environment, Comp. Ind. Eng., 51 (2006), 279-287.

[25] C. Macharis and Y.M. Bontekoning, Opportunities for OR in inter-modal freight transport research: a review, Eur. J. Oper. Res., 153 (2004), 400-416.

[26] J. Sarkis, Manufacturing strategy and environmental consciousness, Technovation, 15 (2) (1995), 79-92.

[27] S. Seuring, Industrial ecology, life cycles, supply chains: differences and interrelations, Business Strategy and the Environment, 13 (2004a), 306-319.

[28] S. Seuring, Integrated chain management and supply chain management comparative analysis and illustrative cases, Journal of Cleaner Production, 12 (2004b), 1059-1071.

[29] M. Turkay, Environmentally conscious supply chain management, in L. Papageorgiou and M. Georgiadis, editors, Process Systems Engineering: Supply Chain Optimization, 45-86. WILEY-VCH, Weinheim, 2008.

[30] S. Yeralan and D. Baker, Sustainable Systems Engineering, 39th ASEE/IEEE Frontiers in Education Conference, (2009).

[31] C.R. Carter, Purchasing and social responsibility: a replication and extension, Journal of Supply Chain Management, 40(4) (2004), 4-16.

[32] C.R. Carter and M.M. Jennings, Social responsibility and supply chain relationships, Transportation Science, 38 (2002), 37-52.

[33] R. Clift, Metrics for supply chain sustainability, Cleaner Technology and Environmental Policy, 5 (2003), 240–247.

[34] T.N. Gladwin, T. Krause and J.J. Kennelly, Beyond eco-efficiency: towards socially sustainable business, Sustainable Development, 3(1) (2006), 35-43.

[35] M.J. Hutchins and J.W. Sutherland, An exploration of measures of social sustainability and their application to supply chain decisions, Journal of Cleaner Production, 16 (2008), 1688-1698.

[36] J. Koplin, S. Seuring and M. Mesterharm, Incorporating sustainability into supply management in the automotive industry: the case of the Volkswagen AG, Journal of Cleaner Production, 15 (2007), 1053-1062.

[37] J. Sarkis, Evaluating environmentally conscious business practices, European Journal of Operational Research, 107(1) (1998), 159-174.

[38] J. Sarkis, A strategic decision framework for green supply chain management, Journal of Cleaner Production, 11 (2003), 397-409.

[39] J. Bauer, T. Bektaş and T.G. Crainic, Minimizing greenhouse gas emissions in intermodal freight transport: an application to rail service design, Journal of the Operational Research Society, 61 (3) (2009), 530-542.

[40] S. Benjaafar, Y. Li and M. Daskin, Carbon footprint and the management of supply chains: insights from simple models, under review, (2010).

[41] M. Bonney and M. Jaber, Environmentally responsible inventory models: non-classical models for a non-classical era, International Journal of Production Economics, in press, (2009).

[42] Y. Bouchery, A. Ghaffari, Z. Jemai and Y. Dallery, How to incorporate sustainability issues into traditional operations management models? The sustainable order quantity example, Laboratoire Génie Industriel, Ecole Centrale Paris, Research Report, (2010).

[43] M. Bruglieri and L. Liberti, Optimal running and planning of a biomass-based energy production process, Energy Policy, 36 (2008), 2430-2438.

[44] Y.P. Cai, G.H. Huang, Z.F. Yang, Q.G. Lin, B. Bass and Q. Tan, Development of an optimization model for energy systems planning in the region of Waterloo, Int. J. Energy Res., 32 (2008), 988-1005.

[45] A. Chaabane, A. Ramudhin and M. Paquet, Design of sustainable supply chains under emission trading scheme, International Journal of Production Economics, in press, (2010).

[46] C.J. Corbett and G.A. DeCroix, Shared-savings contracts for indirect materials in supply chains: channel profits and environmental impacts, Management Science, 47(7) (2001), 881-893.

[47] E. Erkut, A. Karagiannidis, G. Perkoulidis and S.A. Tjandra, A multicriteria facility location model for municipal solid waste management in North Greece, European Journal of Operational Research, 187 (2008), 1402-1421.

[48] H. Hashim, P. Douglas, A. Elkamel and E. Croiset, Optimization model for energy planning with CO2 emission considerations, Ind. Eng. Chem. Res., 44(4) (2005), 879-890.

[49] K.M.R. Hoen, T. Tan, J.C. Fransoo and G.J. Houtum, Effect of carbon emission regulations on transport mode selection in supply chains. http://cms.ieis.tue.nl/Beta/Files/WorkingPapers/Betawp308.pdf [accessed on 20/05/2010].

[50] G. Hua, T.C.E. Cheng and S. Wang, Managing carbon footprints in inventory management, International Journal of Production Economics, in press, (2011).

[51] A. Hugo, P. Rutter, S. Pistikopoulos, A. Amorelli, G. Zoia, Hydrogen infrastructure strategic planning using multi-objective optimization, International Journal of Hydrogen Energy, 30 (2005), 1523-1534.

[52] Y. Kainuma and N.A. Tawara, Multiple attribute utility theory approach to lean and green supply chain management, International Journal of Production Economics, 101(1) (2006), 99-108.

[53] N.S. Kim, M. Janic and B. Wee, Trade-off between carbon dioxide emissions and logistics costs based on multi objective optimization, Transportation Research Record, 2139 (2009), 107-116.

[54] D. Lee, M. Dong and W. Bian, The design of sustainable logistics network under uncertainty, International Journal of Production Economics, 128 (2010), 159-166.

[55] P. Letmathe and N. Balakrishnan, Environmental considerations on the optimal product mix, European Journal of Operational Research, 167 (2005), 398-412.

[56] P. Linares and C. Romero, A multiple criteria decision-making approach for electricity planning in Spain: economic versus environmental objectives, The Journal of Operational Research Society, 51(6) (2000), 736-743.

[57] A. Manikas and M. Godfrey, Inducing green behavior in a manufacturer, Global Journal of Business Research, 4(2) (2010), 27-38.

[58] A. Nagurney and F. Toyasaki, Supply chain super-networks and environmental criteria, Transportation Research, 8 (2003), 185-213.

[59] A. Nagurney, Z. Liu and T. Woolley, Optimal endogenous carbon taxes for electric power supply chains with power plants, Mathematical and Computer Modeling, 44 (2006), 899-916.

[60] J.Q.F. Neto, J.M. Bloemhof-Ruwaard, J.A.E.E. van Nunen and E. van Heck, Designing and evaluating sustainable logistics networks, International Journal of Production Economics, 111 (2008), 195-208.

[61] T. Penkuhn, T. Spengler, H. Pouchert and O. Rentz, Environmental integrated production planning for ammonia synthesis, European Journal of Operational Research, 97 (1997), 327-336.

[62] A.A. Rentizelas, I.P. Tatsiopoulos and A. Tolis, An optimization model for multi-biomass tri-generation energy supply, Biomass and Bioenergy, 33 (2009), 223-233.

[63] J.B. Sheu, Green supply chain management, reverse logistics and nuclear power generation, Transportation Research, 44 (2008), 19-46.

[64] J.B. Sheu, Y. Chou and C. Hu, An integrated logistics operational model for green-supply chain management, Transportation Research, 41(4) (2005), 287-313.

[65] A. Soylu, C. Oruc, M. Turkay, K. Fujita and T. Asakura, Synergy analysis of collaborative supply chain management in energy systems using multi-period MILP, European Journal of Operational Research, 174 (2006), 387-403.

[66] J.A. Stuart, J.C. Ammons and L.J. Turbini, A product and process selection model with multidisciplinary environmental considerations, Operations Research, 47(2) (1999), 221-234.

[67] M. Turkay, C. Oruç, K. Fujita and T. Asakura, Multi-company collaborative supply chain management with economical and environmental considerations, Computers and Chemical Engineering, 28(6-7) (2004), 985-992.

[68] M. Turkay and A. Soylu, Synergy analysis of collaboration with biofuel use for environmentally conscious energy systems, in W. Marquardt and C. Pantelides, editors, Computer-Aided Chem. Eng., 1827-1832. ESCAPE-16, Elsevier, Amsterdam, 2006. Vol.21.

[69] Z. Zhou, S. Cheng and B. Hua, Supply chain optimization of continuous process industries with sustainability considerations, Computers and Chemical Engineering, 24 (2000), 1151-1158.

[70] S.I. Gass, Linear programming, McGraw-Hill, (1984).

[71] G.B. Dantzig, Linear programming and extensions, Princeton University Press, (1963).

[72] C.A. Floudas, Nonlinear and mixed-integer optimization: fundamentals and applications, Oxford University Press, (1995).

[73] H. Williams, Model building in mathematical programming, New York: Wiley, (1993).

[74] T. Wiedmann and J. Minx, A definition of "carbon footprint", in C. C. Pertsova, editor, Ecological Economics Research Trends, 1-11. Nova Science Publishers, Hauppauge NY, USA, 2008.

[75] W. Reitler, M. Rudolph and H. Schaefer, Analysis of the factors influencing energy consumption in industry: a revised method, Energy Economics, 9(3) (1987), 145-148.

[76] E. Worrell, Industrial energy use, status and trends, in C. Cleveland et al., editors, Encyclopedia of Energy, 395-406. Elsevier, Amsterdam, 2004, Vol.3.

[77] D.L. Wise and J. Debra (editors), Process engineering for pollution control and waste minimization, New York: M. Dekker, (1994).

[78] F.F. Saccomanno and J.H. Shortreed, Hazmat transport risks: societal and individual perspectives, Journal of Transportation Engineering, 119 (2) (1993), 177-188.

[79] ISO (International Organization for Standardization), http://www.iso.org/ [accessed on 29/03/2011].

[80] CERES, http://www.ceres.org/principles [accessed on 29.03.2011].

[81] B.T. Oakley, Total quality product design - how to integrate environmental criteria into the production realization process, Total Quality Environmental Management, 2 (3) (1993), 309-321.

[82] ILO (International Labor Organization), http://www.ilo.org [accessed on 29/03/2011].

[83] NZBCSD (New Zealand Business Council for Sustainable Development), Business guide to a sustainable supply chain: a practical guide. http://www.nzbcsd.org.nz/supplychain/ [accessed on 08.01.2011]

[84] OECD (Organization for Economic Co-operations and Development), http://www.oecd.org [accessed on 15.04.2011]

[85] Eurostat, http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/ [accessed on 29.03.2011].

