Designing Sustainable Supply Chain Networks

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ABSTRACT

Designing Sustainable Supply Chain Networks

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Supply chains have grown tremendously in recent years and focusing only on the economic performance to optimize the costs or return on investments (ROIs) cannot alone sustain the development of supply chain operations. The impact of different activities involved in supply chains such as the process of manufacturing, warehousing, distributing etc. on environment and social life of city residents cannot be ignored. Correspondingly, the concepts of green supply chain management (GSCM) and sustainable supply chain management (SSCM) have emerged which emphasize the importance of implementing environment and social concerns along with economical factors in supply chain planning. Other perspectives from the management domain insist that for sustainability, supply chain management should strive for enterprise governance, business regulations, corporate responsibilities, and social justice.

In this thesis, we study the problem of designing sustainable supply chain networks. This involves reviewing state-of-the-art concepts for planning sustainable supply chains, capturing customer and technical requirements using Voice of the Customer (VOC), investigating the relationship between customer requirements and technical requirements using Sustainable Function Deployment (SFD) and finally designing sustainable supply

chain networks by transmitting the weighted technical requirements obtained from SFD into an integer programming model. AIMMS software is used to implement this model.

The proposed approach is novel and deals with the important problem of designing supply chain networks to achieve sustainability from socio-economic-environmental perspective. The strengths and directions for future work are presented using SWOT analysis.

I dedicate this work

to my always loving family,

my patient parents,

my lovely son,

and my devoted wife.

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I would also like to acknowledge my friend Beibei. She has helped improve my English proficiency and corrected the thesis writings. I thank my other friends for helping me without intending to help; for encouraging me without intending to encourage; for suggesting me without intending to suggest and for their unconditional support towards preparation of this thesis.

I would like to thank my always-loving wife. She devotes me constant and wholehearted support and takes care of our three-year old kid when I am conducting the research. With her selfless dedication for our family, I could have the time and the energy to devote myself fully to research activities. Without her consolation on spirit, I would not sustain the tedious and tough exploration on my thesis work.

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List of Acronyms

AHP	- Analytical Hierarchy Process
API	- Application Program Interface
BSC	- Balanced Score Approach
COQ	- Cost of Quality
CR	- Corporate Responsibility
CSR	- Corporate Social Responsibility
DLL	- Dynamic Link Library
DP	- Dynamic Programming
DS	- Decision Support
EDI	- Electronic Data Interchange
ERP	- Enterprise Resource Planning
GSC	- Green Supply Chain
GSCM	- Green Supply Chain Management
GUIs	- Graphical User Interface
LCA	- Life Cycle Analysis
LP	- Linear Programming
MIP	- Mixed Integer Programming
MIQP	- Mixed Integer Quadratic Programming
MRP	- Material Requirement Planning

NLMIP	- Nonlinear Mixed Integer Programming
NLP	- Nonlinear Programming
QA	- Quality Assurance
QC	- Quality Control
QFD	- Quality Function Deployment
QMS	- Quality Management System
RFID	- Radio Frequency Identification
ROI	- Return on Investment
SC	- Supply Chain
SCM	- Supply Chain Management
SCN	- Supply Chain Network
SCND	- Supply Chain Networks Design
SCOR	- Supply Chain Operations Reference
SFD	- Sustainable Function Deployment
SSC	- Sustainable Supply Chain
SSCM	- Sustainable Supply Chain Management
SSCN	- Sustainable Supply Chain Network
SSCND	- Sustainable Supply Chain Networks Design
SWOT	- Strengths, Weaknesses, Opportunities, Threats
VOC	- Voice of Customer
WEEE	- Waste Electrical and Electronic Equipment

Chapter 1

Introduction

1.1 Background

1.1.1 The Supply Chain (SC)

A supply chain is a network consisting of a chain of activities, facilities, people and other resources directly or indirectly involved in fulfilling goods to customers. This term came into prominence when Cooper et al. [1] addressed it as the extension of logistics. Though there is an ambiguity in definition with the term "logistics" and "supply chain management" [2], over the past decades, SC has emerged as a more prominent topic. The supply chain not only contains the material suppliers and manufacturers, but also distributors, retailers, customers and their associated activities (Figure 1.1) whereas logistics is limited to only people and activities involved in delivery of goods from facilities to customers. The SCOR supply-chain operations reference model, developed by the Supply Chain Council describes a common framework of supply chain [3]. The SCOR model addresses the activities and operations on both the upstream and downstream sides.

The main objective of supply chain is to satisfy the customer requirements. As demonstrated in Figure 1.1, the materials and products flow from raw material suppliers to final customers. This is the so-called supply flow or value flow across downstream side. In the upstream side [4], the cash flow occurs when corresponding stakeholders of supply chains exchange their products or services for some form of payment to satisfy customer needs [5]. The information flow occurs in both directions and is related to materials, customer demands, facilities, cash etc.

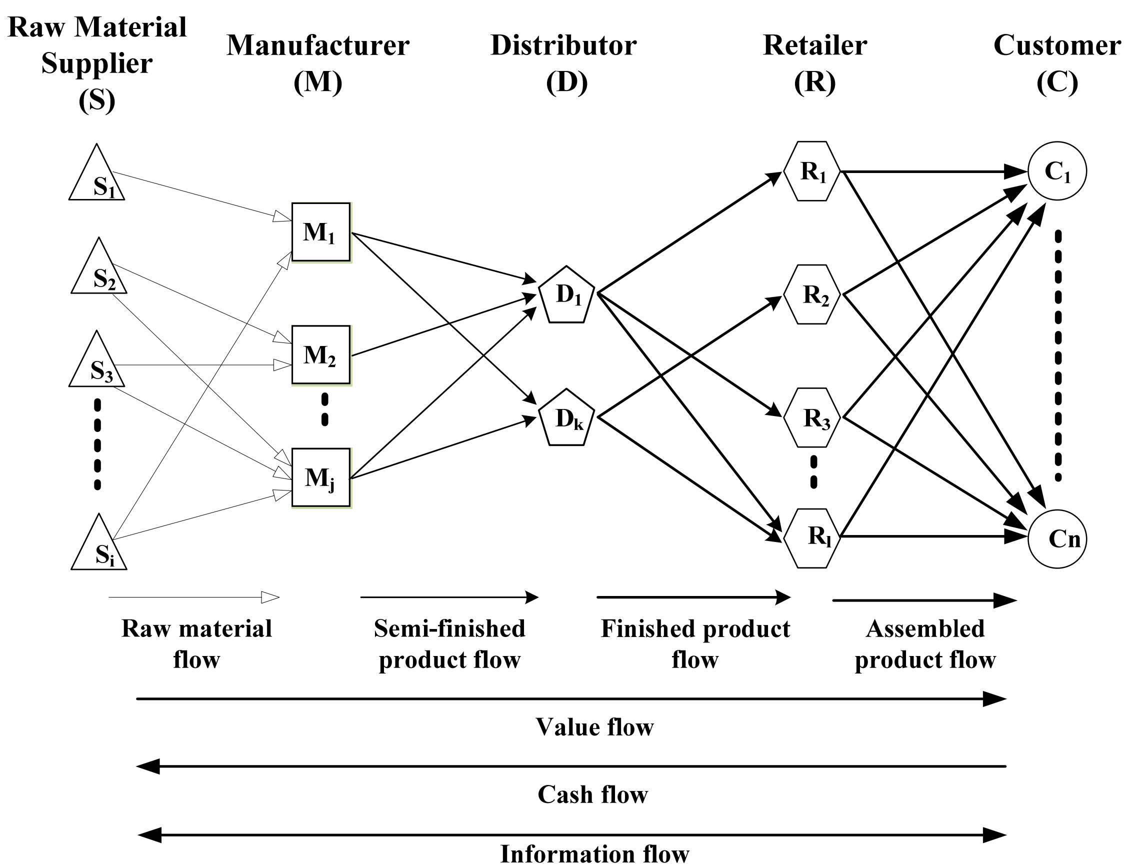


Figure 1.1: Supply Chain Flows

The use of Information technology in development of supply chain operations and efficiency on both supply and demand sides is becoming more important than ever. The real-time management of information has been possible with the help of high technology, facilities and methodologies, such as the web-based system, multi-agent, ERP, EDI, RFID etc, most of which have been used for improving information exchange within different business entities [6-9].

A better performance of supply chain can be further obtained by cooperation and collaboration among various supply chain facilities. It will not only improve the supply flow, value flow, and information flow, but also the demand flow, reused materials flow, goods for maintenance flow, and the after sales service flow etc. Depending upon service or production type of supply chains, additional performance requirements can be integrated.

1.1.2 Supply Chain Management

Supply chain management is a combination of activities, approaches, and knowledge utilized to efficiently integrate raw material suppliers, manufacturers, distributors, retailers, and customers, so that merchandise is produced and distributed in right quantities, to the right locations, and at the right time while minimizing system-wide costs and satisfying service level requirements [4]. The SCOR model categorizes the activities of SCM as plan, source, make, deliver, and return [3]. Additionally deriving from the definition, these activities can be stratified at strategic, tactical, and operational levels [10]. The different levels of SCM concern the different decision-makings about the source, location, production, inventory, and transportation from a time perspective (Strategic – Long term, Tactical – Medium term, Operational- Short term). Furthermore, to reach optimal results, activities such as procurement, capacity planning, technology adoption, facility operation, production management, schedule planning, material requirement planning (MRP), distribution planning, inventory management, order forecasting should also be carefully planned.

Croxton et al. [11] proposed a framework of business processes to achieve high performance of supply flow, value flow, and the information flow in supply chains. Their management process framework contains:

1) Customer relationship management
2) Customer service management
3) Demand management
4) Order fulfillment
5) Manufacturing flow management
6) Supplier relationship management
7) Product development and commercialization
8) Returns management

The processes of each facility in the supply chain should be integrated with the functional activities, such as purchasing, production, logistics, R&D, finance, and marketing, so as to result in high levels of customer satisfaction, economic returns, low level of risks and uncertainties in supply chain.

1.1.3 Supply Chain Network Design (SCND)

The supply chain network design is a strategic level decision that focuses on identifying, selecting, and coordinating the activities of key suppliers, manufacturers, distributors, retailers to meet specific demands from customers so that maximal profits, minimal costs, and optimal resource allocations can be achieved [4, 12, 13]. According to [14], the ultimate goal of designing supply chain networks (SCN) is to succeed in achieving maximal profits and minimal costs to satisfy customer demands by delivering the highest quality product or service order fulfillment.

Different objectives can be considered in designing supply chains. The scale of supply chain network decides the scope of network design. Design of a local supply chain network may differ from the global one in which there are reasonably more considerations, and higher complexity among the operations involved. On the operational level, the elements of network design usually but not only always consider the location planning of logistics facilities and customer allocation, supplier selection, smart pricing, order allocation, strategic sourcing, inventory controlling, distribution scheduling, time periods for delivering, transit route planning, demands fulfilling, etc [15]. The adoption of multiple criteria and multiple objectives in designing supply chain networks represents the system-optimization perspective of SCN integration [16, 17].

The mathematical method has dominated the process of SCND, since they are driven by the nature of the inputs and the objective of study [13]. Four types of models have been commonly used [18] namely:

1) Linear vs. nonlinear models, in which if the mathematical models exhibit linearity they are defined as linear models, otherwise considered nonlinear.
2) Deterministic vs. stochastic analytical models, in which if the variables values are known and specified it is called deterministic. If at least one of the variable values is unknown, and is assumed to follow a particular probability distribution, the model is called as stochastic.
3) Static vs. Dynamic models, in which variables of static models do not change with time, whereas dynamic models consider the change of variables with the time sequence.
4) Discrete vs. Continuous, in which the state of variables changes in fixed time intervals in discrete models whereas they change continuously over time in continuous models.

1.2 Motivation

Globalization has increased the complexity of supply chains with involvement of more stakeholders, facilities, and technologies. Thereof, many new challenges and complexities have emerged in supply chain management [19]. The goal of pursuing minimal operational costs and maximal ROIs in supply chains has been studied over decades [20]. Efforts to achieve the optimal balance between environment care and business performance, or the so-called green supply chain management are fairly new and have been studied in [21]. Some researchers with background in public administration or business management have emphasized on social concerns in SCM [22, 23]. However, studies that endeavor to optimize economic returns, environment concerns, and the social performance altogether for supply chains are rare. The challenging issues are how to achieve balance among the business goals, social concerns, and the environmental impacts of different activities in supply chains. This thesis focuses on the problem of designing sustainable supply chain networks considering the triple goal of maximizing economic returns, minimizing environment impacts, and maximizing social performance for supply chains.

1.3 Contribution

This thesis presents a methodological framework for designing sustainable supply chains. This involves development of a systematic literature review about SSCM, extraction of customer and technical requirements using Voice of the Customer (VOC), investigating relationship between the customer requirements and technical requirements using Sustainable Function Deployment (SFD) and development of an integer programming model for sustainable supply chain network design using AIMMS optimization software [24].

1.4 Research Plan

Figure 1.2 presents the planning steps involved in conducting research for this thesis.

The first step involves establishing research goals followed by literature review, identification of methods and techniques for resolving the problems involved, then conducting the core research using the identified methods, implementation of methods, experimentation and scenario analysis and finally delivering the results of the study. Only when all the designed research objectives and methodologies uniformly succeed in all steps of the proposed plan for conducting this thesis research, the final outputs will be delivered.

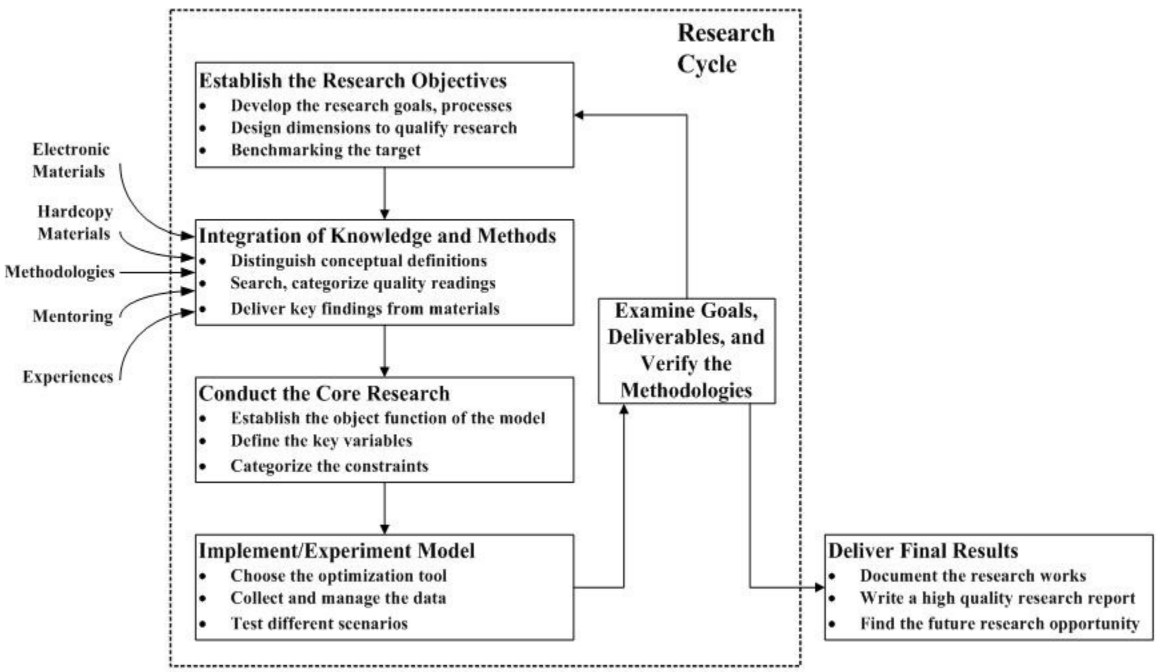


Figure 1.2: Plan for conducting thesis research

1.5 Thesis Structure

The rest of the thesis is organized as follows. In Chapter 2, we present the problem statement.