[86] W.C. Turner, J.H. Mize, K.E. Case and J.W. Nazemetz, Introduction to industrial and systems engineering, Prentice Hall, (1993).

[87] E. Chichester, The A to Z of corporate social responsibility: a complete reference guide to concepts, codes and organizations**,** John Wiley & Sons, (2007).

[88] F.J. Landy and J.M. Conte, Work in the 21st century: an introduction to industrial and organizational psychology, Oxford: Wiley and Sons, (2009).

[89] W.F. Cascio, Managing human resources: productivity, quality of work life, profits, McGraw-Hill/Irwin, (2006).

[90] Supply-Chain Council, SCOR (Supply-chain operations reference-model), (2006).

[91] M.C. Arslan and M. Turkay, EOQ revisited with sustainability considerations, under review, (2011a), http://home.ku.edu.tr/~mturkay/pubs.html.

[92] M.C. Arslan and M. Turkay, The revised newsvendor model with sustainability considerations, in preparation for submission, (2011b), http://home.ku.edu.tr/~mturkay/pubs.html.

[93] M.C. Arslan and M. Turkay, Aggregate planning with sustainability considerations, in preparation for submissions, (2011c), http://home.ku.edu.tr/~mturkay/pubs.html.

[94] M.C. Arslan and M. Turkay, Facility location with sustainability considerations, in preparation for submissions, (2011d), http://home.ku.edu.tr/~mturkay/pubs.html.

[95] P.H. Zipkin, Foundations of inventory management, McGraw Hill, (2000).

[96] F.W. Harris, How many parts to make at once, Operations Research, 38(6) (1990), 947-950. [Reprinted from Factory: The Magazine of Management, 10(2) (1913), 135-136].

[97] GHG Protocol (The Greenhouse Gas Protocol Initiative), http://www.ghgprotocol.org/ [accessed on 29/03/2011].

[98] WRI (World Resource Institute), http://www.wri.org/ [accessed on 29/03/2011].

[99] EcoTransIT, http://www.ecotransit.org/ [accessed on 29.03.2011].

[100] Carbontrust, http://www.carbontrust.co.uk/cut-carbon-reduce-costs/calculate/carbon-footprinting/pages/carbon-footprinting.aspx [accessed on 29.03.2011].

[101] I. Penman and J.R. Stock, Environmental issues in logistics, in J.F. Robeson and W.C. Copacino, editors, The Logistics Handbook, 840-857. New York: The Free Press, 1994.

[102] J.R. Stock, Reverse logistics, green logistics, and packaging, in G.D. Taylor, editor, Logistics Engineering Handbook, 25-116. Boca Raton: CRC, 2008.

[103] J.R. Stock, S.L. Boyer and T. Harmon, Research opportunities in supply chain management, Journal of the Academy of Marketing Science, 38(1) (2010), 32-41.

[104] B. Sundarakani, R. de Souza and M. Goh, Modeling carbon footprints across the supply chain, International Journal of Production Economics, 128(1) (2010), 43-50.

[105] UNFCCC, Kyoto Protocol, http://unfccc.int/kyoto protocol/items/2830.php [accessed on 29/03/2011].

[106] P. Brenton, G. Edwards-Jones and M.F. Jensena, Carbon labeling and low income country exports: a review of the development issues, Development Policy Review, 27 (3) (2009), 243-267.

[107] G. Edwards-Jones, K. Plassmann, E.H. York, B. Hounsome, D.L. Jones and L. Milà i Canals, Vulnerability of exporting nations to the development of a carbon label in the United Kingdom, Environmental Science and Policy, 12 (2009), 479-490.

[108] EU (European Union), Emissions Trading System, http://ec.europa.eu/clima/policies/ets/index_en.htm [accessed on 29.03.2011].

[109] European Commission, Questions and answers on emissions trading and national allocation plans, http://europa.eu/rapid/pressReleasesAction.do?reference=MEMO/08/35&format=HTML&aged=0&lang [accessed on 29.03.2011].

[110] European Carbon Exchange, http://www.ecx.eu [accessed on 29.03.2011].

[111] CONOPT, http://www.gams.com/solvers/solvers.htm#CONOPT [accessed on 15.06.2011].

[112] DICOPT, http://www.gams.com/solvers/solvers.htm#DICOPT/ [accessed on 15.06.2011].

[113] GAMS, GAMSIDE build 2496/2589, License date Dec 24, 2007. Build VIS 22.6 149, (2007).

[114] M. Khouja, The single-period (news-vendor) problem: literature review and suggestions for future research, Omega, 27(5) (1999), 537-553.

[115] E.L. Porteus, Foundations of stochastic inventory theory, Stanford University Press, (2002).

[116] A. Ozler, B. Tan and F. Karaesmen, Multi-product newsvendor problem with value-at-risk considerations, International Journal of Production Economics, 117 (2009), 244-255.

[117] P. Mileff and K. Nehéz, Evaluating the proper service level in a cooperative supply chain environment, in the proceedings of the MIM'07 IFAC Workshop on Manufacturing Modeling, Management and Control, 123-126. Budapest, Hungary, 2007.

[118] T. Choi and C. Chiu, Mean-downside-risk and mean-variance newsvendor models: implications for sustainable fashion retailing, International Journal of Production Economics, in press, (2010).

[119] M.S. Chen and C.C. Chuang, An extended newsboy problem with shortage-level constraints, International Journal of Production Economics, 67 (2000), 269-277.

[120] A. Ruszczynski and A. Shapiro, Stochastic programming, Elsevier, (2003).

[121] B.A. Pasternack, Optimal pricing and return policies for perishable commodities, Marketing Science, 4(2) (1985), 166-176.

[122] Excel Solver, http://www.solver.com/ [accessed on 15.06.2011]

[123] Dow Jones Sustainability Indexes, http://www.sustainability-index.com/ [accessed on 01.03.2011].

[124] B.L. Mak and H. Sockel, A confirmatory factor analysis of IS employee motivation and retention, Information and Management, 38(5) (2001)**,** 265-276.

[125] NIOSH (National Institute for Occupational Safety and Health), Overtime and extended work shifts: recent findings on illnesses, injuries, and health behaviors. www.cdc.gov/niosh [accessed on 08.01.2011]

[126] K. Sparks, C. Cooper, Y. Fried and A. Shirom, The effects of hours of work on health: a meta-analytic review, Journal of Occupational and Organizational Psychology, 70 (1997), 391-408.

[127] D. Yildirim and Z. Aycan, Nurses' work demands and work–family conflict: a questionnaire survey, International Journal of Nursing Studies, 45(9) (2008), 1366-1378.

[128] CPLEX, http://www.gams.com/solvers/solvers.htm#CPLEX [accessed on 15.06.2011].

[129] S. Chopra and P. Meindl, Supply chain management: strategy, planning and operations, Pearson Education, Inc., (2010).

[130] R.B. Chase, N.J. Aquilano and R.F. Jacobs, Production and operations management: manufacturing and services, McGraw-Hill, (1998).

[131] M.T. Melo, S. Nickel and F. Saldanha-da-Gama, Facility location and supply chain management – a review, European Journal of Operational Research, 196 (2009), 401-412.

[132] J.A. Tompkins, J.A. White, Y.A. Bozer and J.M.A. Tanchoco, Facilities planning, John Wiley and Sons, Inc., (2003).

[133] R.D. Galvao, Uncapacitated facility location problems: contributions, Pesquisa Operacional, 24(1) (2003), 7-38.

[134] J. Kratica, V. Filipović and D. Tošić, Solving the uncapacitated warehouse location problem by SGA with add-heuristic, in the proceedings of XV. ECPD International Conference on Material Handling and Warehousing, 28-32. Belgrade, 1998.

[135] J. Krarup and P.M. Pruzan, The simple plant location problem: survey and synthesis, European Journal of Operational Research, 12(1) (1983), 36-81.

[136] V.P. Grishukhin, On polynomial solvability conditions for the simplest plant location problem, in A.K. Kelmans and S. Ivanov, editors, Selected topics in discrete mathematics, 37-46. American Mathematical Society, Providence, RI, 1994.

[137] L. Cooper, Location-allocation problems, Operations Research, 11(3) (1963), 331-343.

[138] K. Miettinen, Nonlinear multiobjective optimization, Kluwer Academic Publishers, (1999).

[139] R.T. Marler and J.S. Arora, The weighted sum method for multi-objective optimization: new insights, Structural and Multidisciplinary Optimization, in press, (2009).

Appendix A: Notation and Experiment Data for the EOQ Model

Notation Used in the EOQ Models

t	*time index*
$I(t)$	*inventory level at time t* (items)
T	*cycle length* (time-units)
λ	*demand rate* (items/time)
K	*fixed/setup cost* (money-units/setup)
c	*variable cost* (money-units/item)
h	*holding cost* (money-units/item/time)
f	*fixed amount of GHG emissions* (emissions/setup)
v	*variable amount of GHG emissions* (emissions/item)
g	*amount of GHG emissions due to inventory holding* (emissions/item/time)
m	*fixed amount of man-hours required* (man-hours/setup)
n	*variable amount of man-hours required* (man-hours/item)
l	*man-hours required due to inventory holding* (man-hours/item/time)
p	*tax rate/carbon price/offset price* (money-units/emission)
a	*a nonnegative scalar*
b	*a nonnegative scalar*
M	*a large nonnegative scalar*
r_1	*product price charged to regular customers* (money-units/item)
r_2	*product price charged to environmentally sensitive customers*
ζ	*GHG emissions cap* (emissions)
W	*available amount of man-hours* (man-hours)
Q	*order/production quantity* (items)
s^+	*amount of allowances sold* (emissions)

s^{-}	*amount of allowances/offsets purchased* (emissions)
y_1	*a binary decision variable*
y_2	*a binary decision variable*
Q^*	*optimal order/production quantity in the standard EOQ model*
Q_e^*	*optimal order/production quantity with pure environmental criterion*
Q_s^*	*optimal order/production quantity with pure social criterion*
Q_{ee}^*	*optimal order/production quantity with economic and environmental criteria*
Q_{se}^*	*optimal order/production quantity with social and economic criteria*
Q_{ees}^*	*optimal order/production quantity with triple bottom line accounting*
$C(Q)$	*total average cost of replenishment* (money-units)
$C'(Q)$	*first derivative of* $C(Q)$ *with respect to* Q
$C''(Q)$	*second derivative of* $C(Q)$ *with respect to* Q
$C(Q^*)$	*optimal total average cost with standard EOQ optimal*
$C(Q_e^*)$	*optimal total average cost with pure environmental criterion*
$C(Q_{ee}^*)$	*optimal total average cost with economic and environmental criteria*
$C(Q_s^*)$	*optimal total average cost with pure social criterion*
$C(Q_{se}^*)$	*optimal total average cost with social and economic criteria*
$C(Q_{ees}^*)$	*optimal total average cost with triple bottom line accounting*
$EM(Q^*)$	*optimal total average emissions with standard EOQ optimal*
$EM(Q_e^*)$	*optimal total average emissions with pure environmental criterion*
$EM(Q_{ee}^*)$	*optimal total average emissions with economic and environmental criteria*
$EM(Q_s^*)$	*optimal total average emissions with pure social criterion*
$EM(Q_{se}^*)$	*optimal total average emissions with social and economic criteria*
$EM(Q_{ees}^*)$	*optimal total average emissions with triple bottom line accounting*
$RM(Q^*)$	*optimal total average required man-hours with standard EOQ optimal*

$RM(Q_e^*)$ *optimal total average required man-hours with pure environmental criterion*

$RM(Q_{ee}^*)$ *optimal total average required man-hours with economic and environmental criteria*

$RM(Q_s^*)$ *optimal total average required man-hours with pure social criterion*

$RM(Q_{se}^*)$ *optimal total average required man-hours with social and economic criteria*

$RM(Q_{ees}^*)$ *optimal total average required man-hours with triple bottom line accounting*

Table A.1 Experiment Data for the EOQ Models

Parameter	Base Value	Parameter	Base Value
λ	50	n	4
K	40	l	2
c	12	p	5
h	2	a	0.04
f	60	b	20
v	5	M	1000000
g	1	r_1	15
m	1		

Appendix B: Expected Overstock and Lost Sales for the Newsvendor Model

In this section, the derivations of $E[(Q-D)^+]$ and $E[(D-Q)^+]$ for an arbitrary order quantity Q under some fundamental continuous probability distributions for the random demand variable D are presented.

D ~ Uniform $[0, \mathrm{L}]$

Assume that demand is uniformly distributed over the closed interval $[0, \mathrm{L}]$; i.e. $f_D(x) = \frac{1}{L}$ for $0 \le D \le L$ and $E[D] = \frac{L}{2}$. Then, the expected amount of unsold items and lost sales are given by the following, respectively:

$$E[(Q-D)^+] = \int_0^Q (Q-x) f_D(x)\,dx = \int_0^Q (Q-x)\frac{1}{L}\,dx = \frac{1}{L}\left(Qx - \frac{x^2}{2}\right)\Big|_0^Q = \frac{Q^2}{2L}$$

$$E[(D-Q)^+] = \int_Q^L (x-Q) f_D(x)\,dx = \int_Q^L (x-Q)\frac{1}{L}\,dx = \frac{1}{L}\left(\frac{x^2}{2} - Qx\right)\Big|_Q^L = \frac{L^2+Q^2-2QL}{2L} \ \blacksquare$$

D ~ Exponential (λ)

Assume that demand is exponentially distributed with rate $\lambda > 0$; i.e. $f_D(x) = \lambda e^{-\lambda x}$ for $x \in [0, \infty)$ and $E[D] = \frac{1}{\lambda}$. Then, the expected amount of unsold items is given by the following:

$$E[(Q-D)^+] = \int_0^Q (Q-x) f_D(x)\,dx = \int_0^Q (Q-x)\lambda e^{-\lambda x}\,dx = \int_0^Q Q\lambda e^{-\lambda x}\,dx - \int_0^Q x\lambda e^{-\lambda x}\,dx$$

Using integration by parts and simplifying, we obtain

$$= Q\lambda \left(\frac{e^{-\lambda x}}{-\lambda} \Big|_{0}^{Q} \right) - \lambda \left(\frac{e^{-\lambda x}}{\lambda^2} (-\lambda x - 1) \Big|_{0}^{Q} \right) = \frac{\lambda Q + e^{-\lambda Q} - 1}{\lambda}$$

Similarly,

$$E[(D-Q)^+] = \int_Q^{\infty} (x-Q) f_D(x)\, dx = \int_Q^{\infty} (x-Q)\lambda e^{-\lambda x}\, dx = \int_Q^{\infty} x\lambda e^{-\lambda x}\, dx - \int_Q^{\infty} Q\lambda e^{-\lambda x}\, dx = \lambda \left(\frac{e^{-\lambda x}}{\lambda^2} (-\lambda x - 1) \Big|_{Q}^{\infty^*} \right) - Q\lambda \left(\frac{e^{-\lambda x}}{-\lambda} \Big|_{Q}^{\infty} \right) = \frac{e^{-\lambda Q}}{\lambda}$$

∞^* Note that $\lim_{x\to\infty} \frac{e^{-\lambda x}}{\lambda^2}(-\lambda x - 1) = 0.\infty$, leading to an indeterminate form. In order to evaluate this limit, we investigate $\lim_{x\to\infty} \frac{-\lambda x - 1}{\lambda^2 e^{\lambda x}} = \lim_{x\to\infty} \frac{-\lambda}{\lambda^3 e^{\lambda x}} = 0$ (by L'Hospital rule). ∎

D ~ Normal (μ, σ)

Assume that demand is normally distributed with mean μ and standard deviation σ; i.e. $f_D(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{(x-\mu)^2}{2\sigma^2}}$ for $x \in (-\infty, \infty)$ and $E[D] = \mu$. Then, the expected amount of unsold items and lost sales are given by the following, respectively:

$$E[(Q-D)^+] = (Q-\mu)\Phi(z) + \sigma f_Z(z)$$

$$E[(D-Q)^+] = (\mu - Q)\big(1 - \Phi(z)\big) + \sigma f_Z(z)$$

Where $z = \frac{Q-\mu}{\sigma}$ denotes a standard normal random variable with $\mu = 0$ and $\sigma = 1$, $f_Z(z) = \frac{1}{\sqrt{2\pi}} e^{\frac{z^2}{2}}$ its probability density function, and $\Phi(z)$ its cumulative distribution function (see [95]). ∎

Appendix C: Notation and Experiment Data for the Newsvendor Model

Notation Used in the Newsvendor Models

D	*random variable for demand* (items)
μ	*mean of the normal demand distribution* (items)
σ	*standard deviation of the normal demand distribution* (items)
λ	*rate of the exponential demand distribution* (items per unit time)
L	*maximum value of the uniform demand distribution* (items)
$f_D(.)$	*the probability density function (pdf) of the demand distribution* (probability)
z	*standard normal random variable*
$f_Z(z)$	*the pdf of the standard normal distribution* (probability)
$F_D(.)$	*the cumulative distribution function (cdf) of the demand distribution* (probability)
$\Phi(z)$	*the cdf of the standard normal distribution* (probability)
$F_D^{-1}(.)$	*the inverse of the cumulative distribution function of the demand distribution* (items)
Q	*production lot size* (items)
π	*total profit* (money-units)
$E[\pi]$	*expected total profit* (money-units)
r	*sales price* (money-units/item)
K	*fixed cost of setups* (money-units)
c	*variable production cost* (money-units/item)
h	*inventory holding cost* (money-units/item)
f	*fixed amount of emissions due to setups* (emissions)

v	*variable amount of emissions due to the actual production* (emissions/item)
g	*amount of emissions due to inventory holding/processing of unsold items* (emissions/item)
ξ	*emission cap* (emissions)
t	*emission tax rate* (money-units/emission)
α	*target service level* (percentage)
p	*lost sales penalty* (money-units/item)
Q^*	*standard optimal production lot size* (items)
Q^*_{ee}	*optimal production lot size with economic and environmental considerations* (items)
Q^*_{se}	*optimal production lot size with social and economic considerations* (items)
Q^*_{ees}	*optimal production lot size with economic, environmental, and social considerations* (items)

Table C.1 Experiment Data for the Newsvendor Models

Parameter	Base Value
μ	100
σ	25
λ	0.01
L	200
K	50
r	10
c	4
h	2
f	5
v	3
g	2
t	1
p	6

Appendix D: Constrained Newsvendor Models

Emission Cap Constraint

D ~ Uniform $[0, \mathrm{L}]$

$$max\ E[\pi] = r\frac{L}{2} - (r+p)\left(\frac{L^2+Q^2-2QL}{2L}\right) - (K+tf) - (c+tv)Q - (h+tg)\frac{Q^2}{2L} \quad \text{(D.1)}$$

$s.t.$

$$f + vQ + g\frac{Q^2}{2L} \leq \xi \quad \text{(D.2)}$$

$$Q \geq 0 \quad \text{(D.3)}$$

D ~ Exponential (λ)

$$max\ E[\pi] = r\frac{1}{\lambda} - (r+p)\frac{e^{-\lambda Q}}{\lambda} - (K+tf) - (c+tv)Q - (h+tg)\frac{\lambda Q+e^{-\lambda Q}-1}{\lambda} \quad \text{(D.4)}$$

$s.t.$

$$f + vQ + g\frac{\lambda Q+e^{-\lambda Q}-1}{\lambda} \leq \xi \quad \text{(D.5)}$$

$$Q \geq 0 \quad \text{(D.6)}$$

D ~ Normal (μ, σ)

$$max\ E[\pi] = r\mu - (r+p)\Big((\mu - Q)\big(1-\Phi(z)\big) + \sigma f_Z(z)\Big) - (K+tf) - (c+tv)Q - (h+tg)\big((Q-\mu)\Phi(z) + \sigma f_Z(z)\big) \quad \text{(D.7)}$$

$s.t.$

$$f + vQ + g\big((Q-\mu)\Phi(z) + \sigma f_Z(z)\big) \leq \xi \quad \text{(D.8)}$$

$$Q \geq 0 \quad \text{(D.9)}$$

Service Level Target Constraint

D ~ Uniform $[0, \mathrm{L}]$

$$max\ E[\pi] = r\frac{L}{2} - (r+p)\left(\frac{L^2+Q^2-2QL}{2L}\right) - (K+tf) - (c+tv)Q - (h+tg)\frac{Q^2}{2L} \quad \text{(D.10)}$$