Chapter 3 presents our 3-step solution approach for designing sustainable supply chain networks.

Chapter 4 presents the approaches used for capturing customer and technical requirements for sustainable supply chain network design. This consists of systematic literature review and questionnaires development (C-REQ and T-REQ) for listening to Voice of the Customer (VOC) and identifying customer and technical requirements.

Chapter 5 presents the Sustainable Function Deployment (SFD) approach used for establishing relationship between customer requirements and technical requirements and weighting them for designing sustainable supply chains.

Chapter 6 presents the integer programming model used for designing sustainable supply chain networks.

The conclusions and future work are presented in Chapter 7.

Finally, the references complete the thesis.

Chapter 2

Problem Statement

The goal of this thesis is to develop a modeling framework for designing sustainable supply chains considering economic, environmental and social objectives. In order to achieve this goal, following sub-problems will be investigated in this thesis.

1. Identification of social, economic, and environmental factors for developing sustainable supply chains.
2. Identification of customer and technical requirements based on social, economic and environmental factors, investigating their intra- and inter-relationships, and allocation of priorities (ratings) for developing sustainable supply chains.
3. Designing the sustainable supply chain (SCND model) using the weighted customer requirements, technical requirements, supply and demand constraints, and other network modeling parameters.

All the above mentioned sub-problems will be addressed step by step in a sequential manner to achieve the goal of designing sustainable supply chain networks.

Chapter 3

Solution Approach

In Chapter 2, we presented the various sub-problems to be resolved in order to achieve the goal of designing sustainable supply chain networks. Figure 3.1 presents the three steps involved in the solution approach.

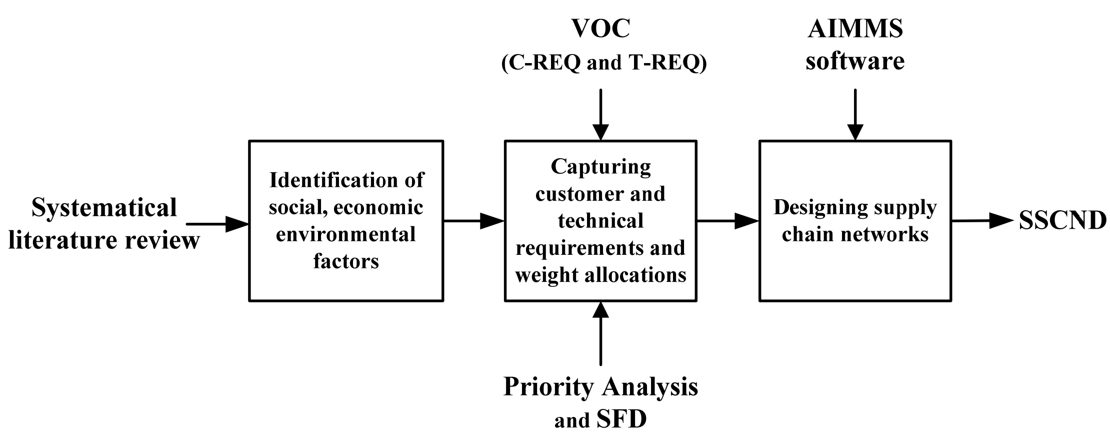


Figure 3.1: The 3-step integrated solution approach for SSCND

In the first step, we identify the economical, environmental, and social factors by systematic literature review. In the second step, we identify the customer and technical requirements using Voice of the Customer (VOC), study the relationships, and allocate weights using Sustainable Function Deployment (SFD). In the third and the last step, we develop a mathematical programming based model for designing sustainable supply chain network using the weighted technical requirements and network modeling parameters.

The 3-step integrated solution approach for SSCND is presented in detail as follows:

1. *Identification of economic, social and technical factors for developing sustainable supply chains*

   To identify the economic, social and technical factors for developing sustainable supply chains, we conducted a systematic literature review. A systematical literature review is a method to systematically analyze, categorize, and generalize the concepts and the tendencies in a specific research area by investigating relevant publications. It is different from the usual literature review, in which researchers summarize the existing state of art about a particular research topic. Therefore, the common literature review is not able to deeply identify and analyze the evolution of research issues, and is not able to discover the research tendency by investigating the relationships among the issues/topics concerned by researchers. Hence, in this thesis, systematical literature review is used to identify the three socio-economic-environmental factors and all other important parameters involved in designing sustainable supply chains, their relationships with each other and how it can be exploited to reach the concept of "sustainability" for supply chain management. Chapter 4 will presents the results obtained from systematic literature review in detail.

2. *Capturing customer and technical requirements and priority (weights) allocation*

Capturing customer and technical requirements for developing sustainable supply chain networks is very important. We developed questionnaire surveys C-REQ and T-REQ to collect Voice of the Customer (VOC). To capture the technical requirements, T-REQ (Appendix B) is used whereas to capture the customer requirements C-REQ (Appendix A) is used. In order to establish the relationship between the customer requirements and technical requirements and weigh them, we propose a technique called Sustainable function deployment (SFD) which is based on the concept of Quality function deployment (QFD). It has been given the name SFD since it integrates the three metrics for sustainable supply chain management namely economic, environmental and social views rather than quality management view. Chapter 5 presents the details of the proposed SFD approach.

3. *Designing sustainable supply chain networks*

Once the weighted technical requirements have been obtained from SFD, they are integrated in the objective function of sustainable supply chain network design. The sustainable supply chain network design problem consists of identifying the best configuration of supply chain network considering joint optimization of three sustainability dimensions (social, economic, and environmental) weighted using SFD subject to capacity constraints of logistics facilities and demand constraints of customers. An integer programming model is developed in AIMMS for designing sustainable supply chain networks. Chapter 6 presents details of the proposed model.

Chapter 4

Systematic Literature Review

4.1 Method Description

A systematic literature review is a method to systematically analyze, categorize, and generalize the concepts and the tendencies in a specific research area by investigating relevant publications from wide perspectives, scopes, domains etc. It is used to identify gaps, issues, and opportunities in a specific research field. The end result of a systematic literature review is a conceptual model based on existing gaps, available research and opportunities for future work. Thereof, it helps to identify the contents and guides towards theory building. It is different from the usual literature review, in which researchers summarize the existing state of art about a particular research topic. Therefore, the common literature review is not able to deeply identify and analyze the evolution of research issues, and is not able to discover the research tendency by investigating relationships among the issues/topics of concern to researchers. Hence, in this thesis, systematic literature review is used instead of general literature review.

Meredith [25] illustrated this method in a theoretical way. Easterby-Smith et al. [26] propose theoretical and practical guidance to do the research with a balance of qualitative and quantitative methods. Srivastava [27] suggested the following steps in doing literature view : 1) Defining unit of analysis, 2) Classification of context, 3) Material evaluation, and 4) Collecting publications and delimiting the field. Similarly, Seuring et al. [28] proposed a closed-loop process for conducting literature review, where the process includes a feedback loop for the analysis of the collected materials.

The objectives of systematic literature review in our thesis are to investigate what is a “sustainable supply chain”, how does it differs from the traditional supply chain, its state of application in industries, metrics that can be used to measure it, potential areas of application, and the methods that can be used to design sustainable supply chain networks etc. In order to achieve this objective, we will collect and thoroughly analyze research materials focusing on:

1) Sustainable supply chain management
2) Supply chain network design
3) Sustainable supply chain network design
4) Supply chain optimization
5) Etc..

At the end, we will evaluate and examine these materials along different structural dimensions.

4.2 Data Collection

Two resources were used to collect materials for systematic literature review. One was the hardcopy readings, which means published books, references, magazines etc.

Such materials can be acquired in libraries from many academic institutions. The other was online search in which relevant material was extracted by conducting electronic search for the research articles by search engines. Following sources were used for on-line collection of articles:

- www.sciencedirect.com
- www.emeraldinsight.com
- www.springerlink.com
- www.intescience.wiley.com
- www.ebsco.com
- www.metapress.com
- www.subito-doc.de
- www.scopus.com

The major databases used for searching related articles were major publishers such as Elsevier, Emerald, Springer, and Wiley. Some library services also provide article search engines, such as Ebsco, Scopus, Metapress, and Subito etc. To increase the reliability of data collected from the two sources for our thesis research, the databases, journals, references as well as the individual papers or books were double checked by a second researcher.

The key words used for searching the resources were “Sustainable Supply Chain”, “Greening Supply Chain (GSC)”, “Supply Chain Optimization”, “Supply Chain Networks Design”, “Supply Chain Management”, “Sustainable Supply Chain

Management" etc., However, compared to on-line resources, the amount of researched materials from hardcopy publications was limited.

Table 4.1: Sources for Information Collection on SSCM

Reading Resources	**Number of Literatures**
Business Strategy and the Environment	10
Journal of Cleaner Production	9
Supply Chain Management: An International Journal	5
Journal of Supply Chain Management	2
International Journal of Production Economics	10
International Journal of Production Research	4
Corporate Social Responsibility and Environmental Management	3
International Journal of Logistics Management	3
IEEE Transactions	3
Transportation Research Part E: Logistics and Transportation Review	2
Logistics Information Management	2
International Journal of Operations & Production Management	4
Conference Papers	1
Government Publications	3
Other Journals *(one paper from each other journal)*	31
Books	14
Online Materials	7
Magazine	1
Graduate Thesis	1

The basic body of literature was identified from 115 publications. Table 4.1 shows the allocation of the publications along with their relevant sources. The number of total cited readings from each resource is shown in the second column of Table 4.1. It can be seen in Table 4.1 that the body of literature covers not only specialized supply chain journals but also general popular management journals. Furthermore, the distribution of publications for 2005-2010 is provided in Figure 4.1.

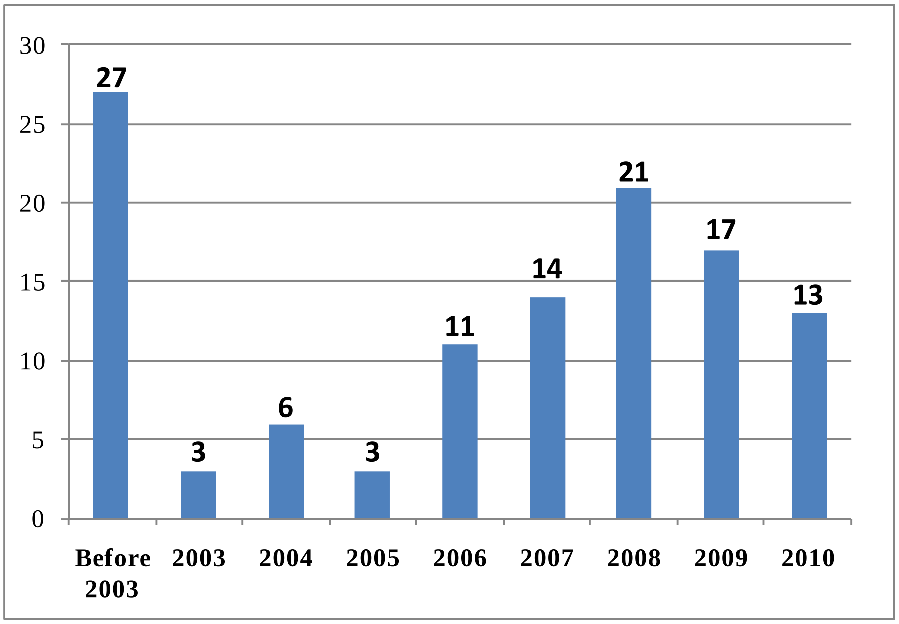


Figure 4.1: Distribution of Selected Publications

(2005 – 2010)

4.3 Literature Analysis

4.3.1 Evolution of Supply Chain Management

4.3.1.1 The Horizontal Expansion of Supply Chain Management

In the 1980s, the term "Supply Chain Management" was mentioned by Oliver and Webber [29] to integrate the critical business process to satisfy the customer demands.

Cooper et al. [1], Porter [30], Mentzer et al. [10], and Mouritsen et al. [31] provide a conceptual framework and operating details for SCM. They emphasize the fact that SCM has significantly evolved from the "internalization" of processes and activities to the "externalization" of performance measurement in the field of operations management. This new trend of SCM has been accelerated mainly by the requirements of information technology, business collaboration, and the globalization.

Hence, research on SCM has evolved from its core concerns on logistics, operations, processes, and facilities to the integration of theoretical concepts, strategic planning, industrial management, cost-based economics efforts, inter-organizational relationships, intellectual knowledge management and systems scheme. This indicates that the general scope of SCM has stepped over the boundaries of physical, functional, and legal issues in companies [16]. The SCM focus is not only on supply-buy activities between some business entities, but also on management of the chains across organizations, regions, industries, cultures [32, 33]. Thus, researchers started to work on new areas such as investigating the influence of environmental practices in supply chain management also called as greening the supply chain [34-36]. Some others tried to discover how social factors affect the operations of supply chains, together with economic and environmental issues. This field of research has come to be known as the sustainable supply chain management (SSCM) [37, 38]. Although the name GSCM and SSCM are not strictly coined, the contents of SSCM have horizontally expanded from economic concerns to environment care, and social activities [39, 40].

4.3.1.2 The Vertical Expansion of Supply Chain Management

The previous section discussed the complexity of supply chain networks from the point of view of horizontal expansion. In this section, we discuss the vertical expansion of supply chains that amplified further the research scope and the research domains involved. The vertical expansion involves increase in the number of organizational units involved at different stages of the supply chain to meet ever growing customer demand. According to the illustrations of Croom [41]:

> …… *domain of supply chain management does not concentrate solely on the single function or firm as the unit of analysis, but takes a broader view across interacting and interdependent functions, groups and organizations* …….

The inclusion of multi-organizations increases the layers of supply chains. Hence, researchers such as Porter [42] and Feller et al. [5] focused on multi-stage facilities of supply chains and associated flows. These are the so-called multi-echelon supply chain networks. Some other researchers investigated how to minimize the influences between the upper and lower stages [43]; the activities to strengthen information exchange between upstream and downstream [8]; and the processes to efficiently supply and source in each facilities [44-46].

4.3.2 The Concepts of Sustainable Supply Chain Management

There are many discussions on the definitions of SSCM. Linton et al. [39] reviewed the definitions of “sustainability” and proposed that the SSCM should satisfy the relationship, in which

> *…… anthropology, political science, psychology and sociology interact with the natural sciences and are interpreted and managed through the development of policy ……*

Piplani et al. [47] proposed the scope of SSCM in terms of economic, non-economic, environment, especially including social responsibility of supply chains. Other researchers also illustrated the SSCM from three aspects to achieve the balance among financial returns, social performance, and environment concerns [28, 48, 49].

In traditional supply chains, the goal is to balance the benefits among multi stakeholders, improve the operating efficiency throughout the facilities, and maximize the profitability of processes and activities. However, in sustainable supply chains (SSC) consideration of environment concerns and social responsibilities along with economic gains are of top priority.Figure 4.2 presents the conceptual model we developed based on systematic literature review. It can be seen from Figure 4.2 that the scope of sustainable supply chain management (SSCM) is no more limited to individual objectives of economic, social or environmental dimension, but towards their integration in all operations throughout multi-echelon supply chains [17].

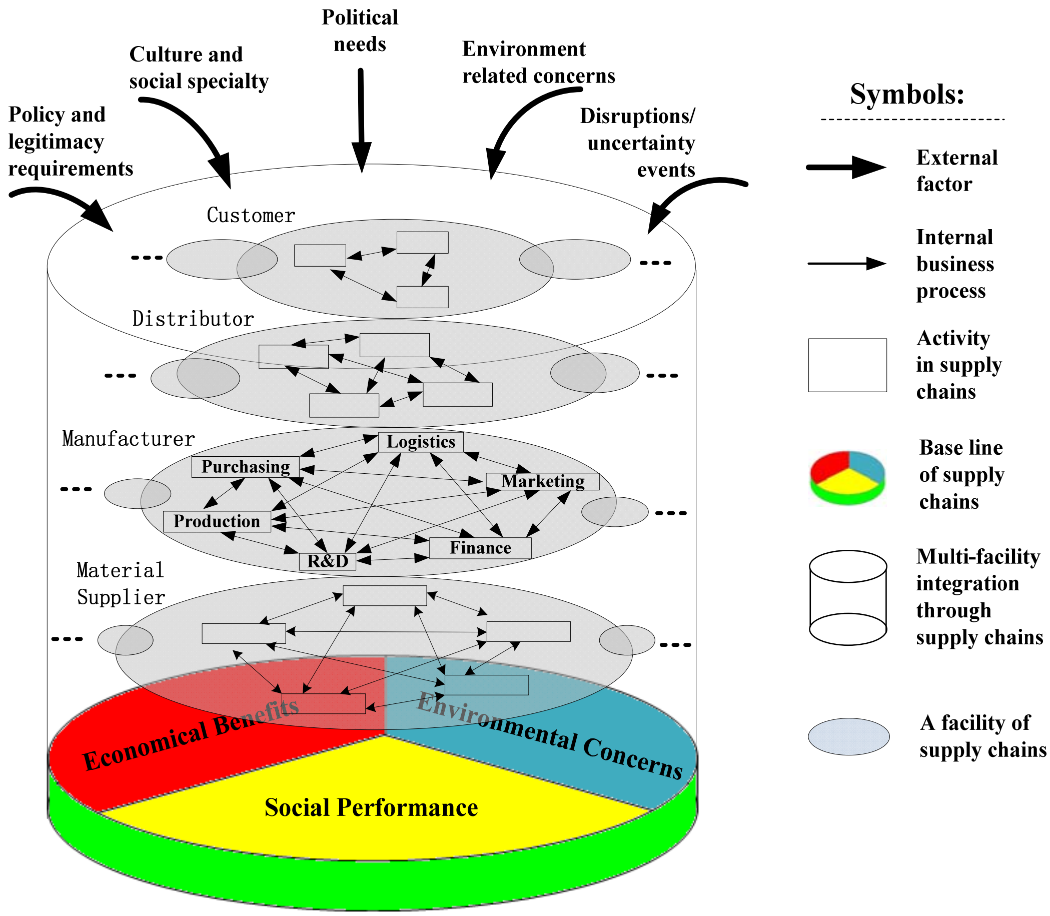


Figure 4.2: The Framework of SSCM

Integrated with external factors and internal processes and activities, the operations of SSCM should focus on the balance among three objectives:

1) Maximal benefits or financial returns

2) Minimal environmental impacts

3) Meeting the social requirements

4.3.3 Metrics for Assessing Sustainability of Supply Chains

Metrics are used for evaluating the performance of supply chains. Lapide [50] proposes five types of metrics namely 1) Function-based, 2) Process-based, 3) Cross-enterprise, 4) Numerical, and 5) Alignment of executive to management level. Gunasekarana et al. [51, 52] proposed metrics to evaluate the order planning, supply link, production level, delivery link, customer service, and logistics cost etc. at strategic, tactical, and operational levels in traditional supply chains. Brewe [53] suggested an innovative method to evaluate supply chains using quality-oriented, time-based, flexibility-oriented, and cost-based measures. Beamon [54] discussed the use of resources, outputs, and flexibility as the metrics. Shepherd [55] proposed measurements in line with SCOR model, in which metrics should be established as plan, source, make, deliver, and return.

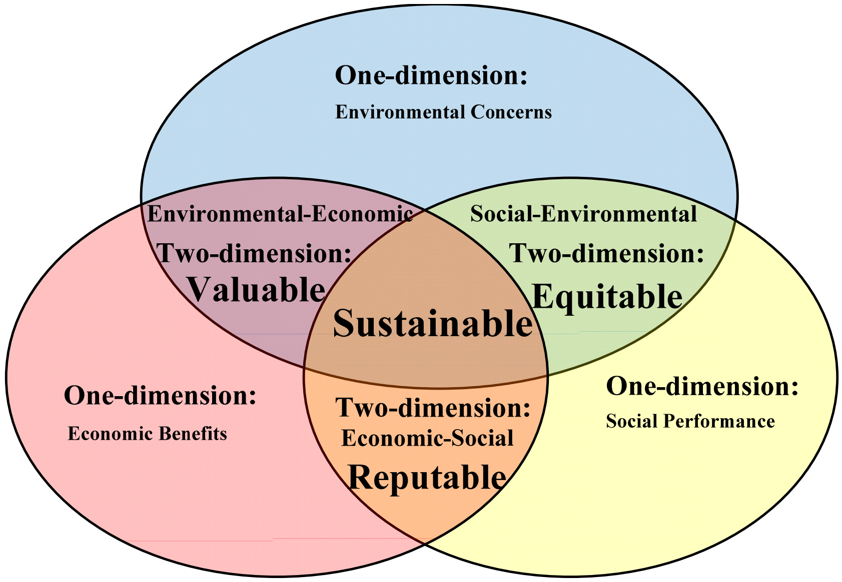


Figure 4.3: The Three Base Line of SSCM

(Adapted from [56, 57])

According to the descriptions in section 4.3.2, the measurements of SSCM will be more meaningful if based on the scope of functions, activities, and processes, and the benefits of stakeholders. Therefore, in this thesis we will measure the “sustainability” of supply chain at the strategic level. Figure 4.3 presents a multi-dimensional view for measuring the sustainability of supply chains. Using Figure 4.3, multi-dimension metrics will be derived from the three base lines (Social, Economic, and Environmental) to measure the “sustainability” of SCM. The one-dimension metrics are from each one of three base lines. The two-dimension metrics are the combinations between any two of the three base lines. They can be used to evaluate the degree of operations, processes, and activities integration in sustainability in supply chains. The three-dimension metrics also called as sustainable metrics consider will consider three base lines altogether at a time.

4.3.3.1 One-dimension Metrics

One-dimension metric is the first level, in which only one baseline factor is used at a time to evaluate the performance of SSCM. There are three kinds of one-dimension metrics:

1) Economic dimension
2) Environmental dimension
3) Social dimension

Table 4.2: One-dimension Metrics – Economical Benefits

Economical Metric	**Factor**	**Literature**
Order planning	Order entry, lead time, order patch, cycle time, etc.	[51, 52]
Operation/Management	Operation on the strategic, tactical, or operational level	[51, 52]
Supply link	Supplier evaluation, supply capacity, etc.	[51, 52]
Production evaluation	Scheduling, capacity, quality, techniques, etc.	[51, 52, 58]
Delivery performance	Flexibility, order fulfillment, least faultiness	[51-53, 55]
Costs	Logistics, supply, inventory, transaction, etc.	[51-54, 59]
ROI	Revenue, profits, tax payment	[51, 53, 54]
Information sharing	Technology, system, equipment, flow, process, etc.	[52, 53, 60]
Business co-operation	Collaboration, globalization, QMS, work to standards	[52, 60-63]
Customer service	Process time, query time,	[52, 53]
BSC	Balanced Score Approach	[64, 65]

Table 4.2 presents the indicators for the one-dimension metric based on the Economic dimension. These indicators apply on the strategic, tactical, and operational levels and consider function-based, process-based, cost-based, time-based, quality-based,

and management-based aspects of supply chain management.

Table 4.3: One-dimension Metrics – Environmental Concerns

Environmental Metric	**Factor**	**Literature**
Waste processing	Waste reducing, recycling, reusing	[34, 53, 66-68]
Natural resources	protect, conserve, utilize, regenerate	[40, 58, 62, 66, 68, 69]
Pollution controlling	Water, air, transportation pollution	[35, 36, 40, 66]
Emission preventing	Gas, fluid, chemical, emission trade	[35, 36, 66, 70]
Policy	Public pressure on environment,	[63, 66, 71]
Legislation	Act on environment protection	[34, 59, 66]
Management/Operation	EMS, ISO, LCA, technology, collaborate, monitor	[36, 60, 63, 66, 72-76]
Biodiversity	Natural species diversity,	[60, 62, 69]
Energy saving	Save the energy either in natural or renewable	[35, 68]

Table 4.3 presents indicators for the one-dimension metric based on Environmental Dimension. For example, waste processing, natural resources, pollution control etc.

Table 4.4 presents the indicators for the one-dimension metric based on the social dimension. For example, equity, safety, ethics etc.

Table 4.4: One-dimension Metrics – Social Performance

Social Metric	**Factor**	**Literature**
Customer benefits	Service level, satisfaction, flexibility,	[51, 53-55]
Reputation	Quality, CR outcomes, code of conduct, brand name	[23, 38, 53, 54, 77-80]
Ethics/Moral	For public health, safety, transparency	[22, 23, 68, 76-78, 81]
Legislative	Act, law, legislation responsibility,	[23, 68, 71, 77]
Equity	Income, political, economic, social fairness, right	[59, 76, 82]
Trust	Interpersonal trust, brand trust,	[62, 79, 80]
Culture respect	Respect culture in local,	[62]
Safety	Product safety, consumer safety	[59, 62, 76]
Public benefits	Welfare, training, work condition, quality of life	[62, 68, 76, 83]
Social relationship	Collaboration, Community, stakeholder	[22, 40, 68, 74, 84, 85]
Social standards	SA 8000, AA 100, OECD Guidelines etc.	[73]

4.3.3.2 Two-dimension Metrics

The two-dimension metrics consider two baseline measures at a time (Figure 4.3). There are three kinds of two-dimensional metrics namely valuable, equitable, or reputable (Figure 4.3).

1) The valuable sustainable supply chain management

When supply chains consider both economic benefits and environment concerns, the performance of SSCM is termed valuable. The factors related with the two-dimension metrics are the combinations of the factors listed in Table 4.2 and Table 4.3. Supply chains can have specific objectives to attain valuable performance by concentrating on various combinations of economical and environmental factors. In literature, examples of valuable SSCM can be found in [53, 58-60, 62, 63].

2) The equitable sustainable supply chain management

The equitable performance involves consideration of environmental and social baseline factors. To achieve the equitable performance for SSCM, the operations and managerial activities should focus on integration of different factors listed in Table 4.3 and Table 4.4 respectively. Research on practices of equitable SSCM can be found in [40, 53, 59, 62, 68, 71, 73, 76].

3) The reputable sustainable supply chain management

The reputable SSCM considers the economical and social baseline factors. To succeed in reputable performance for a specific SSCM, it is not obligatory to consider all the factors listed in Table 4.2 and Table 4.4, only certain combinations are enough. In literature, the examples of reputable SSCM can be found in [51, 53-55, 59, 62].

4.3.3.3 Three-dimension Metrics

The highest level of SSCM performance is said to be “sustainable”, which is achieved when the three requirements of sustainability, that is, the economical, environmental, and social performance are achieved at the same time. The different needs of SSCM decide the specific objectives to be reached for attaining sustainability.

Accordingly, all or part of the various indicators or factors listed in Table 4.2, Table 4.3, and Table 4.4 can be considered for achieving the sustainability objective. Some examples of sustainable supply chain management can be found in [53, 59, 62, 68, 85].

4.3.4 Application Areas

Table 4.5 presents the various industry/sectors where sustainable supply chain has been applied.

Table 4.5: Application Areas in SSCM

Industry or Sector	**Application of SSCM**	**Level**	**Ref.**
Agriculture/Environment	Agriculture materials production	Equitable	[62]
	Agriculture fresh product supply	Sustainable	[40]
	Forest, wood supply	Economical	[8]
Chemical/Material	The rubber and plastics production	Sustainable	[85]
	Aluminum manufacturing	Valuable	[35]
	SSCM of concrete products in construction	Sustainable	[68]
General Manufacturing	Green manufacturing (economical), LCA	Valuable	[75, 86]
	Green manufacturing (social)	Equitable	[71]
Food/Medical	Food production, supply	Social	[23, 80, 84]
	Food supply, production, and sales	Equitable	[62]
	Green purchasing	Reputable	[77]
Machinery/Equipment	Automotive production	Equitable	[60]
	Electrical and electronic product LCA	Environmental	[34]
	EMS (ISO 14001) in automotive industry	Environmental	[72]
Consuming/Retail	Toys production	Social	[23]
	Package printing	Environmental	[36]
	Retail and consumer product goods	Valuable	[87]
Transportation/Logistics	Air transportation	Valuable	[70]
	Greening logistics and transportation	Valuable	[74, 88]
	Greening supply, source	Reputable	[77]
Electricity/Electronics	Telecommunication, electronics production	Social	[23, 78]
	WEEE SC planning, reverse logistics	Valuable	[67]
	Consumer electronics design, production	Valuable	[45]
Information/Service	Design social welfare chain	Social	[83]
	E-commerce	Economical	[6]
	Green supply and source planning	Reputable	[77]
Apparel/Textile	Garments, sportswear, footwear production	Social	[23, 78]
	Fashion retail industry LCA	Sustainable	[59]

4.3.5 Methods for Designing Sustainable Supply Chain Networks

Table 4.6 lists the most commonly used methods for designing sustainable supply chain networks. This includes mathematical modeling, optimization, empirical analysis etc.