$s.t.$

$$\frac{\frac{L^2+Q^2-2QL}{2L}}{\frac{L}{2}} \leq (1-\alpha) \quad \text{(D.11)}$$

$$Q \geq 0 \quad \text{(D.12)}$$

D ~ Exponential (λ)

$$max\ E[\pi] = r\frac{1}{\lambda} - (r+p)\frac{e^{-\lambda Q}}{\lambda} - (K+tf) - (c+tv)Q - (h+tg)\frac{\lambda Q + e^{-\lambda Q} - 1}{\lambda} \quad \text{(D.13)}$$

$s.t.$

$$\frac{\frac{e^{-\lambda Q}}{\lambda}}{\frac{1}{\lambda}} \leq (1-\alpha) \quad \text{(D.14)}$$

$$Q \geq 0 \quad \text{(D.15)}$$

D ~ Normal (μ, σ)

$$max\ E[\pi] = r\mu - (r+p)\Big((\mu - Q)\big(1-\Phi(z)\big) + \sigma f_Z(z)\Big) - (K+tf) - (c+tv)Q - (h+tg)\big((Q-\mu)\Phi(z) + \sigma f_Z(z)\big) \quad \text{(D.16)}$$

$s.t.$

$$\frac{(\mu - Q)\big(1-\Phi(z)\big) + \sigma f_Z(z)}{\mu} \leq (1-\alpha) \quad \text{(D.17)}$$

$$Q \geq 0 \quad \text{(D.18)}$$

Triple Bottom Line Accounting

D ~ Uniform $[0, \mathrm{L}]$

$$max\ E[\pi] = r\frac{L}{2} - (r+p)\left(\frac{L^2+Q^2-2QL}{2L}\right) - (K+tf) - (c+tv)Q - (h+tg)\frac{Q^2}{2L} \quad \text{(D.19)}$$

$s.t.$

$$f + vQ + g\frac{Q^2}{2L} \leq \xi \quad \text{(D.20)}$$

$$\frac{\frac{L^2+Q^2-2QL}{2L}}{\frac{L}{2}} \leq (1-\alpha) \quad \text{(D.21)}$$

$$Q \geq 0 \quad \text{(D.22)}$$

D ~ Exponential (λ)

$$max\ E[\pi] = r\frac{1}{\lambda} - (r+p)\frac{e^{-\lambda Q}}{\lambda} - (K+tf) - (c+tv)Q - (h+tg)\frac{\lambda Q + e^{-\lambda Q} - 1}{\lambda} \quad \text{(D.23)}$$

$s.t.$

$$f + vQ + g\frac{\lambda Q + e^{-\lambda Q} - 1}{\lambda} \leq \xi \quad \text{(D.24)}$$

$$\frac{\frac{e^{-\lambda Q}}{\lambda}}{\frac{1}{\lambda}} \leq (1-\alpha) \quad \text{(D.25)}$$

$$Q \geq 0 \quad \text{(D.26)}$$

D ~ Normal (μ, σ)

$$max\ E[\pi] = r\mu - (r+p)\Big((\mu - Q)\big(1 - \Phi(z)\big) + \sigma f_Z(z)\Big) - (K + tf) - (c + tv)Q - (h + tg)\big((Q - \mu)\Phi(z) + \sigma f_Z(z)\big) \quad \text{(D.27)}$$

$s.t.$

$$f + vQ + g\big((Q - \mu)\Phi(z) + \sigma f_Z(z)\big) \leq \xi \quad \text{(D.28)}$$

$$\frac{(\mu - Q)\big(1 - \Phi(z)\big) + \sigma f_Z(z)}{\mu} \leq (1 - \alpha) \quad \text{(D.29)}$$

$$Q \geq 0 \quad \text{(D.30)}$$

Appendix E: Notation and Experiment Data for the Aggregate Planning Model

Table E.1 Notation Used in the Aggregate Planning Models

Notation	Description
Sets	
T	*planning horizon* (periods)
Variables	
W_t	*number of workers in period t* (workers)
H_t	*number of workers hired in period t* (workers)
F_t	*number of workers fired in period t* (workers)
P_t	*number of items produced in period t* (items)
O_t	*number of items produced on overtime in period t* (items)
I_t	*inventory on hand in period t* (items)
B_t	*number of items backlogged in period t* (items)
S_t	*number of items subcontracted in period t* (items)
Parameters	
D_t	*demand forecast at each period* (items)
h	*regular time working hours per day* (hours/day)
n_t	*number of working/production days in period t* (days)
K	*number of items produced in one day by one worker* (item/day)
W_{init}	*initial workforce level* (workers)
I_{init}	*initial inventory level* (items)
B_{init}	*initial backlog level* (items)
c_L	*cost of labor per hour* (money-units/worker/hour)
c_H	*cost of hiring a worker* (money-units/worker)
c_F	*cost of firing a worker* (money-units/worker)
c_M	*cost of material used in producing one item* (money-units/item)
c_O	*incremental cost of producing one item on overtime* (money-units/item)
c_I	*cost of holding one item of inventory for one period* (money-units/item/period)
c_B	*cost of backlogging one item* (money-units/item)
c_S	*cost of subcontracting one item* (money-units/item)
$c_I^{'}$	*amount of GHG emissions per item hold in the inventory* (emission-units/item)
$c_P^{'}$	*amount of GHG emissions per item produced* (emission-units/item)
$c_S^{'}$	*amount of GHG emissions per item subcontracted* (emission-units/item)
$c_I^{''}$	*amount of electricity used per item hold in the inventory* (electricity-

	units/item)
c''_P	*amount of electricity used per item produced* (electricity-units/item)
c''_O	*incremental amount of electricity used per item produced in overtime* (electricity-units/item)
ε_C	*cap on GHG emissions during the entire planning horizon* (emission-units)
ε_E	*cap on electricity consumption during the entire planning horizon* (electricity-units)
S_{lim}	*smoothing limit for the entire planning horizon* (workers)
L_{lim}	*layoff limit at each period* (workers)
O_{lim}	*overtime limit at each period* (hours)
α	*desired customer service level as a percentage of demand* (percentage)

Table E.2 Experiment Data for the Aggregate Planning Models

Parameter	Base Value
T	6 months
t	a month ($t \in \{1, \ldots, 6\}$)
D_t	[1600, 3000, 3200, 3800, 2200, 2200]
h	8
n_t	[21, 20, 23, 21, 22, 22]
K	2
W_{init}	80
I_{init}	1000
B_{init}	0
c_L	4
c_H	200
c_F	250
c_M	100
c_O	6
c_I	1
c_B	50
c_S	120
c'_I	0.005
c'_P	0.011
c'_S	0.001
c''_I	0.01
c''_P	0.2
c''_O	0.1
ε_C	100
ε_E	2000
S_{lim}	10
L_{lim}	2
O_{lim}	0.5
α	0.80

The above table (Table E.2) provides the data used in the numerical analysis. Most of the data including the values for T, t, D_t, h, W_{init}, I_{init}, B_{init} has been adopted from the

"Red Tomato Tools" example in Chopra and Meindl [129]. However, some minor modifications have been made, such as:

- Changing values for n_t are used, whereas it is originally fixed to the value of 20 days/month.
- A throughput rate of $K = 2$ units/day is used instead of a throughput time of four hours/unit as in the original example. However, these two quantities are equivalent since the regular work hours, h, is assumed to be eight hours/day both in this chapter and in the original example.

All other technological parameters are expressed in terms of generic units (e.g. money-units, emission-units, and electricity-units); thus giving the modeler to convert the analysis into any specific unit of measurement. Also for this reason, the specific values of these parameters used in the analysis are not determinant but the relative magnitude of these parameters with respect to each other. Still, the specific values of the financial parameters have been partially adopted from the previously mentioned Red Tomato Tools example and the CA&J Company example in Chase et al. [130]; again with some minor changes. For the standard economic parameters $(c_L, c_H, c_F, c_M, c_O, c_I, c_B, c_S)$, for instance, it is logical to assume that $c_S > c_M$, $c_M \gg c_I$, and $c_H \cong c_F \gg c_L \cong c_O$. For c_B, on the other hand, one cannot assert a straightforward relationship as such and the value very much depends on the market. Hence, the choice for the value of c_B in this analysis is arbitrary.

Similarly for the environmental parameters $(c_I^{'}, c_P^{'}, c_S^{'}, c_I^{''}, c_P^{''}, c_O^{''})$, it makes sense to assume that $c_P^{'} > c_I^{'} > c_S^{'}$ and $c_P^{''} \cong c_O^{''} > c_I^{''}$. Finally for the exogenous parameters $(\varepsilon_C, \varepsilon_E, S_{lim}, L_{lim}, O_{lim},$ and $\alpha)$, varying values have been used as depicted in §6.3.1.

Appendix F: Revised Optimal Aggregate Plans and Interpretations

Table F.1 Optimal Aggregate Plan Resulting from the Standard Formulation

t	D_t	P_t	O_t	I_t	B_t	S_t	W_t	H_t	F_t
Jan	1600	2664	1320	2064	.	.	32	.	48
Feb	3000	2480	1240	1544	.	.	31	.	1
Mar	3200	2852	1426	1196	.	.	31	.	.
Apr	3800	2604	1302	.	.	.	31	.	.
May	2200	.	.	.	2200	.	.	.	31
June	2200	.	.	.	4400	.	.	.	.
Total Cost	**1,531,524.00**								

The solution of the standard model (Table F.1) suggests a time flexibility plan for the first four periods of the planning horizon where workforce level is almost constant and a notable portion of the demand is met by overtime production. Furthermore, for the first half of the horizon, a large amount of inventory is held. For the rest of the planning horizon; however, the optimal strategy is to backlog all of the cumulative demand and fire the available workforce. No additional workers are hired and none of the items are subcontracted during the entire planning horizon. The above plan leads to a total cost of 1,531,524.00 money-units.

Table F.2 Plan with Carbon Cap Criterion

t	D_t	P_t	O_t	I_t	B_t	S_t	W_t	H_t	F_t
Jan	1600	1764	798	1164	.	.	23	.	57
Feb	3000	1840	920	4	.	.	23	.	.
Mar	3200	2484	1242	.	.	712	27	4	.
Apr	3800	2268	1134	.	.	1532	27	.	.
May	2200	.	.	.	2200	.	.	.	27
June	2200	.	.	.	4400	.	.	.	.
Total Cost	**1,550,604.00**								

When carbon footprint constraint is embedded into the standard model, the production, overtime, and inventory levels are reduced (Table F.2). More workers are fired at the beginning of the horizon except for period *Mar* where some workers are hired back at the beginning of this period. Furthermore, a considerable amount of demand is subcontracted from a third party, since subcontracting is relatively cheaper than in-house operations in terms of reducing the carbon footprint of the company. This is due to the fact that the major part of GHG emissions are released during the transportation phase, for which the subcontractor carries out and is responsible for in a decentralized setting as assumed in this chapter. Note that this environmental constraint does not have an impact on the standard backlog level. On the other hand, it affects the production, inventory and workforce levels. This plan leads to a total cost of 1,550,604.00 money-units, 1.24% above the standard cost.

Table F.3 Plan with Energy Consumption Criterion

t	D_t	P_t	O_t	I_t	B_t	S_t	W_t	H_t	F_t
Jan	1600	1973.75	965.75	1373.75	.	.	24	.	56
Feb	3000	1920	960	293.75	.	.	24	.	.
Mar	3200	2116	1058	.	.	790.25	23	.	1
Apr	3800	1932	966	.	.	1868	23	.	.
May	2200	.	.	.	2200	.	.	.	23
June	2200	.	.	.	4400	.	.	.	.
Total Cost	**1,552,403.00**								

The plan with energy consumption constraint (Table F.3) proposes a similar policy as in the plan with carbon footprint constraint. The plan again suggests subcontracting, since subcontracting does not contribute to the in-house electricity consumption. Again a majority of the workforce is being fired and the last two periods' demand is backlogged. This plan leads to a total cost of 1,552,403.00 money-units, 1.36% above the standard cost.

Table F.4 Plan with Job Security and Morale-Motivation Criterion

t	D_t	P_t	O_t	I_t	B_t	S_t	W_t	H_t	F_t
Jan	1600	1132	.	532	.	.	78	.	2
Feb	3000	3040	.	572	.	.	76	.	2
Mar	3200	3404	.	776	.	.	74	.	2
Apr	3800	3024	.	.	.	.	72	.	2
May	2200	.	.	.	2200	.	70	.	2
June	2200	.	.	.	4400	.	70	.	.
Total Cost	**1,696,844.00**								

The job security and morale-motivation constraint enforces changes in the standard plan substantially. This plan (Table F.4) suggests keeping most of the initial workforce for the entire horizon and utilizing this capacity in making regular time production. Items are neither subcontracted from outside nor produced overtime. Furthermore, a relatively smaller amount of inventory is carried over in the first half of the horizon and the last two periods' demand is again backlogged. This plan leads to a total cost of 1,696,844.00 money-units, 10.79% above the standard cost.

Table F.5 Plan with Health and Work-Family Balance Criterion

t	D_t	P_t	O_t	I_t	B_t	S_t	W_t	H_t	F_t
Jan	1600	2620.625	142.625	2020.625	.	.	59	.	21
Feb	3000	2507.500	147.500	1528.125	.	.	59	.	.
Mar	3200	2883.625	169.625	1211.750	.	.	59	.	.
Apr	3800	2588.250	152.250	.	.	.	58	.	1
May	2200	.	.	.	2200	.	.	.	58
June	2200	.	.	.	4400	.	.	.	.
Total Cost	**1,578,240.50**								

Imposing overtime limit yields a plan (Table F.5) where there is still overtime production in contrast with the plan in Table F.4 but which is controlled. The decrease in overtime production leads to firing a relatively less number of workers than what the standard plan suggests. The rest of the policy is not very much affected from overtime control. This plan leads to a total cost of 1,578,240.50 money-units, 3.05% above the standard cost.

Table F.6 Plan with Customer Service Level Criterion

t	D_t	P_t	O_t	I_t	B_t	S_t	W_t	H_t	F_t
Jan	1600	2664	1320	2064	.	.	32	.	48
Feb	3000	2480	1240	1544	.	.	31	.	1
Mar	3200	2852	1426	1196	.	.	31	.	.
Apr	3800	2604	1302	.	.	.	31	.	.
May	2200	2200	1100	.	.	.	25	.	6
June	2200	1760	880	.	440	.	20	.	5
Total Cost	**1,658,084.00**								

Imposing a customer service level target suggests utilizing the idle two periods of the standard plan (Table F.6) as well as making overtime production and holding inventories. In order to make production in these last two periods, not all of the workers are fired at the end of the fourth period. As a result, backlog level decreases notably and this plan leads to a total cost of 1,658,084.00 money-units, 8.26% above the standard cost.

Table F.7 Plan with Triple Bottom Line Accounting

t	D_t	P_t	O_t	I_t	B_t	S_t	W_t	H_t	F_t
Jan	1600	.	.	.	.	600	78	.	2
Feb	3000	.	.	.	.	3000	76	.	2
Mar	3200	1560	.	.	.	1640	74	.	2
Apr	3800	3024	.	.	.	776	72	.	2
May	2200	2200	.	.	.	.	70	.	2
June	2200	1760	.	.	440	.	70	.	.
Total Cost	**1,903,284.00**								

Finally, when all of the additional environmental and social constraints are embedded into the standard model, a completely different plan is obtained (Table F.7) compared to the standard one. Production takes place in all periods except the first two and most of the workforce is retained. Furthermore, these workers do not work overtime. Most of the customer demand is satisfied on-time and no inventory is carried over the horizon. In return, a fundamental part of the demand is subcontracted which suggests strong collaboration among the parties in the supply chain when environmental and social considerations are met simultaneously. On the other hand, this plan leads to a total cost of 1,903,284.00 money-units which is 24.27% above the standard cost.

Appendix G: Notation and Experiment Data for the Facility Location Model

Table G.1 Notation Used in the Facility Location Models

Notation	Description
Sets	
i	*customers*
j	*facilities*
Variables	
x_{ij}	*proportion of customer i demand supplied by facility at site j*
y_j	*1, if a facility is located at site j; 0, otherwise*
Parameters	
m	*number of customers*
n	*number of potential sites*
f_j	*fixed cost of locating a facility at site j* (money-units)
c_{ij}	*cost of supplying all demand of customer i from a facility located at site j* (money-units)
g_t	*GHG emissions factor per unit cost due to the transportation of goods (emissions/money-units)*
w_j	*waste generated when a facility is located at site j* (waste-units)
u_j	*social utility gained when a facility is located at site j* (utility)

Table G.2 Experiment Data for the Facility Location Models

Parameter	Value
m	10
n	10
g_t	3
f_j	Uniform ~ (50-100)
w_j	Uniform ~ (100-150)
u_j	Uniform ~ (0-100)
c_{ij}	Uniform ~ (100-300)

As can be seen from Table G.2, the values of the vector parameters are generated using a uniform distribution of various intervals. The generated values can be found below:

***f(j)* fixed cost of locating a facility at site j**

/1	86
2	93
3	83
4	79
5	94
6	52
7	66
8	58
9	84
10	75/

w(j) **waste generated when a facility is located at site j**

/1	121
2	142
3	126
4	113
5	141
6	136
7	142
8	124
9	117
10	120/

u(j) **social utility gained when a facility is located at site j**

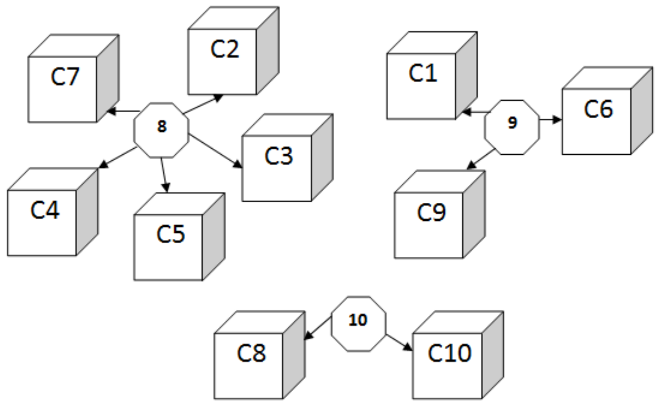
/1	-8
2	-48
3	-68
4	-22
5	-53
6	-1
7	-40
8	0
9	-50
10	-37/

c(i,j) **cost of supplying all demand of customer i from a facility located at site j**

	1	2	3	4	5	6	7	8	9	10
1	168	212	174	211	108	264	261	287	160	185
2	204	294	283	257	216	300	169	162	259	210
3	171	201	257	279	173	294	287	181	255	198
4	249	223	263	289	213	252	241	119	192	166
5	193	152	126	291	141	112	126	147	231	277
6	126	200	289	167	227	250	279	193	132	234
7	220	300	292	282	154	282	281	155	236	179
8	258	231	259	253	253	228	231	274	232	200
9	197	204	248	259	269	266	249	247	129	284
10	287	149	186	160	214	206	290	286	230	166

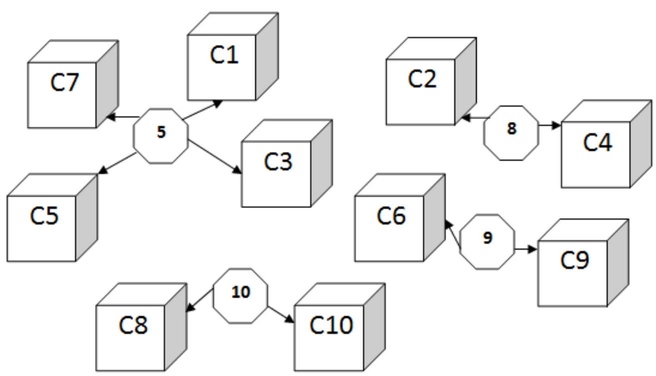
Appendix H: Revised Network Configurations

Allocations under Cost and Emissions Criteria



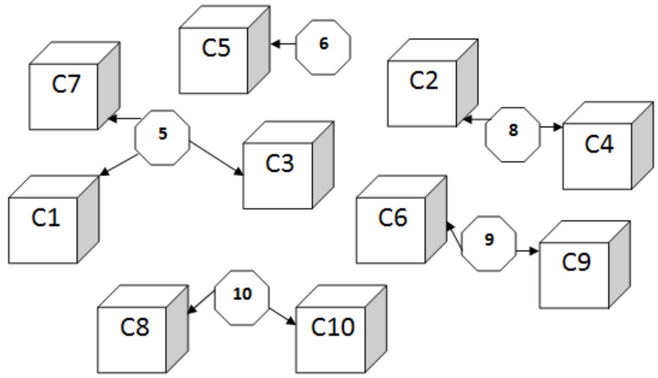
$\lambda_{\text{cost}} = 0.9$ $\lambda_{\text{emissions}} = 0.1$ $\lambda_{\text{waste}} = 0$ $\lambda_{\text{development}} = 0$
$z_{cost} = 1768$ $z_{emissions} = 4653$ $z_{waste} = 361$ $z_{development} = 224$