Table 4.6: Methods Used in Sustainable SCND

Method	**Description**	**Application**	**Ref.**
Mathematical Model	Linear programming (LP)	Service chains and food chains	[83, 89]
	Dynamic programming (DP)	Ecommerce supply, source	[6]
	Nonlinear programming (NP)	Optimize supply and source	[12]
	Mixed Integer Linear Programming	Design valuable, reputable SCNs	[90, 91]
Optimization	Multi-objective programming	WEEE SC, valuable SCND	[67, 92]
	Multi-criteria optimization	LCA design, equitable SCN	[75, 93-95]
	System dynamics (SD) methodology	Sustainable SCND	[34, 96]
	Multi-objective optimization	Design a sustainable SCN	[96, 97]
	fuzzy goal programming approach	Multi-criteria & multi-objective	[98]
Simulation	Emission trade scheme influence SCM	Transportation	[70]
IT Application	Information sharing, internet application	Material supply	[8]
Stochastic Model	Stochastic dynamic programming model	Consumer electronics	[45]
	Stochastic programming approach	Design equitable SCNs	[99]
Heuristic Model	Model energy, cost, allocation with time	Aluminum production	[35]
SPC Analysis	Hypothesis testing, statistic analysis	Package printing, sourcing	[36, 77]
Empirical Analysis	Questionnaire surveying and analysis	Manufacturing	[71, 72, 86]
	Survey, case study	Planning, source, supply in retail	[59, 78, 87]
	Survey, case study	Transportation, Logistics	[74, 88]
Conceptual Analysis	The theoretical analysis for SCND	Design a (valuable) green SCN	[62, 66]
	Case-based for sustainable SCND	Planning sustainable SCN	[100]

4.3.6 Enablers Vs Barriers to Sustainable Supply Chain Management

Table 4.7 presents the enablers for sustainable supply chain management. Many literatures indicate that internal and external pressures drive the supply chains towards environmental, social and economical performance. Legislation pressure, market needs, government pressures, competitive advantages, collaboration requirements etc. are the main external enablers to practice SSCM. In addition, managerial drivers, costs pressures etc. are the internal enablers of supply chains.

Table 4.7: Enablers for Sustainable Supply Chain Management

Enabler	Literatures	Remarks
Legislation	[28, 67, 71, 101]	Legislation from social and environmental concerns
Pressures from stakeholders	[23, 63, 71, 74]	High performance of SSCM to achieve their benefits
Consumer concern towards SSCM	[28, 101, 102]	Customer and market pressure for implementing SSCM
Information Sharing	[102]	Efficient information sharing and communication
Collaborative relationships	[28, 102, 103]	Supplier integration, reduce risks among supplier-buyer
Government pressures	[104]	Pressures from government requirements for SSCM
High cost of energy, logistics etc.	[86-88]	Least costs will reach a part of economical SSCM
Competitive advantage	[28, 86-88, 105]	A higher competitive has a higher SSCM performance
Desire to be a leader	[86-88]	Best-in-class, best-in-best is the highest performance
Compliance in product/service	[87]	Satisfy customer needs, and establish brand reputation
Access to foreign markets	[87]	Globalization & collaboration reach higher performance

Table 4.8 presents the barriers in sustainable supply chain management. The performance of SSCM is negatively influence by the presence of barriers, such as high investments, expenses, requirements of intellectuals, and so on. Some researchers also emphasize that the limited awareness among the stakeholders of SC also slows down the

performance of SSCM.

Table 4.8: Barriers in Sustainable Supply Chain Management

Barriers	**Literatures**	**Remarks**
Crisis-oriented management	[81]	Difficult to reach multi risks control
Cost-oriented management	[28, 74, 81, 101]	High costs for SSCM in environmental, social, economic efforts
Coordination complexity	[28]	Difficult to reach results for multi-objective within stakeholders
Supplier obstacle	[71, 101]	Lack of sustainable suppliers from upstream
Internal obstacle	[28, 71, 101, 105]	Lack of internal process, regulation, policy etc. to support SSCM
Lack of understanding SSCM	[105]	Lack of how to incorporate SSCM among stakeholders
Lack expertise	[23]	No enough expertise to support SSCM in wide scope operations
Lack budget	[23]	Limited budgets for SMEs
Outdated technology	[23]	Lack of innovations, state-of-the-art technologies
Limited awareness	[23, 74, 105]	Difficult to reach the accordance of SSCM in management

4.3.7 State of Sustainable Supply Chain Management in Canada

Due to the predominance of forest and wood industry in Canada, researchers are focusing on reducing the bullwhip effects in wood supply chains to attain economical benefits. An example is the Quebec Wood Supply Game [8]. However, this application is only able to achieve the economical performance but not the environmental and social performance in supply chains.

For green supply chain management, economical and environmental performance for equitable level is discussed in [36]. In addition, researchers investigated the practice of implementing SSCM on waste electrical and electronic equipment (WEEE) industry in [67]. The deliverable is a model that addresses the legislation, environment concerns, and the economical objectives. In 2009, Industry Canada proposed a series of publications [86-88] that report the practice of GSCM in manufacturing, retail, and logistics/transportation industry. These publications present the current situation, practices, and drivers for sustainable supply chain management in both manufacturing and service sectors.

Chapter 5

Sustainable Function Deployment (SFD)

In this chapter, we propose a technique called Sustainable Function Deployment (SFD) developed on the concept of Quality Function Deployment (QFD) to establish the relationship between customer and technical requirements and prioritize them for developing sustainable supply chains. The quality function deployment (QFD) approach, also called the House of Quality, developed by Dr. Yoji Akao [106] is used to listen and integrate the voice of customer (VOC) with the designed features of products or services. Implementation of QFD requires eight steps [107] which are described as follows:

1) Develop a list of customer requirements collected from both internal and external customers for designing quality goals.
2) Develop a list of technical requirements to design elements or features for quality.
3) Demonstrate the relationships between the customer requirements and technical requirements.
4) Identify the inter- and intra-relationships among the technical and customer requirements within technical requirements itself for developing the roof in the QFD house.

5) Perform a competitive assessment of the customer requirements and technical requirements.

6) Prioritize customer requirements considering their importance, target value, effect on sales, and generate absolute weight.

7) Prioritize technical requirements based on the degree of difficulty, target value, and calculate absolute weights, and relative weights.

8) Analysis of absolute and relative weights to determine quality goals or features based on the design inputs from customer needs.

The customer requirements for SFD are obtained through questionnaire surveys (Voice of the Customer) and technical requirements are obtained from systematic literature review. In addition, priority matrix and cause-and-effect diagram techniques are applied to screen the customer and technical requirements for designing sustainable supply chains. The weighting of customer and technical requirements is another purpose of developing these techniques.

In order to reach a sustainable performance, researchers should not only focus on improving economical benefits, but also satisfying environmental and social requirements. The current situation of research on SSCM focuses more on the one-dimension and two-dimension level. However, to reach “sustainable” SCM on the three-dimension level is worthy of exploring and is the focus of our research in this thesis.

5.1 Identifying the Social, Economic and Environmental Factors

Before developing the SFD, we identify the social, economic, and environmental factors required to develop a basic understanding of sustainable supply chains. This will be achieved in two tasks. The first task intends to identify, analyze, and generalize the factors, which will influence the performance of SSCM. The second task performs an analysis of SSCM requirements, which decide the direction of improving SSCM performance.

Table 5.1: A Strategic Factor Analysis of SSCM

Economical Factor	**Environmental Factor**	**Social Factor**
Cost and expense	Environment operation	Customer satisfaction
Business profit	Natural resource protection	Stakeholder satisfaction
Technology Application	Resource utilization and regeneration	Social equity
Business expansion	Waste recycling	Public benefits
Enterprise globalization	Emission control	Business trust and reputation
Process collaboration	Pollution elimination and prevention	Legal compliance and ethics
Business operation	Environment policy and legislation	Culture protection

In section 4.3.3, we presented the metrics for assessing the performance of sustainable supply chains (Table 4.2, Table 4.3, and Table 4.4). In those selected readings, researchers emphasized that the degree of improving the performance of those metrics/factors will positively influence the performance of SCM. Although different levels of SSCM performance can be achieved, the sustainable one should involve the crucial factors for improving economical benefits, environmental concerns, and social performance. Table 5.1 summarizes the factors on the strategic level.

In order to improve the overall performance of sustainable supply chains, customers and stakeholders' requirements should also be taken into account besides considering technical factors. Using the analysis of enablers and barriers of SSCM in section 4.3.6, we identified the customer requirements and stakeholder requirements. Table 5.2 categorizes these requirements from both the internal, external customer and stakeholder point of view for supply chains.

Table 5.2: Requirements from Customer and Stakeholder in SCs

Internal Customer	**External Customer**	**Internal Stakeholder**	**External Stakeholder**
High employee benefits	Consumer safety	Competitive advantage	Best returns on investing
Efficient communication	Consumer health	Good to be a leader	Good in public benefits
Effective work processes	Compliance in product	Good for globalization	Legislation compliance
Human rights protection	Best in service	Good for collaboration	Good in public safety
Least work pressures	Least costs on product	Least operation costs	Good for public health
Safe in work environment			Good for social diversity

The strategic factors (Table 5.1) integrated with the customer requirements (Table 5.2) provide the basic infrastructure for developing SFD.

5.2 Voice of Customer (VOC)

Voice of customer is a technique used for collecting customer requirements through questionnaires, personal interviews, field studies etc. In the thesis, we will use VOC to collect the customer preferences and requirements for designing sustainable supply chain networks. Thereafter, the collected preferences will be screened by the degree of benefits to be achieved in terms of the efforts to be devoted.

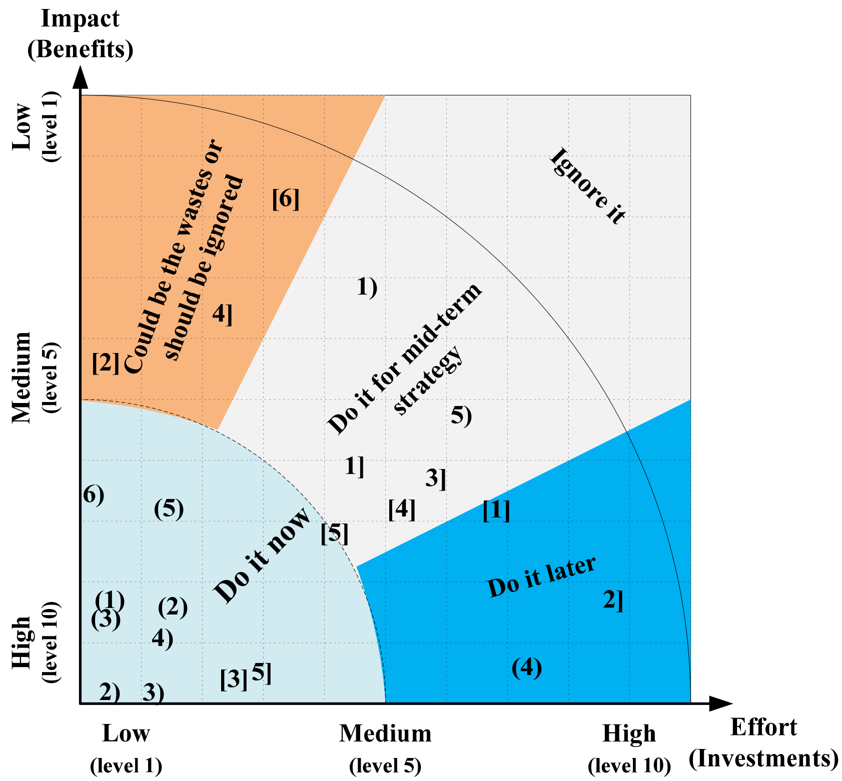
5.2.1 Collecting Customer Requirements

Design of sustainable supply chain networks is highly dependent on the customer requirements whose satisfaction degree decides the level of performance achieved in SSCM. There are several ways to collect the VOC [108-110], however, in this research, questionnaire survey study with the employees in all stages of the supply chain is suggested. We designed a questionnaire (C-REQ) based on the outputs of systematic literature review in section 4.3. The details of the questionnaire survey can be found in Appendix A. To design the questions in our survey, we used the factors summarized in Table 5.2. A total of twelve questionnaires were distributed, and responses were received for all of them (five students, two faculty members, and other five full time employees working for different companies in the field of supply chains).

5.2.2 Screening Customer Requirements

After obtaining customer requirements from the VOC, the next issue is how to process them. Are all VOCs able to be satisfied [111]? Are there any risks in fulfilling the VOC [112]? Schwalbe [113] suggested a risk management method to fulfill the customer requirements. In addition, is there any pre-defined sequence to implement the VOCs [114]?

In this thesis, based on the requirements from customers and stakeholders of sustainable supply chains, a priority matrix (Figure 5.1) is developed in terms of the potential benefits to achieve and the efforts to be devoted for planning sustainable supply chains. In Figure 5.1, the VOC is defined as the combination of customer demands and the requirements from stakeholders in SSCM. The priority matrix indicates the relationship between the efforts to invest on satisfying VOCs and the benefits achieved by those practices. Consequently, the data collected from questionnaires is represented on Figure 5.1 in terms of final scores where each final score for the impact and effort is the average of the feedbacks from the respondents.



Customer Requirements:

Internal customer needs	Impact	Effort
1) High employee benefits	3.2	4.7
2) Efficient communication	9.7	1.4
3) Effective work processes	9.8	2.2
4) Human rights protection	8.9	2.3
5) Least work pressures	5.3	7.3
6) Safe in work environment	6.5	1.2

External stakeholder demands	Impact	Effort
[1] Best returns on investing	6.8	7.8
[2] Good in public benefits	4.4	1.4
[3] Legislation compliance	9.6	2.6
[4] Good in public safety	6.8	5.2
[5] Good for public health	7.1	4.2
[6] Good for social diversity	1.7	3.4

External customer demands	Impact	Effort
(1) Consumer safety	8.3	1.4
(2) Consumer health	8.4	2.4
(3) Compliance in product	8.6	1.3
(4) Best in service	9.4	7.4
(5) Least costs on product	6.8	2.4

Internal stakeholder needs	Impact	Effort
1] Competitive advantage	6.1	4.4
2] Good to be a leader	8.2	8.8
3] Good for globalization	6.3	5.8
4] Good for collaboration	4.6	3.3
5] Least operation costs	9.5	2.9

Figure 5.1: Priority Matrix for Analyzing VOCs of SSCM

The customer requirements with high priority levels (in terms of impact) in Figure 5.1 are listed in Table 5.3.

Table 5.3: Screened Customer Requirements

Screened Customer Requirements	Impact Level	Effort Level
Efficient communication within facilities in supply chains	9.7	1.4
Effective work processes within facilities in supply chains	9.8	2.2
Employee rights protection throughout the supply chains	8.9	2.3
Protect the safety while employees are working	6.5	1.2
Assure consumer safety while they consume products/services	8.3	1.4
Protect consumer health while they consume products/services	8.4	2.4
Provide the compliance in products/services as claimed	8.6	1.3
Minimize the cost of clients consuming products/services	6.8	2.4
Minimize managerial or operations costs throughout supply chains	9.5	2.9
Comply with the legislations on economic, environment, and society	9.6	2.6

Ideally all the VOCs are important to improve the performance of SSCM, though practically it is difficult to adopt all of them together or implement them in one-step. In Table 5.3, we choose those customer requirements that are located within “Do it now” area, where the impact level is from 5.0 to 10.0 and the effort level is from 1.0 to 5.0. After screening the VOCs from the matrix in Table 5.3, the following customer requirements are the first ones to be satisfied:

1) Efficient communication within facilities in supply chains

   This category of customer requirements concentrates on improving the performance of information sharing, data exchange, communication technology application, business collaboration, equipment or system innovation etc.

2) Effective work processes within facilities in supply chains

   This requirement includes implementing standards for work, improving product and/or service quality, order fulfillment rate, handling product returns, business process management, supply management, source management, after sales service, risk management in processes etc.

3) Employee rights protection throughout the supply chains

This requirement includes customer concerns such as human rights, work rights, right to quality for life, training, welfares, employee benefits etc.

4) Protect the safety while employees are working

This requirement includes safety concerns for employees during work such as good working environment, safety control during working etc.

5) Assure consumer safety while they consume products/services

This requirement includes safety concerns for customers during consumption of products or services, that is, they should not be dangerous or explosive and should satisfy the consumers' safety requirements.

6) Protect consumer health while they consume products/services

This requirement includes consumer health protection which means the products or services should be harmless to consumers upon consumption for example avoiding the use of lead in child toys etc.

7) Provide the compliance in products/services as claimed

Customers expect that the products or services have consistent function, characters, price etc. as the companies advertise or claim, therefore, the products or services should not be changed without official declaration.

8) Minimize the cost of clients for consuming products/services

Clients always welcome lower costs for spending on products or services with the same function or characteristics. They sometimes even expect more functions and characters within the same price if there are competitions in the market.

9) Minimize managerial or operational costs throughout supply chains

The internal customers of a supply chain, especially managers, are always making efforts to reduce costs and expenses through all processes and operations of supply chains. External customers such as buyers of products or services also prefer products or services with reduced costs or expenses.

10) Comply with the legislations on economic, environment, and society

The clients who consume the products or services expect the processes of production, services to be legal in terms of following economic regulations, environment legislations, social acts etc. Other customers, such as government (who is the customer of social activities or organizational activities) also expect all activities to be legal.

5.3 Technical Requirements

This part of research will collect the technical requirements by conducting questionnaire surveys (Appendix B) with people at managerial, technical and supervisory levels in supply chain. The collected technical requirements will then be analyzed to identify areas for improving the performance of sustainable supply chains.

5.3.1 Collecting Technical Requirements

In order to collect technical requirements, we developed a questionnaire survey (T-REQ) based on the concept of SERVQUAL [107]. SERVQUAL has been used in many situations, especially in service quality assessment.

Based on the technical factors summarized in Table 5.1, T-REQ (Appendix B) was designed for surveying managerial and professional people in the supply chain and collecting their thoughts on what technical factors should be considered in improving the performance of SSCM, investigating their relationships with each other and with customer requirements.

Figure 5.2 illustrates a cause-and-effect diagram developed through brainstorming to analyze all the technical requirements for improving the performance of SSCM. It can be seen in Figure 5.2 that there are three main factors namely the economical factors, the environmental factors, and the social factors. Besides, certain uncertainties may also exist in sustainable supply chains.

Using the results of the cause-and-effect diagram and the questionnaire survey, we acquired information on technical requirements that are most important in SSCM, the ones to be implemented, relationship between them, their competitive level with respect to traditional supply chains etc.

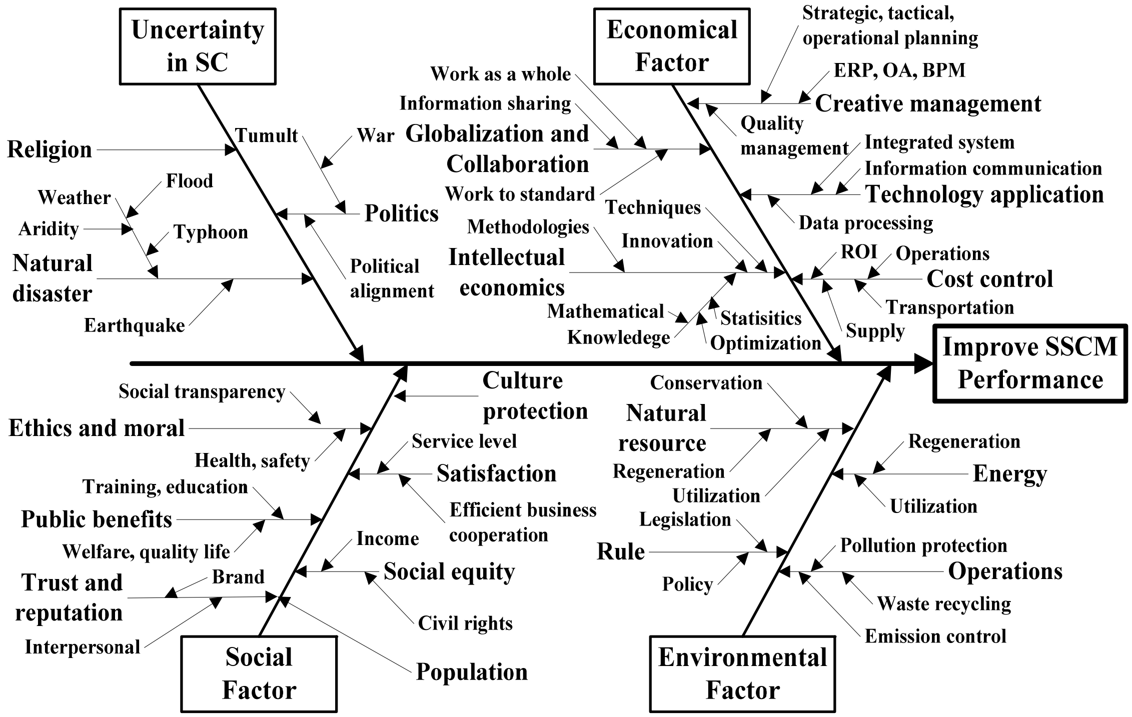


Figure 5.2: Cause-and-Effect Analysis for SSCM Technical Factors

Although there exist different technical requirements for different stages in supply chains, in our research we will concentrate on the general technical requirements for SSCND. That is, strategic planning of SSCND is the main objective rather than solving an operational SSCND problem. Hence, the data are representatively collected from the professionals researching and instructing in the areas of SCM, instead of surveying from a group of managerial people in a supply chain. Four out of four respondents have indicated their feedbacks in surveys. The data collected is shown in Table 5.4.

Table 5.4: Technical Requirements of SSCM Indicated by Respondents

Technical Requirements	EXP.	PER.
Economical Factors		
E1: Costs and expenses control	8.25	7.50
E2: Reach the high business profitability	9.00	8.50
E3: Widely apply new technology and integrated systems	7.25	6.00
E4: Efficient business process management, activity operations	8.75	6.50
E5: Apply the optimization techniques or methodologies in SCs	6.75	4.50
E6: Collaborative operations among facilities in SCs	8.50	9.50
Environmental Factors		
N1: Good environment operation, such as pollution and waste prevention	9.25	7.25
N2: High efforts in utilizing natural resources, such as mining, exploring	8.25	2.00
N3: High efforts in conserving natural resources	7.25	1.75
N4: High efforts of natural resource regeneration, such as reuse	9.25	1.00
N5: Effective energy utilization, such as fossil energy, bio energy	8.25	0.75
N6: High efforts of planning and conducting environment policy	4.75	4.25
N7: High compliance in environment legislations	3.75	9.00
Social Factors		
S1: High satisfaction of customers and business partners in SCs	7.75	8.00
S2: High efforts to manage business trust and reputation, as product compliance	7.75	9.00
S3: High efforts in the social equity, such as salary, work load	8.00	4.00
S4: High efforts in public benefits, such as provide training, welfare	8.50	4.25
S5: High efforts in culture protection, such as respect personal culture habits	2.75	8.00
S6: High efforts in business ethics and moral attempts	4.50	7.00
Uncertainty Factors		
U1: Natural environment decides the performance of SSCM	0.50	6.00
U2: The politics satisfaction decides the performance of SSCM	2.25	1.50
U3: The religion situation decides the performance of SSCM	0.25	1.00

5.3.2 Analyzing Technical Requirements

The data collected from the questionnaire survey T-REQ is shown in Table 5.4. The index "EXP." means the "Expectation" level, or the expected degree of performance of the relevant technical factor for SSCM. Similarly, the index "PER." means the "Perception" level, or the perceived degree of performance with respect to the chosen technical factor for SSCM. Each number for "EXP." and "PER." in Table 5.4 is the average of total scores by the evaluations from four respondents for the different questions of T-REQ survey (Appendix B).

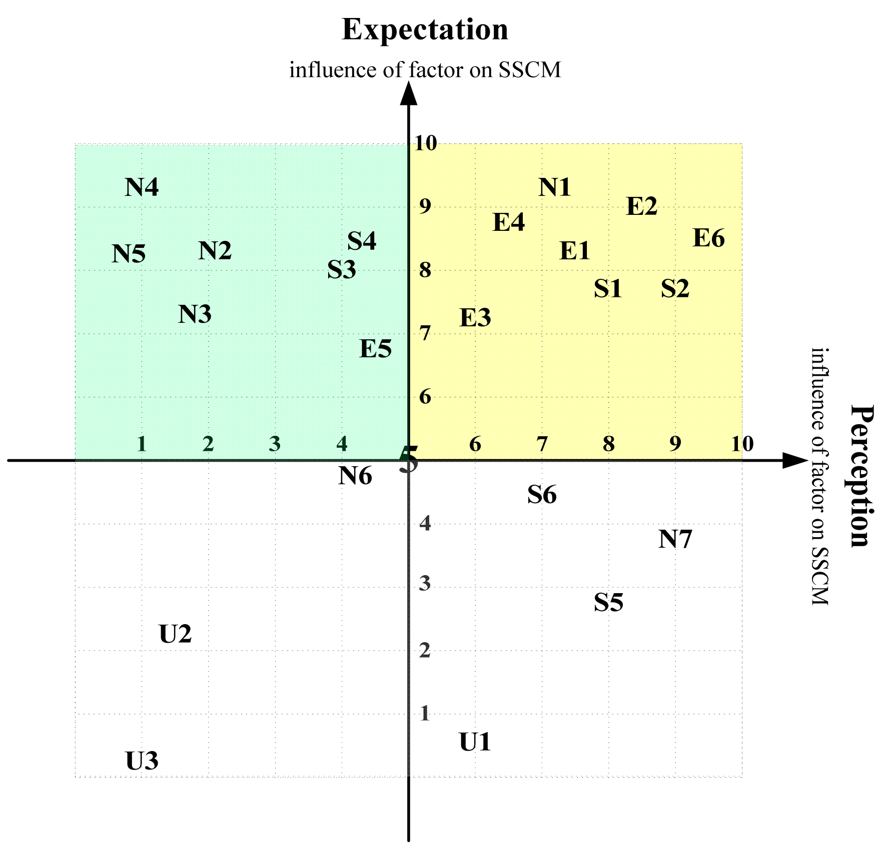


Figure 5.3: Screening Technical Requirements for SFD

Figure 5.3 presents a graphical illustration of the technical factors data obtained from Table 5.4. All the technical factors with “EXP.” levels higher than the average level (EXP = 5) are considered important and used in SFD for designing sustainable supply chain networks. The details of these factors are presented as follows:

1) Cost control

   This design attribute includes E1 and E2. That is, the cost factor is one of crucial elements that affect the performance of SSCM. The costs refer to operational costs, product costs, managerial expenses, tax, and so on. Hence, “Cost control” is a general indicator for all the cost-based technical requirements.

2) New technology application and innovation

   This factor derived from E3, which means new technology is one of crucial factors to improve the performance of SSCM such as ERP system, EMS system, RFID, OA, and so on.

3) Operation processes and procedures optimization

   This category generalizes E4, E5, and E6. It emphasizes that the methodologies, techniques, new knowledge of SC operations will highly impact the performance of SSCM. Furthermore, collaboration will become more and more important for SSCM.

4) Environmental operations

   Environmental operations indicate the technical requirement N1. This factor denotes that effectively managing the activities and processes, such as pollution prevention, emission control, waste recycling etc. will positively impact the performance of SSCM.

5) Natural resource utilization, regeneration, and reservation

This factor contains N2, N3, and N4. There are many topics in this category, such as natural resource exploration, mining, recycling bio species conservation, and so on. Effective and efficient implementation of these factors will positively affect the performance of SSCM.

6) Energy utilization and regeneration

This technical requirement about energy utilization and regeneration indicates N5, which includes how to improve the efficiency of energy utilization, how to achieve energy regeneration, how to save the energy, etc.

7) Improve service level for customers and business partners

This technical factor implies the matters of S1 namely improving the customer service level and the satisfactions of stakeholders in SC such as reducing the order processing and delivery time, reducing the risks from suppliers and so on.

8) Improve business trust and reputation operations

This factor, namely, S2 is concentrating on improving business trust, interpersonal trust, product brand reputation etc to improve the performance of SSCM. This can be achieved through methods or techniques such as quality in product design, compliance in product and services, best-in-class program, best-in-best program, and so on.

9) Efforts for improving public benefits and social equity

This factor includes S3 and S4, in which public safety, public health, training, social rights, economic equity, quality of life etc are emphasized for improving the performance of SSCM.