Figure H.1 Revised network configuration 1



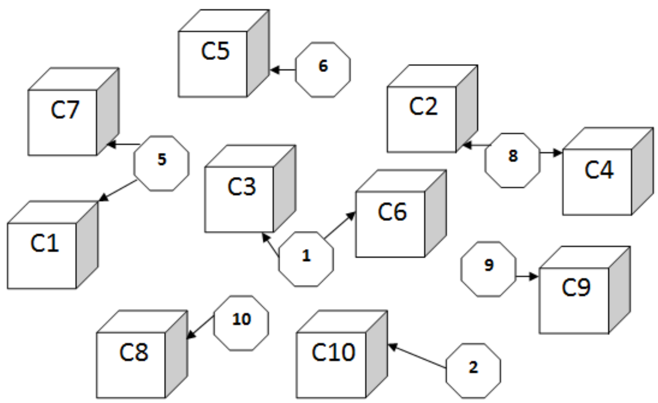
$\lambda_{\text{cost}} = 0.8$ $\lambda_{\text{emissions}} = 0.2$ $\lambda_{\text{waste}} = 0$ $\lambda_{\text{development}} = 0$
$z_{cost} = 1795$ $z_{emissions} = 4452$ $z_{waste} = 502$ $z_{development} = 386$

Figure H.2 Revised network configuration 2



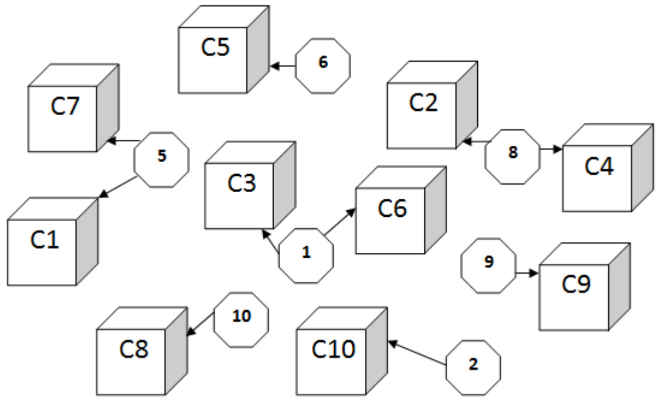
$\lambda_{\text{cost}} = 0.5$ $\lambda_{\text{emissions}} = 0.5$ $\lambda_{\text{waste}} = 0$ $\lambda_{\text{development}} = 0$
$z_{cost} = 1818$ $z_{emissions} = 4365$ $z_{waste} = 638$ $z_{development} = 334$

Figure H.3 Revised network configuration 3



$\lambda_{\text{cost}} = 0.2$ $\lambda_{\text{emissions}} = 0.8$ $\lambda_{\text{waste}} = 0$ $\lambda_{\text{development}} = 0$
$z_{cost} = 1972$ $z_{emissions} = 4290$ $z_{waste} = 901$ $z_{development} = 258$

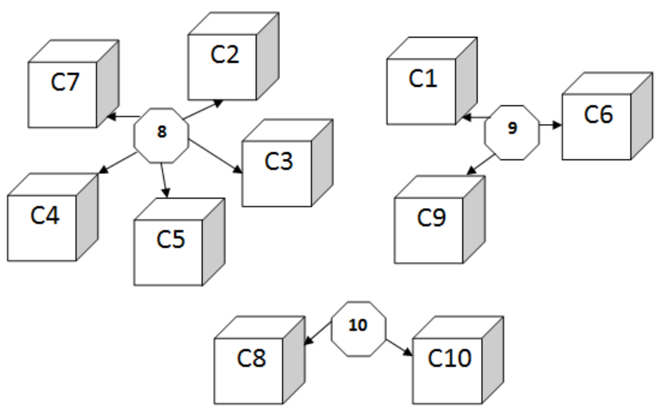
Figure H.4 Revised network configuration 4



$\lambda_{\text{cost}} = 0.1\ \lambda_{\text{emissions}} = 0.9\ \lambda_{\text{waste}} = 0\ \lambda_{\text{development}} = 0$
$z_{cost} = 1972\ z_{emissions} = 4290\ z_{waste} = 901\ z_{development} = 258$

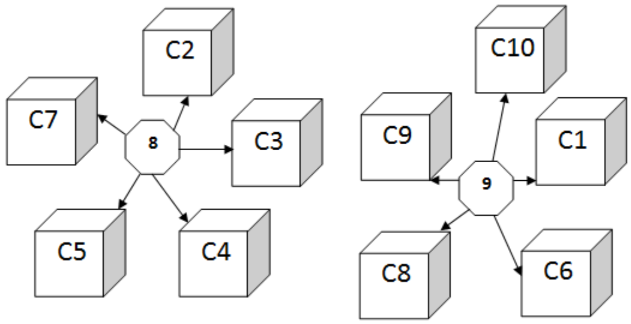
Figure H.5 Revised network configuration 5

Allocations under Cost and Waste Criteria



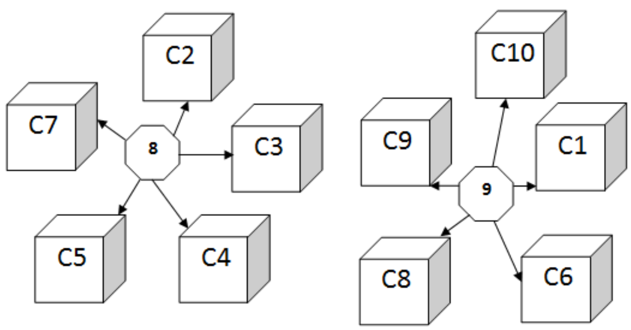
$\lambda_{\text{cost}} = 0.9\ \lambda_{\text{emissions}} = 0\ \lambda_{\text{waste}} = 0.1\ \lambda_{\text{development}} = 0$
$z_{cost} = 1768\ z_{emissions} = 4653\ z_{waste} = 361\ z_{development} = 224$

Figure H.6 Revised network configuration 6



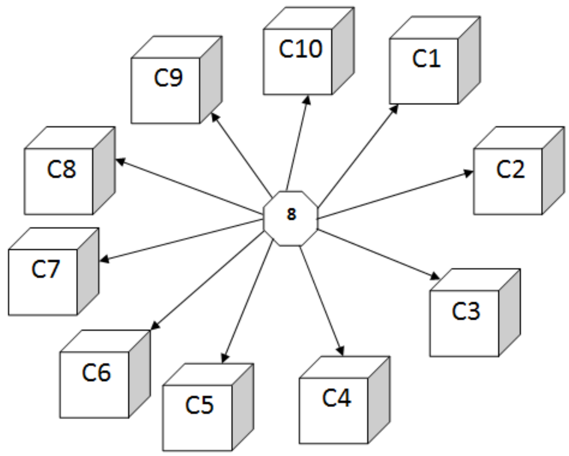
$\lambda_{\text{cost}} = 0.8$ $\lambda_{\text{emissions}} = 0$ $\lambda_{\text{waste}} = 0.2$ $\lambda_{\text{development}} = 0$
$z_{cost} = 1789$ $z_{emissions} = 4941$ $z_{waste} = 241$ $z_{development} = 250$

Figure H.7 Revised network configuration 7



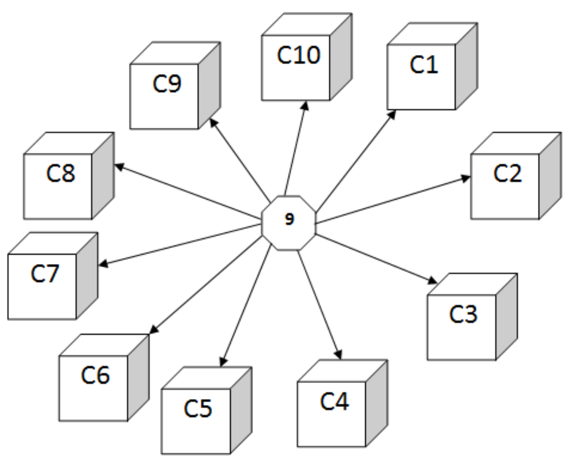
$\lambda_{\text{cost}} = 0.5$ $\lambda_{\text{emissions}} = 0$ $\lambda_{\text{waste}} = 0.5$ $\lambda_{\text{development}} = 0$
$z_{cost} = 1789$ $z_{emissions} = 4941$ $z_{waste} = 241$ $z_{development} = 250$

Figure H.8 Revised network configuration 8



$\lambda_{\text{cost}} = 0.2$ $\lambda_{\text{emissions}} = 0$ $\lambda_{\text{waste}} = 0.8$ $\lambda_{\text{development}} = 0$
$z_{cost} = 2109$ $z_{emissions} = 6153$ $z_{waste} = 124$ $z_{development} = 0$

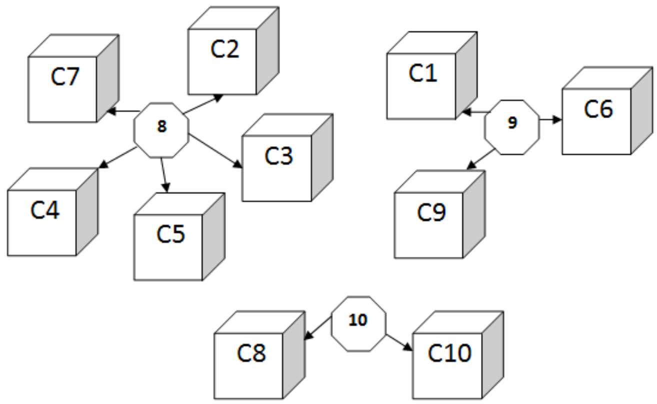
Figure H.9 Revised network configuration 9



$\lambda_{\text{cost}} = 0.1$ $\lambda_{\text{emissions}} = 0$ $\lambda_{\text{waste}} = 0.9$ $\lambda_{\text{development}} = 0$
$z_{cost} = 2140$ $z_{emissions} = 6168$ $z_{waste} = 117$ $z_{development} = 500$