5.4 Establishing SFD and Evaluating the Weights

This section will establish the SFD. Based on the results of surveys C-REQ and T-REQ, the SFD will integrate the customer requirements with technical requirements to show their relationships and generate weights or ratings for each of them.

5.4.1 Relationships between Customer and Technical Requirements

Figure 5.4 shows the customer and technical requirements obtained from sections 5.1 and 5.2. The interrelationships between them are presented on a 3-level scale in the center matrix enclosed between the customer and technical requirements. The number 9 represents high level of correlation, 3 medium, and 1 means a low level of correlation. Responses from four professional respondents were used to obtain the relationships between customer requirements and technical requirements.

Customer Requirements \ Technical Requirements	Cost control	New technology application and innovation	Operation processes and procedures optimization	Environment friendly operations	Natural resource utilization, regeneration, and conservation	Energy utilization and regeneration	Improve service level for customers and business partners	Improve business trust and reputation operations	Efforts for improving public benefits and social equity
Efficient communication within facilities in supply chains	Δ	●	●				o		
Effective work processes within facilities in supply chains	o	●	●	o			●	o	Δ
Employee rights protection throughout the supply chains	●	o	Δ	Δ			o	Δ	●
Protect the safety while employees are working	●	●	●	o	Δ		●	o	●
Assure consumer safety while they consume products/services	o	●	o	●	Δ	Δ	●	●	o
Protect consumer health while they consume products/services	●	o	Δ	o	Δ		●	●	o
Provide the compliance in products/services as claimed	o	Δ	o				●	●	Δ
Minimal cost of clients consuming products/services	●	●	o	Δ	Δ	o	o	Δ	
Minimal managerial or operation costs throughout supply chains	●	o	●	o	o	o	o	Δ	
Comply with legislations on economic, environment, and society	o	Δ	●	●	o	Δ	Δ	Δ	●

Symbols
- ● =9 (Strong association)
- o =3 (Somewhat association)
- Δ =1 (Weak association)

Figure 5.4: Relationships between Customer and Technical Requirements

5.4.2 Correlations among Technical Requirements

The responses from the questionnaire T-REQ (Appendix B) provided the intercorrelations between the technical requirements presented in the roof of Figure 5.5. A six level scale (+9 (Strong positive), +5 (Positive), +1 (Weak positive), -1 (Weak Negative), -5(Negative), -9 (Strong Negative)) was used.

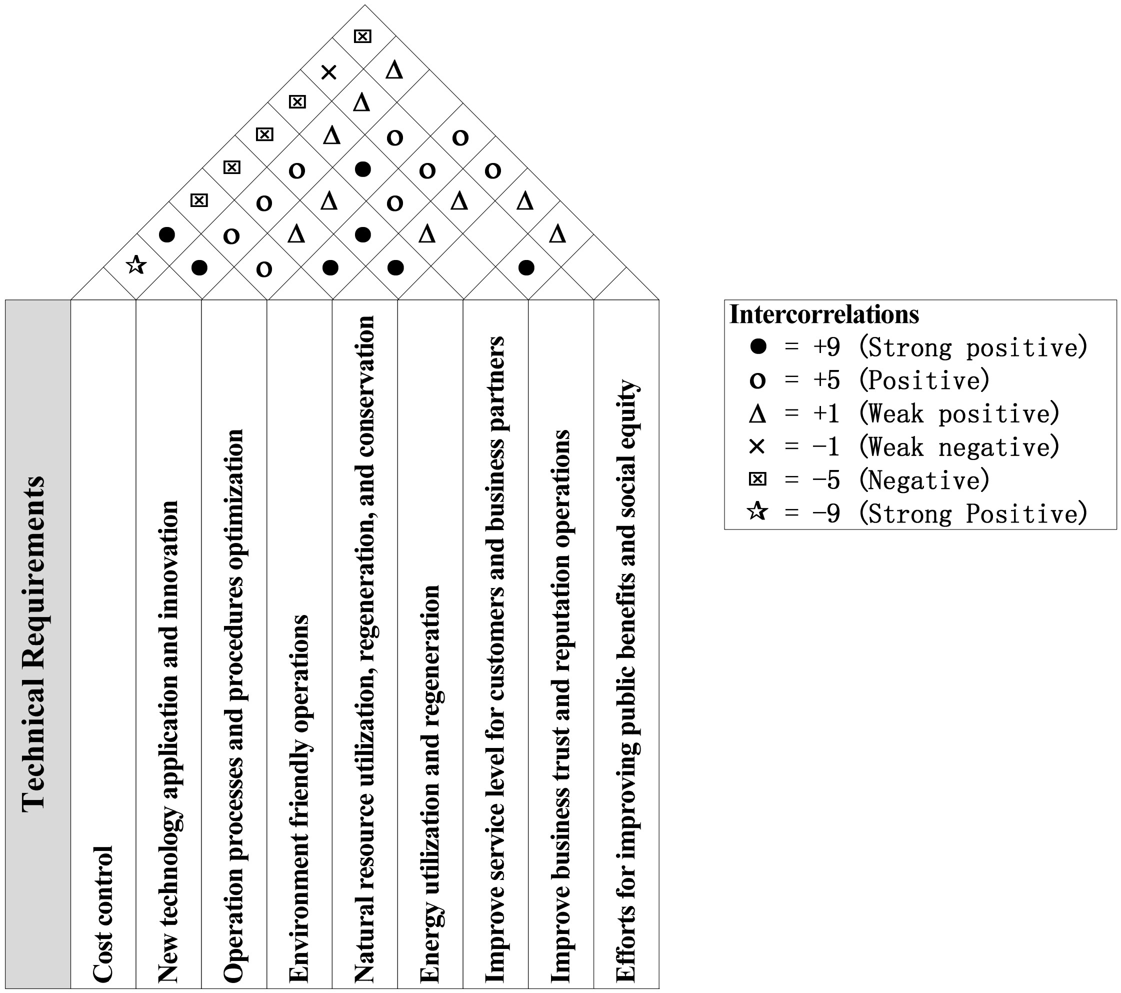


Figure 5.5: Correlation within Technical Requirements

5.4.3 Competitive Assessments

The competitive assessment for four types of supply chains namely Sustainable, Equitable, Reputable, Valuable (Chapter 4) was done from both customer requirements and technical requirements perspective. It can be seen in Figure 5.6 that based on the competitive assessments, sustainable supply chain management has overall higher performance than reputable, equitable, and valuable supply chains. The reason is that

SSCM considers not only one aspect to improve such as reaching economic benefits, satisfying environmental concerns, or fulfilling social performance, but all of them together to optimize the total performance of supply chain. Other types of supply chains only achieve partial successes when compared with SSCM on these three dimensions.

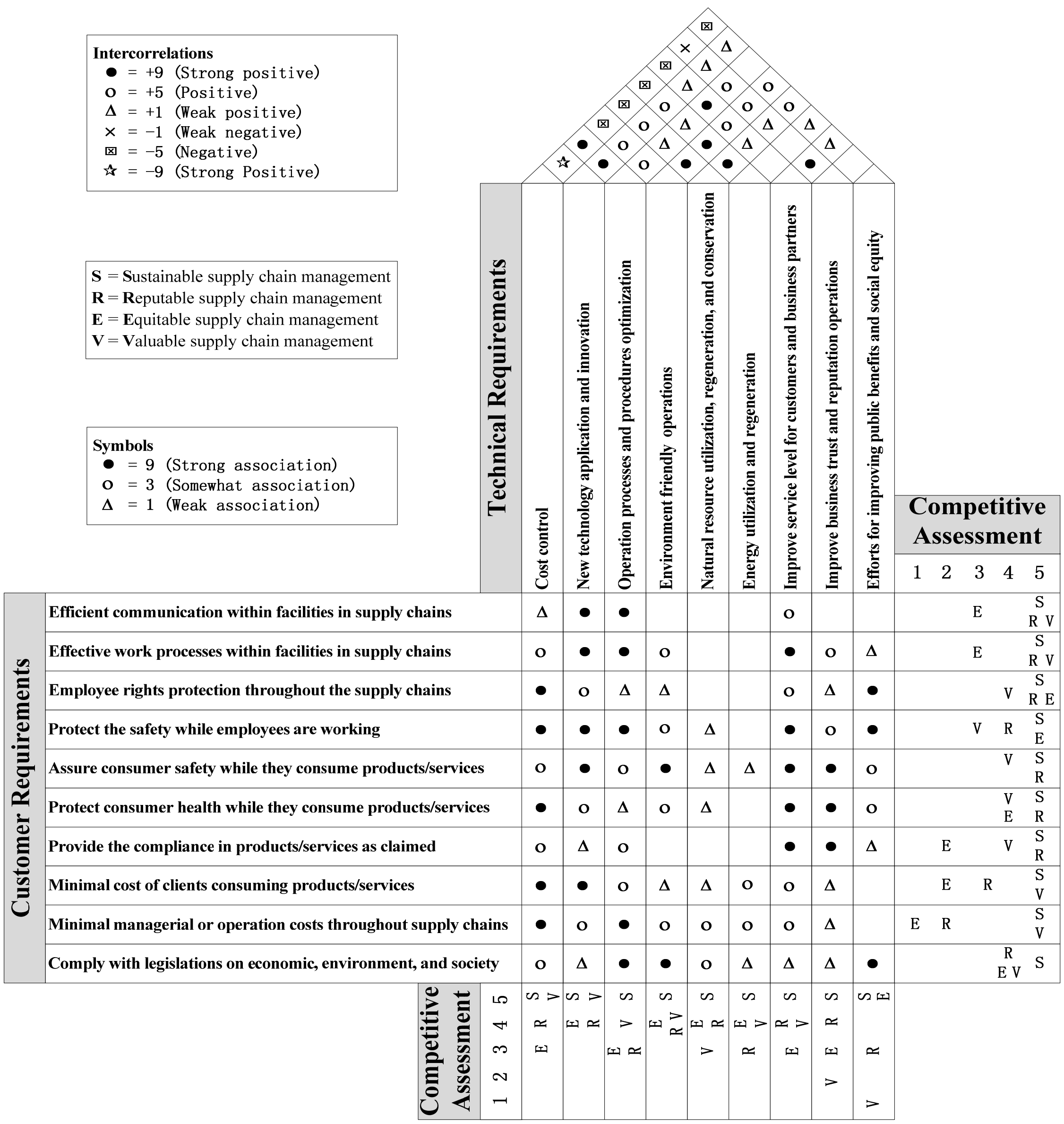
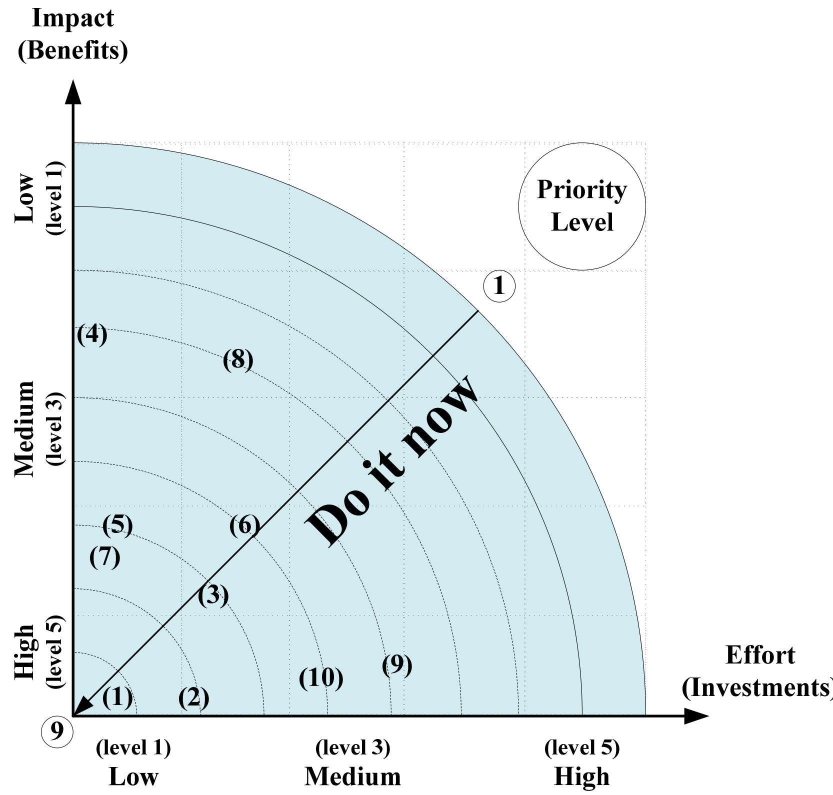


Figure 5.6: Competitive Assessments of Customer and Technical Requirements

In Figure 5.6, for the same customer requirements and technical requirements in a supply chain, the competitive assessments show that the sustainable supply chain management has higher total performance than reputable supply chain management, equitable supply chain management, and valuable supply chain management. The reason is that SSCM considers not only one aspect to improve economic benefits, satisfy environmental concerns, or fulfill social performance, but integrates all three factors together to optimize the total performance of supply chains. Thus, other types of supply chains only achieve partial successes when compared with SSCM.

5.4.4 Weighting Customer and Technical Requirements

Figure 5.1 showed the priority allocations for customer requirements in terms of impacts and efforts. To establish their weights in SFD, we developed a priority analysis matrix (Figure 5.7). It can be seen in Figure 5.7 that the impacts (Y-axis) and efforts (X-axis) are categorized into five-levels. To obtain the priority numbers, we divide the "Do it now" area into nine partitions, in which the priority level ranges from the highest (No. nine) to the lowest (No. one). After this standardization, the customer requirements are represented on the priority analysis matrix on a scale of 1-9. The customer requirements located in the "Do it now" area are high priority requirements.



	Customer Requirements	Impact Level	Effort Level	Priority
(1)	Efficient communication within facilities in supply chains	9.7 – 5 ≈ 5	1.4 ≈ 1	9
(2)	Effective work processes within facilities in supply chains	9.8 – 5 ≈ 5	2.2 ≈ 2	8
(3)	Employee rights protection throughout the supply chains	8.9 – 5 ≈ 4	2.3 ≈ 2	7
(4)	Protect the safety while employees are working	6.5 – 5 ≈ 2	1.2 ≈ 1	4
(5)	Assure consumer safety while they consume products/services	8.3 – 5 ≈ 4	1.4 ≈ 1	6
(6)	Protect consumer health while they consume products/services	8.4 – 5 ≈ 4	2.4 ≈ 2	5
(7)	Provide the compliance in products/services as claimed	8.6 – 5 ≈ 4	1.3 ≈ 1	7
(8)	Minimal cost of clients consuming products/services	6.8 – 5 ≈ 2	2.4 ≈ 2	3
(9)	Minimal managerial or operation costs throughout supply chains	9.5 – 5 ≈ 5	2.9 ≈ 3	4
(10)	Comply with legislations on economic, environment, and society	9.6 – 5 ≈ 5	2.6 ≈ 3	6

Figure 5.7: Priority Analysis for Satisfying Customer Requirements

In Figure 5.8, the SFD table integrates all the numerical relationships between the customer and technical requirements. The priority level in the SFD table for customer requirements is based on the priority ratings by customer (Figure 5.7). Using these numerical values, we generate priority weights for customer and technical requirements.

Three key points that should be considered in performing these calculations are:

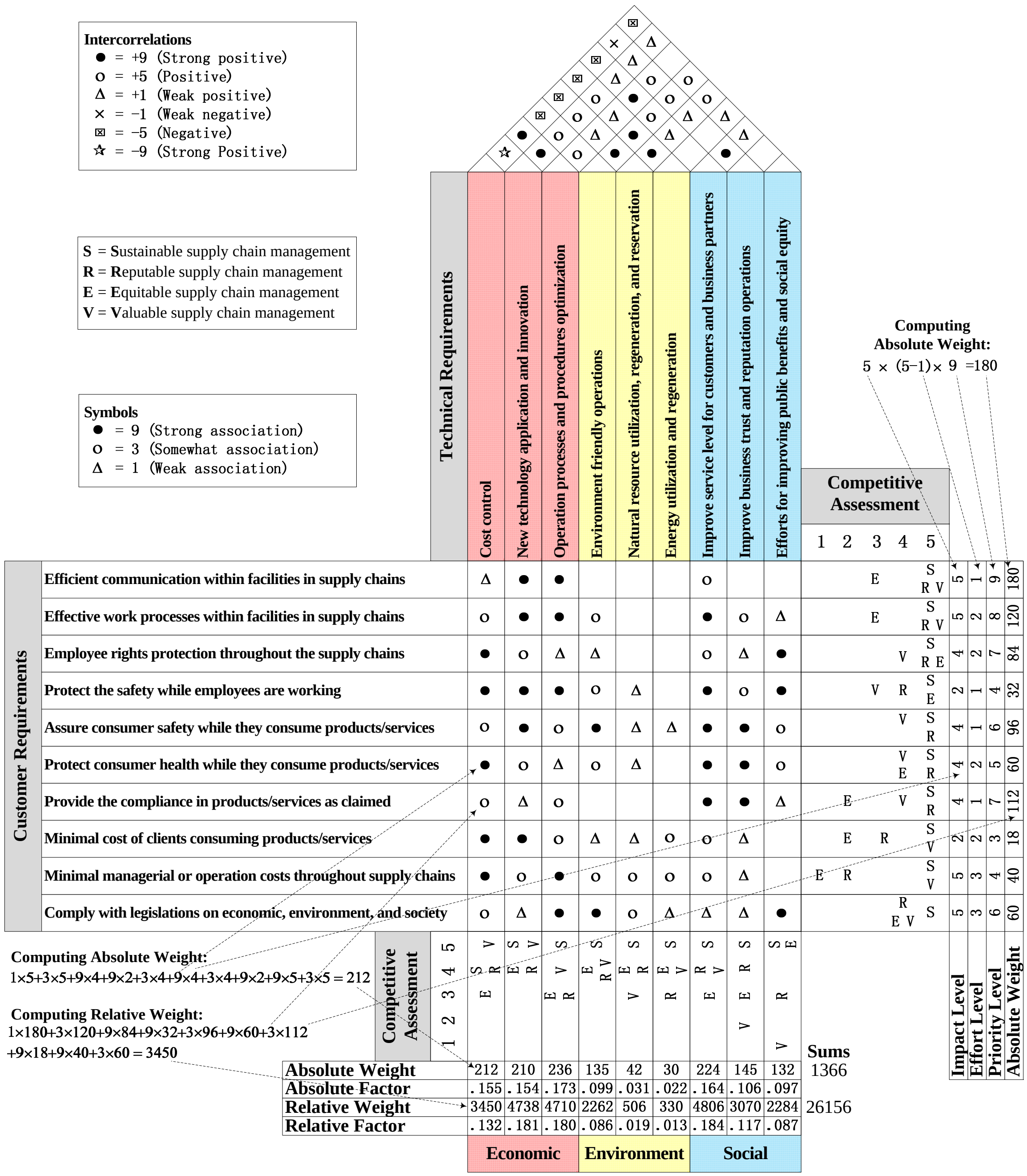


Figure 5.8: Weights Analysis in SFD

1) *Calculation of absolute weights for customer requirements.*

This takes into account the impact level, effort level and priority level for each customer requirement. To fulfill a customer requirement, it should have a higher priority level and a lower effort level. The priority sequence of actions to fulfill customer requirements is in terms of their absolute weights from a higher level to the lower level. These absolute weights have considered the priorities of impacts and efforts. Therefore, to calculate the absolute weight of each customer requirement, we propose the highest effort level (five) minus its current effort level. This method will obviously magnify the values and differentiate priorities for satisfying customer requirements.

2) *Calculation of absolute weights of technical requirements.*

This is based on the relationships of technical requirements with customer requirements and the impact levels of customer requirements. A technical requirement with a higher score of absolute weight has higher priority to be adopted as a key factor for improving the performance of SSCM. However, the absolute weights partially demonstrate the importance degrees of technical requirements to the performance of SSCM since only impact levels of customer requirements are used.

3) *Calculation of relative weight of technical requirements.*

This considers the priority levels of customer requirements and the numerical relationships between technical requirements and customer requirements in calculations. The relative weights constructively indicate the priority sequence to adopt technical factors to improve the performance of SSCM.

It can be seen from the results of Figure 5.8 that the relative weights of economic factors is 0.493, 0.118 for environmental factors, and 0.388 for social factors. That means, based on the results of our surveys, economic factor is more important followed by social and environmental categories. Please note our goal in this section is to demonstrate the utility of SFD in weighting customer and technical requirements. The results obtained from SFD are highly dependent on the ratings provided in C-REQ and T-REQ, therefore, the selection of number of respondents, their familiarity with the subject and experience with SSCM should be carefully evaluated before launching the questionnaire surveys.

5.5 Contribution of SFD in SSCND

The sustainable supply chain network design is a strategic decision that integrates the objectives of economic benefits, environment concerns, and social requirements to achieve sustainable performance in processes, activities, and operations throughout the supply chain. Using the SFD analysis, we were able to integrate the Economical, Environmental and Social dimensions altogether. Variables addressing these dimensions from customer requirements and technical requirements point of view were studied in detail. Their interrelationships were analyzed to finally generate priority scores for both customer (absolute requirements) and technical requirements (relative weights) which will be used in prioritizing different objectives in the mathematical programming model for designing sustainable supply chain network in the next stage of our thesis.

Chapter 6

Model Development for SSCND

6.1 Assumptions

Based on the framework described in section 5.5, three main factors are considered in SSCND namely “economical benefits”, “environmental concerns”, and “social needs”. Each of these factors has different weights. We will mathematically represent these factors in terms of costs namely social, economic and environmental costs for different stages of the supply chain. Before developing the mathematical model, following assumptions are used:

1. The supply involves four stages (Figure 6.1).

    1) Stage one: Supplier – Manufacturer

    2) Stage two: Manufacturer – Distributor or Wholesaler

    3) Stage three: Distributor – Retailer

    4) Stage four: Retailer – Customer

    The facilities involved in the different stages of the supply chain are manufacturing units, warehouses, distribution platforms, retail stores etc.

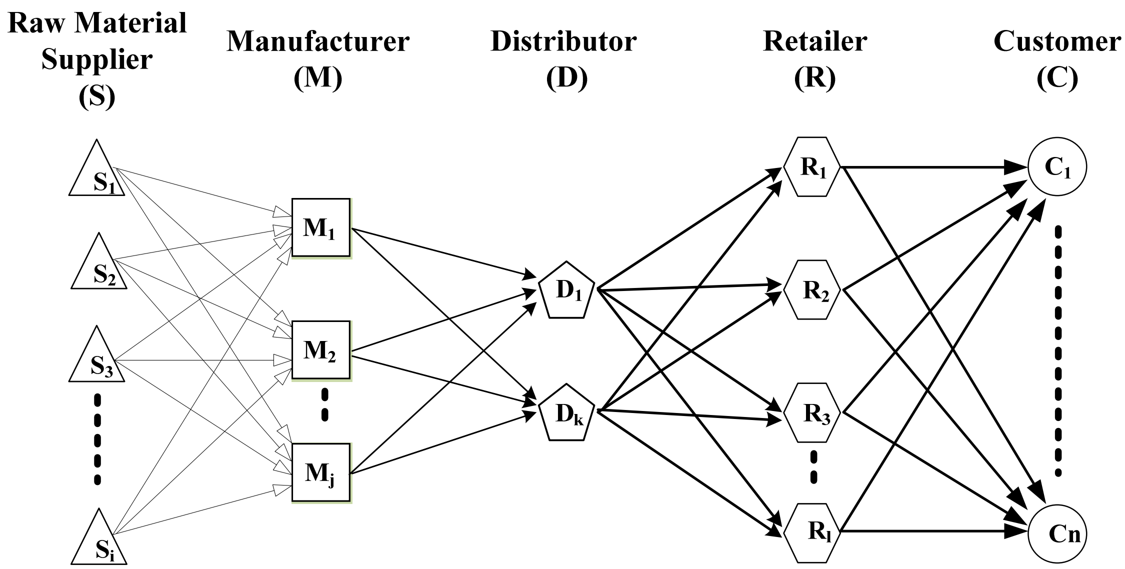


Figure 6.1: A Four-stage Supply Chain

2. All the facilities at different stages of the supply chain (Figure 6.1) are interconnected to each other. For example, each supplier is connected to all the manufacturing units and vice versa. This implies that the raw material can be procured from any of the suppliers for any manufacturer (subject to capacity and demand restrictions); all manufacturers are eligible to supply semi-finished products to distributors or wholesaler; all distributors for finished products supply to any of the retailers; and finally all retailers can supply package products to customers.
3. It is possible to have different weights for economical, environmental and social costs at different stages in supply chains. In Chapter 5, we showed different weights 0.493:0.118:0.388 for economical benefits, environmental concerns, and social needs. This ratio was derived from the results of surveying the customers and managerial

people throughout the supply chains. In this thesis, the modeler assumes that the ratios are the same for different stages of the supply chains. However, specific managerial requirements may require usage of different ratios for different stages of supply chain.

4. In our model, the Bill of Material involves the usage of 1:1 ratio of products at any stage until final delivery to customer. This implies one unit of finished product involves usage of one unit and one kind of semi-finished materials that again requires usage of one type of raw material only. In reality, several raw materials may be required to achieve at a finished product, however, we have kept the 1:1 product usage ratio to avoid computational complexity arising from complex BOM in our model that already is computationally challenging considering the three objectives and size of the supply chain network.

6.2 Mathematical Notations

Sets

S	- Set of raw material suppliers
M	- Set of manufacturers
D	- Set of distributors
R	- Set of retailers
C	- Set of customers

Parameters

- *Number of suppliers to be selected*

$Ns =$ Total number of raw material suppliers

$Nm =$ Total number of manufacturers

$Nd =$ Total number of distributors

$Nr =$ Total number of retailers

- *Weights of the three objectives*

$w^{ec} =$ Weight of economical costs

$w^{en} =$ Weight of environmental costs

$w^{so} =$ Weight of social costs

- *Facility opening costs*

$Cl_i^s =$ Facility opening cost for the raw material supplier i; $i \in S$

$Cl_j^m =$ Facility opening cost for the manufacturer j; $j \in M$

$Cl_k^d =$ Facility opening cost for the distributor k; $k \in D$

$Cl_l^r =$ Facility opening cost for the retailer l; $l \in R$

- *Transportation costs*

$Ct_{j,i}^{sm} =$ Transportation cost per unit to supply materials from raw material supplier i to manufacturer j; $i \in S, j \in M$

$Ct_{k,j}^{md} =$ Transportation cost per unit to supply semi-finished products from manufacturer j to distributor k; $j \in M, k \in D$

$Ct_{l,k}^{dr}$ = Transportation cost per unit to supply finished products from distributor k to retailer l; $l \in R, k \in D$

$Ct_{n,l}^{rc}$ = Transportation cost per unit to supply assembled products from retailer l to customer n; $n \in C, l \in R$

- *Environmental costs*

$Ce_{j,i}^{sm}$ = Environmental cost per unit to supply materials from raw material supplier i to manufacturer j; $i \in S, j \in M$

$Ce_{k,j}^{md}$ = Environmental cost per unit to supply semi-finished products from manufacturer j to distributor k; $j \in M, k \in D$

$Ce_{l,k}^{dr}$ = Environmental cost per unit to supply finished products from distributor k to retailer l; $l \in R, k \in D$

$Ce_{n,l}^{rc}$ = Environmental cost per unit to supply assembled products from retailer l to customer n; $n \in C, l \in R$

- *Social costs*

$Cs_{j,i}^{sm}$ = Social cost per unit to supply materials from raw material supplier i to manufacturer j; $i \in S, j \in M$

$Cs_{k,j}^{md}$ = Social cost per unit to supply semi-finished products from manufacturer j to distributor k; $j \in M, k \in D$

$Cs_{l,k}^{dr}$ = Social cost per unit to supply finished products from distributor k to retailer l; $l \in R, k \in D$

$Cs^{rc}_{n,l}$ = Social cost per unit to supply assembled products from retailer l to customer n ; $n \in C, l \in R$

- *Supply capacities*

Cps_i = Raw material supply capacity of supplier i ; $i \in S$

Cpm_j = Semi-finished product supply capacity of manufacturer j ; $j \in M$

Cpd_k = Finished product supply capacity of distributor k ; $k \in D$

Cpr_l = Assembled product supply capacity of retailer l ; $l \in R$

- *Demands from customers*

Dem_n = Finished product demands from the customer n ; $n \in C$

Decision Variables

- *Supplier selection (Assuming supplier is different for each stage)*

x^s_i = Decision variable to select the raw material supplier i if $x^s_i = 1$, else 0; $i \in S$

x^m_j = Decision variable to select the manufacturer j if $x^m_j = 1$, else 0; $j \in M$

x^d_k = Decision variable to select the distributor k if $x^d_k = 1$, else 0; $k \in D$

x^r_l = Decision variable to select the whole seller/retailer l if $x^r_l = 1$, else 0; $l \in R$

- *Order quantity allocation*

$q_{j,i}^{sm} =$ Order quantity of raw materials shipped from raw supplier i to manufacturer j; $i \in S,\ j \in M$

$q_{k,j}^{md} =$ Order quantity of semi-finished product shipped from manufacturer j to distributor k; $j \in M, k \in D$