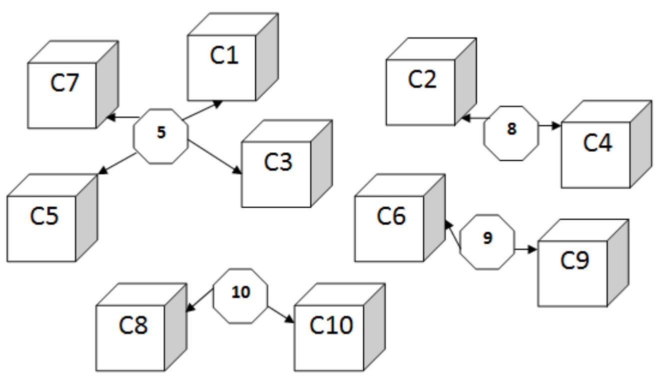
Figure H.10 Revised network configuration 10

Allocations under Cost, Emissions and Waste Criteria



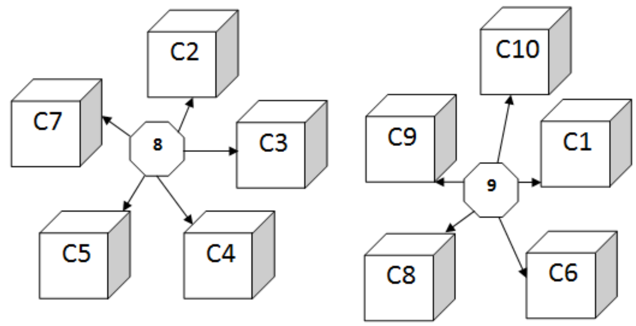
$\lambda_{\text{cost}} = 0.8\ \lambda_{\text{emissions}} = 0.1\ \lambda_{\text{waste}} = 0.1\ \lambda_{\text{development}} = 0$
$z_{cost} = 1768\ z_{emissions} = 4653\ z_{waste} = 361\ z_{development} = 224$

Figure H.11 Revised network configuration 11



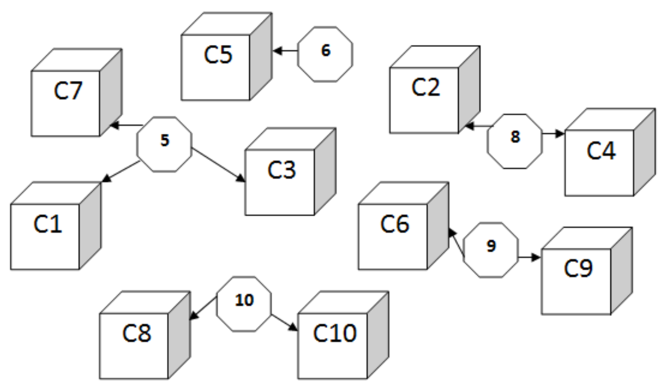
$\lambda_{\text{cost}} = 0.5\ \lambda_{\text{emissions}} = 0.25\ \lambda_{\text{waste}} = 0.25\ \lambda_{\text{development}} = 0$
$z_{cost} = 1795\ z_{emissions} = 4452\ z_{waste} = 502\ z_{development} = 386$

Figure H.12 Revised network configuration 12



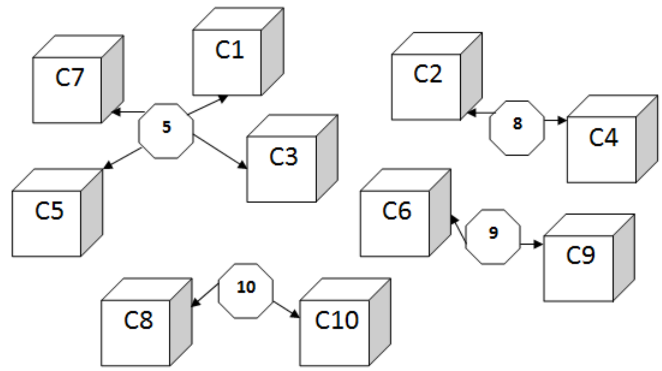
$\lambda_{\text{cost}} = 0.5\ \lambda_{\text{emissions}} = 0.1\ \lambda_{\text{waste}} = 0.4\ \lambda_{\text{development}} = 0$
$z_{cost} = 1789\ z_{emissions} = 4941\ z_{waste} = 241\ z_{development} = 250$

Figure H.13 Revised network configuration 13



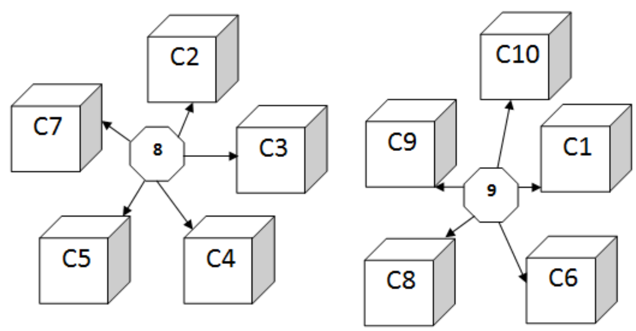
$\lambda_{\text{cost}} = 0.5\ \lambda_{\text{emissions}} = 0.4\ \lambda_{\text{waste}} = 0.1\ \lambda_{\text{development}} = 0$
$z_{cost} = 1818\ z_{emissions} = 4365\ z_{waste} = 638\ z_{development} = 334$

Figure H.14 Revised network configuration 14



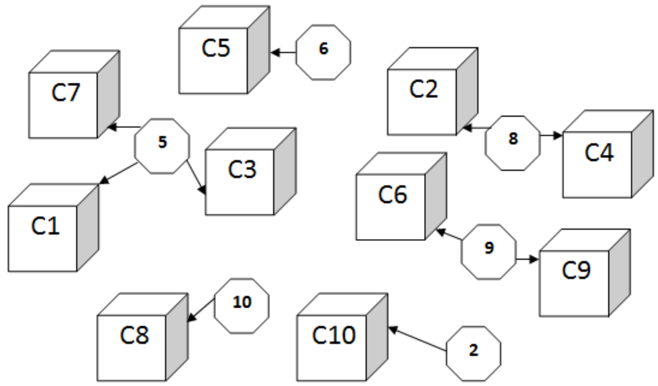
$\lambda_{\text{cost}} = 0.2$ $\lambda_{\text{emissions}} = 0.4$ $\lambda_{\text{waste}} = 0.4$ $\lambda_{\text{development}} = 0$
$z_{cost} = 1795$ $z_{emissions} = 4452$ $z_{waste} = 502$ $z_{development} = 386$

Figure H.15 Revised network configuration 15



$\lambda_{\text{cost}} = 0.2$ $\lambda_{\text{emissions}} = 0.1$ $\lambda_{\text{waste}} = 0.7$ $\lambda_{\text{development}} = 0$
$z_{cost} = 1789$ $z_{emissions} = 4941$ $z_{waste} = 241$ $z_{development} = 250$

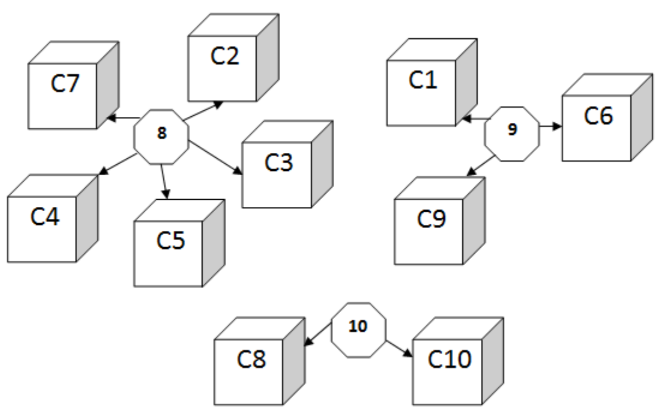
Figure H.16 Revised network configuration 16



$\lambda_{\text{cost}} = 0.2\ \lambda_{\text{emissions}} = 0.7\ \lambda_{\text{waste}} = 0.1\ \lambda_{\text{development}} = 0$
$z_{cost} = 1894\ z_{emissions} = 4314\ z_{waste} = 780\ z_{development} = 345$

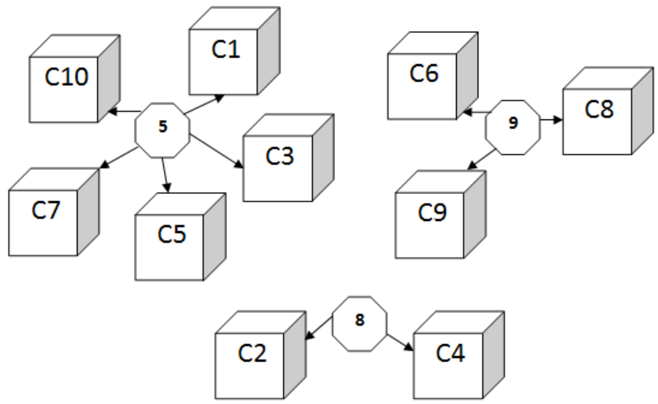
Figure H.17 Revised network configuration 17

Allocations under Cost and Development Criteria



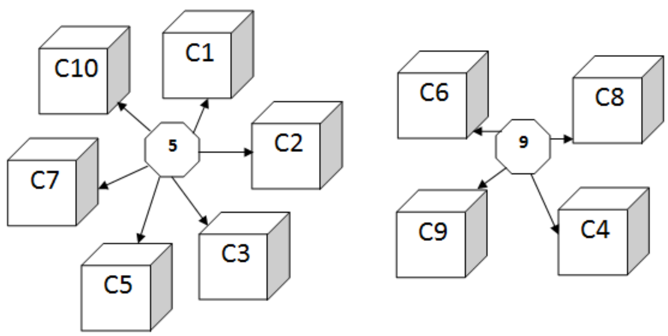
$\lambda_{\text{cost}} = 0.9\ \lambda_{\text{emissions}} = 0\ \lambda_{\text{waste}} = 0\ \lambda_{\text{development}} = 0.1$
$z_{cost} = 1768\ \ z_{emissions} = 4653\ z_{waste} = 361\ z_{development} = 224$

Figure H.18 Revised network configuration 18



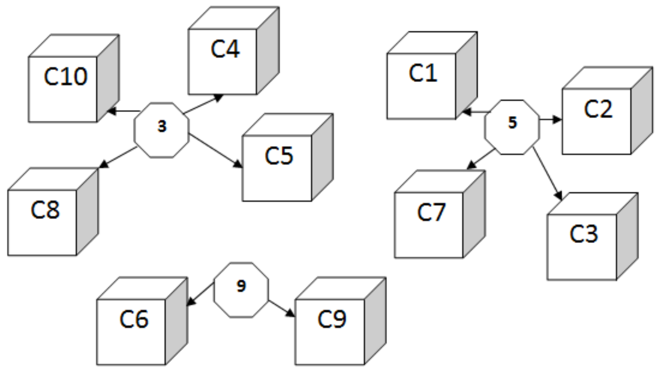
$\lambda_{\text{cost}} = 0.8\ \lambda_{\text{emissions}} = 0\ \lambda_{\text{waste}} = 0\ \lambda_{\text{development}} = 0.2$
$z_{cost} = 1800\ \ z_{emissions} = 4692\ z_{waste} = 382\ z_{development} = 415$

Figure H.19 Revised network configuration 19



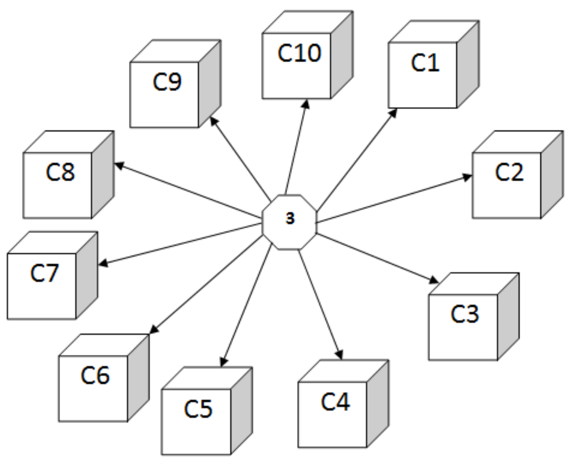
$\lambda_{\text{cost}} = 0.5\ \lambda_{\text{emissions}} = 0\ \lambda_{\text{waste}} = 0\ \lambda_{\text{development}} = 0.5$
$z_{cost} = 1869\ \ z_{emissions} = 5073\ z_{waste} = 258\ z_{development} = 518$

Figure H.20 Revised network configuration 20



$\lambda_{\text{cost}} = 0.2$ $\lambda_{\text{emissions}} = 0$ $\lambda_{\text{waste}} = 0$ $\lambda_{\text{development}} = 0.8$
$z_{cost} = 2007$ $z_{emissions} = 5238$ $z_{waste} = 384$ $z_{development} = 584$

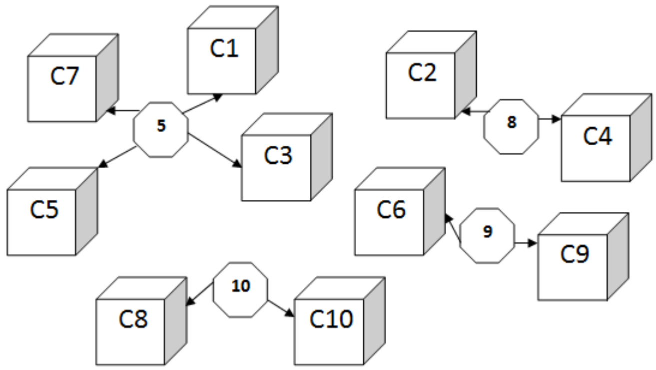
Figure H.21 Revised network configuration 21



$\lambda_{\text{cost}} = 0.1$ $\lambda_{\text{emissions}} = 0$ $\lambda_{\text{waste}} = 0$ $\lambda_{\text{development}} = 0.9$
$z_{cost} = 2460$ $z_{emissions} = 7131$ $z_{waste} = 126$ $z_{development} = 680$

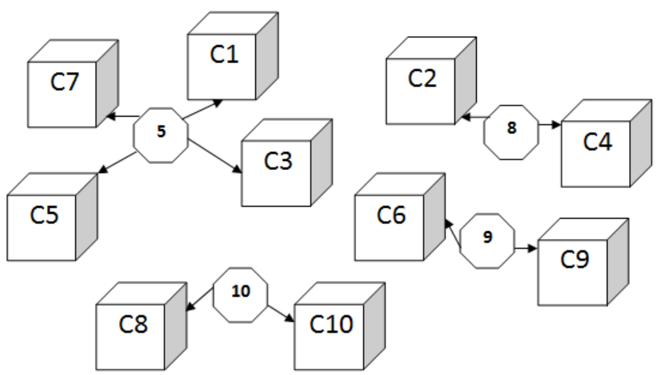
Figure H.22 Revised network configuration 22

Allocations under TBL Accounting



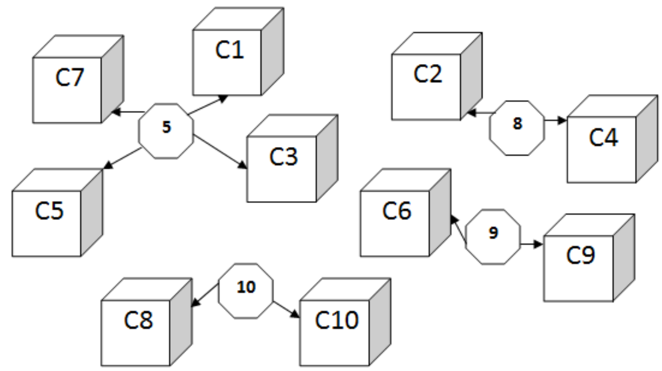
$\lambda_{\text{cost}} = 0.6$ $\lambda_{\text{emissions}} = 0.1$ $\lambda_{\text{waste}} = 0.1$ $\lambda_{\text{development}} = 0.2$
$z_{cost} = 1795$ $z_{emissions} = 4452$ $z_{waste} = 502$ $z_{development} = 386$

Figure H.23 Revised network configuration 23



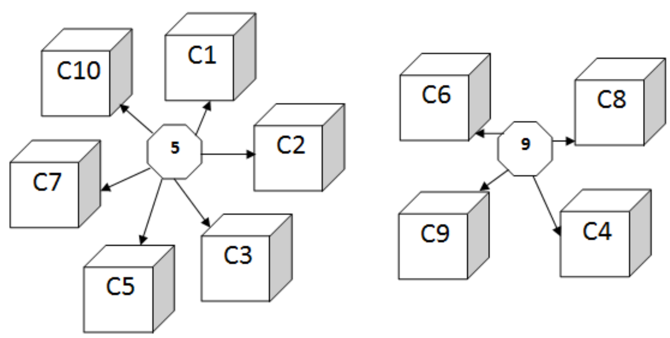
$\lambda_{\text{cost}} = 0.33$ $\lambda_{\text{emissions}} = 0.165$ $\lambda_{\text{waste}} = 0.165$ $\lambda_{\text{development}} = 0.33$
$z_{cost} = 1795$ $z_{emissions} = 4452$ $z_{waste} = 502$ $z_{development} = 386$

Figure H.24 Revised network configuration 24



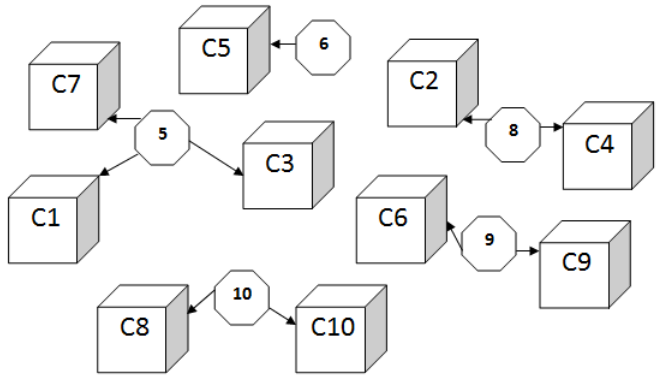
$\lambda_{\text{cost}} = 0.2\ \lambda_{\text{emissions}} = 0.3\ \lambda_{\text{waste}} = 0.3\ \lambda_{\text{development}} = 0.2$
$z_{cost} = 1795\ z_{emissions} = 4452\ z_{waste} = 502\ z_{development} = 386$

Figure H.25 Revised network configuration 25



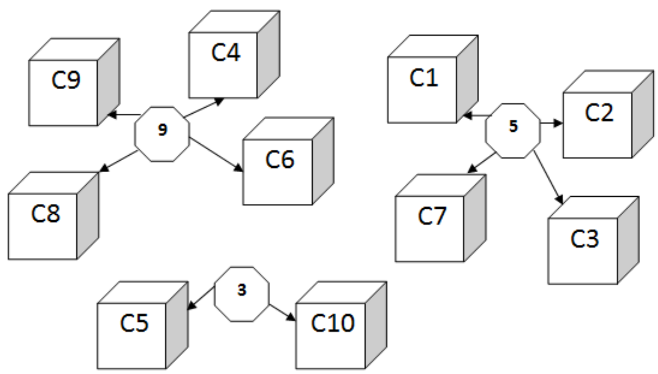
$\lambda_{\text{cost}} = 0.2\ \lambda_{\text{emissions}} = 0.1\ \lambda_{\text{waste}} = 0.5\ \lambda_{\text{development}} = 0.2$
$z_{cost} = 1869\ z_{emissions} = 5073\ z_{waste} = 258\ z_{development} = 518$

Figure H.26 Revised network configuration 26



$\lambda_{\text{cost}} = 0.2$ $\lambda_{\text{emissions}} = 0.5$ $\lambda_{\text{waste}} = 0.1$ $\lambda_{\text{development}} = 0.2$
$z_{cost} = 1818$ $z_{emissions} = 4365$ $z_{waste} = 638$ $z_{development} = 334$

Figure H.27 Revised network configuration 27



$\lambda_{\text{cost}} = 0.2$ $\lambda_{\text{emissions}} = 0.1$ $\lambda_{\text{waste}} = 0.1$ $\lambda_{\text{development}} = 0.6$
$z_{cost} = 1909$ $z_{emissions} = 4944$ $z_{waste} = 384$ $z_{development} = 548$

Figure H.28 Revised network configuration 28

VITA

Mehmet Can Arslan was born in Adana, Turkey, on November 14, 1984. He was graduated from Izmir Fen Lisesi in 2002. He received his Bachelor of Science degree in Manufacturing Systems Engineering from Sabanci University in 2007. Following that, he joined the PhD program in Industrial Engineering and Operations Management at Koc University. Until graduation, he served as a research and teaching assistant.