$q_{l,k}^{dr} =$ Order quantity of finished product shipped from distributor k to retailer l; $k \in D, l \in R$

$q_{n,l}^{rc} =$ Order quantity of assembled product shipped from retailer l to customer n; $l \in R, n \in C$

6.3 Problem Formulation

Our mathematical model for sustainable supply chain network design minimizes the facility selection costs, transportation costs, environmental costs, and social costs, and performs order quantity allocations for facilities at different stages of the supply chain considering the demand and capacity constraints. The mathematical description of the problem is presented as follows:

Minimize $z = Economical\ Costs + Environmental\ Costs + Social\ Costs$ (6.1)

$$= w^{ec}\left(\sum_{i \in S} x_i^s Cl_i^s + \sum_{j \in M} x_j^m Cl_j^m + \sum_{k \in D} x_k^d Cl_k^d + \sum_{l \in R} x_l^r Cl_l^r \right)$$

$$+ w^{ec}\left(\sum_{j \in M}\sum_{i \in S} q_{j,i}^{sm} Ct_{j,i}^{sm} + \sum_{k \in D}\sum_{j \in M} q_{k,j}^{md} Ct_{k,j}^{md} + \sum_{l \in R}\sum_{k \in D} q_{l,k}^{dr} Ct_{l,k}^{dr} + \sum_{n \in C}\sum_{l \in R} q_{n,l}^{rc} Ct_{n,l}^{dr} \right)$$

$$+ w^{en}\left(\sum_{j \in M}\sum_{i \in S} q_{j,i}^{sm} Ce_{j,i}^{sm} + \sum_{k \in D}\sum_{j \in M} q_{k,j}^{md} Ce_{k,j}^{md} + \sum_{l \in R}\sum_{k \in D} q_{l,k}^{dr} Ce_{l,k}^{dr} + \sum_{n \in C}\sum_{l \in R} q_{n,l}^{rc} Ce_{n,l}^{rc} \right)$$

$$+ w^{so}\left(\sum_{j \in M}\sum_{i \in S} q_{j,i}^{sm} Cs_{j,i}^{sm} + \sum_{k \in D}\sum_{j \in M} q_{k,j}^{md} Cs_{k,j}^{md} + \sum_{l \in R}\sum_{k \in D} q_{l,k}^{dr} Cs_{l,k}^{md} + \sum_{n \in C}\sum_{l \in R} q_{n,l}^{rc} Cs_{n,l}^{md} \right)$$

Subject to

$$\sum_{j \in M} q_{j,i}^{sm} \le x_i^s Cps_i \ , \forall i \qquad (6.2)$$

$$\sum_{k \in D} q_{k,j}^{md} \le x_j^m Cpm_j \ , \forall j \qquad (6.3)$$

$$\sum_{l \in R} q_{l,k}^{dr} \le x_k^d Cpd_k \ , \forall k \qquad (6.4)$$

$$\sum_{n \in C} q_{n,l}^{rc} \le x_l^r Cpr_l \ , \forall l \qquad (6.5)$$

$$\sum_{i \in S} q_{j,i}^{sm} = \sum_{k \in D} q_{k,j}^{md} \ , \forall j \qquad (6.6)$$

$$\sum_{j \in M} q_{k,j}^{md} = \sum_{l \in R} q_{l,k}^{dr} \ , \forall k \qquad (6.7)$$

$$\sum_{k \in D} q_{l,k}^{dr} = \sum_{n \in C} q_{n,l}^{rc} \ , \forall l \qquad (6.8)$$

$$\sum_{l \in R} q_{n,l}^{rc} = Dem_n \ , \forall n \qquad (6.9)$$

$$\sum_{i \in S} x_i^s \le Ns \qquad (6.10)$$

$$\sum_{j \in M} x_j^m \le Nm \qquad (6.11)$$

$$\sum_{k \in D} x_k^d \le Nd \qquad (6.12)$$

$$\sum_{l \in R} x_l^r \le Nr \qquad (6.13)$$

$$x_i^s \in \{0,1\}, \quad x_j^m \in \{0,1\}, \quad x_k^d \in \{0,1\}, \quad x_l^r \in \{0,1\}, \quad \forall i, j, k, l, n$$

$$q_{j,i}^{sm} \geq 0, \quad q_{k,j}^{md} \geq 0, \quad q_{l,k}^{dr} \geq 0, \quad q_{n,l}^{rc} \geq 0, \quad \forall i, j, k, l, n$$

It can be seen in objective function (6.1) that different costs are weighted according to the category they belong to (w^{ec} , w^{en} , and w^{so}).

The constraints from (6.2) to (6.5) represent the capacity constraints for the different facilities. These constraints ensure that the total order quantities/allocations to meet buyers demands should be less than the supply capacities of respective facilities at different stages of supply chain.

Constraints (6.6) - (6.8) are the balancing constraints for material flow at different facilities of the supply chain. These constraints imply that the quantity of inflow of materials at any facility is equal to its outflow.

Constraint (6.9) ensures the demand satisfaction constraint for the customer. It implies that quantity of material supplied by the retailer should satisfy the demands from customers/final clients in the market.

Constraints from (6.10) to (6.13) restrict the number of suppliers, manufacturers, distributors, and retailers selected in the sustainable supply chain network design to the maximum values available.

In our model there are four binary variables ($x_i^s, x_j^m, x_k^d, x_l^r \in \{0,1\}, \quad \forall i, j, k, l$) related to selection of suppliers, manufacturers, distributors, and retailers at different stages of the supply chain. Besides, the variables for order quantity allocations for different facilities at various stages of the supply chain are non-negative and real in nature, that is, $q_{j,i}^{sm}, q_{k,j}^{md}, q_{l,k}^{dr}, q_{n,l}^{rc} \geq 0, i, j, k, l, n$

It can be seen from above that our problem is a linear integer programming problem. To solve the problem, we will use the AIMMS optimization software developed by Paragon Decision Inc. The AIMMS software has an advanced development environment for building and experimenting optimization algorithms. The latest version 3.11 of AIMMS has three main components (Figure 6.2) [115]:

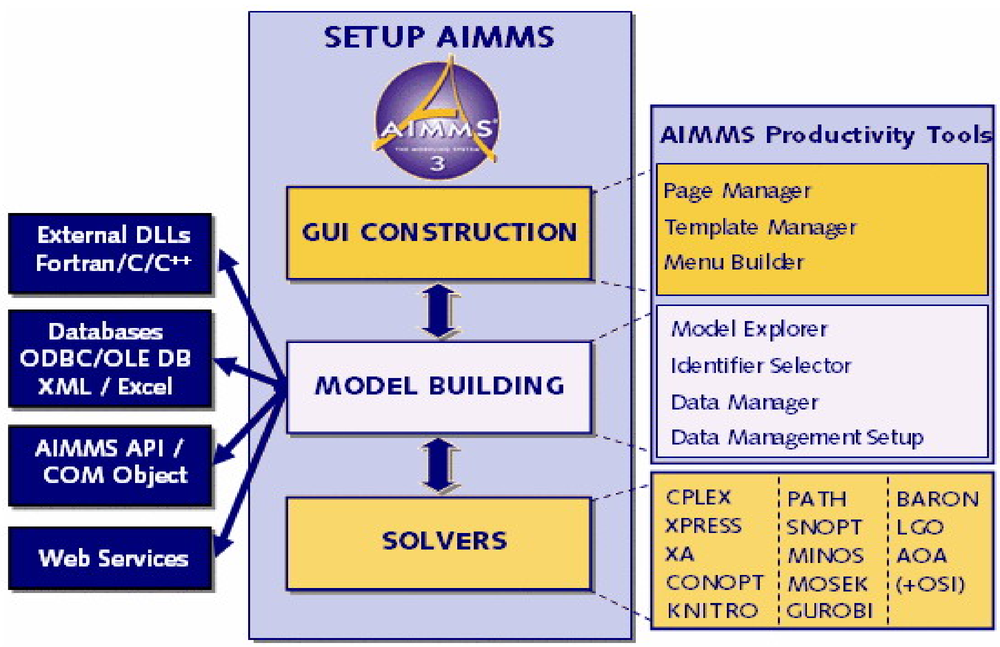


Figure 6.2: Introduction of AIMMS Components

1) Solvers, that allow you to solve both small and large scale mathematical programming problems, such as linear programming (LP), nonlinear programming (NLP), and mixed integer programming (MIP).

2) Mathematical modeling language to build customized mathematical models integrated with external DLLs, databases, API, and web-based applications.

3) Graphical user interface (GUIs) to help design easily understandable and operational interfaces for mathematical models.

AIMMS has a very open and friendly on-line service for software download, operation manual inquiry, license application, access to manuals etc. More details can be found at AIMMS website (www.aimms.com).

6.4 Numerical Example

Let us consider a supply chain network comprising of 4-raw material supplier, 4-manufacturer, 3-distributor, 3-retailer, and 5-customer as shown in Figure 6.3. The objective is to design a sustainable supply chain that satisfies the given customer demands considering the economical, environmental, and social objectives.

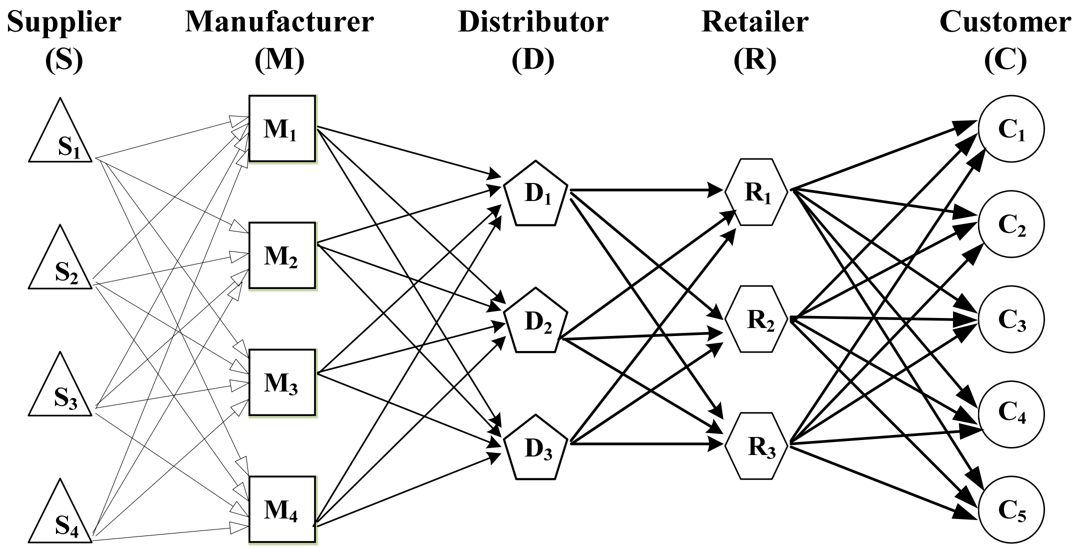


Figure 6.3: The Supply Chain Network for Numerical Example

The input data on transportation costs, social costs and environmental costs for each stage of the supply chain has been presented in Tables 6.1 – 6.4. The weights associated with the three objectives namely Eco: Env: Soc are equal to 0.493:0.118:0.388 (obtained from SFD). The capacities of the different facilities and the customer demands are presented in Table 6.5.

Table 6.1: Data Input for Stage One: Supplier – Manufacturer

Input Data One

Stage One: Raw Material Supplier -- Manufacturer

Facilitiy Cost		Transportation Cost					Environmental Cost					Social Cost				
		i	S1	S2	S3	S4	i	S1	S2	S3	S4	i	S1	S2	S3	S4
i		j					j					j				
S1	49613	M1	30	21	27	16	M1	19	12	11	18	M1	28	13	26	29
S2	21127	M2	22	19	28	19	M2	28	22	22	13	M2	10	21	26	28
S3	44933	M3	16	16	23	13	M3	23	30	15	25	M3	14	15	28	12
S4	45660	M4	24	14	10	24	M4	22	15	18	15	M4	13	29	15	14

Table 6.2: Data Input for Stage Two: Manufacture – Distributor

Input Data Two

Stage Two: Manufacturer -- Distribution Centor

Facilitiy Cost		Transportation Cost						Environmental Cost					Social Cost			
		j	M1	M2	M3	M4	j	M1	M2	M3	M4	j	M1	M2	M3	M4
j		k					k					k				
M1	46333	D1	11	26	15	12	D1	30	14	16	14	D1	12	13	30	28
M2	29023	D2	20	29	19	26	D2	30	15	27	27	D2	16	27	21	29
M3	41699	D3	19	22	15	17	D3	22	11	12	28	D3	27	22	19	11
M4	16732															

Table 6.3: Data Input for Stage Three: Distributor – Retailer

Input Data Three

Stage Three: Distribution Centor -- Retailer

Facilitiy Cost		Transportation Cost				Environmental Cost				Social Cost			
		k	D1	D2	D3	k	D1	D2	D3	k	D1	D2	D3
k		l				l				l			
D1	17624	R1	25	27	21	R1	25	13	27	R1	30	23	23
D2	10717	R2	10	14	21	R2	14	16	24	R2	22	11	20
D3	49482	R3	12	17	19	R3	20	20	29	R3	19	14	21

Table 6.4: Data Input for Stage Four: Retailer – Customer

Input Data Four

Stage Four: Retailer -- Customer

Facilitiy Cost		Transportation Cost				Environmental Cost				Social Cost			
		l	R1	R2	R3	l	R1	R2	R3	l	R1	R2	R3
l		n				n				n			
R1	42688	C1	28	14	14	C1	10	12	29	C1	14	14	30
R2	43094	C2	18	28	27	C2	14	22	23	C2	14	22	26
R3	46456	C3	22	17	20	C3	15	14	28	C3	18	16	29
		C4	16	18	21	C4	26	24	25	C4	19	24	26
		C5	17	11	24	C5	23	13	11	C5	26	23	22

Table 6.5: Facility Capacities and Customer Demands

Demands from Customer		**Supply Capacity of Each Facility**							
		Raw Material Supplier		**Manufacturer**		**Distribution Center**		**Retailer**	
n									
C1	500	i		j		k		l	
C2	1200	S1	3000	M1	8000	D1	9000	R1	6000
C3	2000	S2	1400	M2	5000	D2	10000	R2	3000
C4	800	S3	3809	M3	2000	D3	15000	R3	5000
C5	1600	S4	4000	M4	7000				

The above input data and the supply chain network were fed into the AIMMS software to run the SSCND model. Figure 6.4 demonstrates the results for our numerical example. In the lower left corner in Figure 6.4, we find details on model type, solver, best solution, running time etc. Other details such as variable statistics, constraint solution, etc can also be found on the same screen.

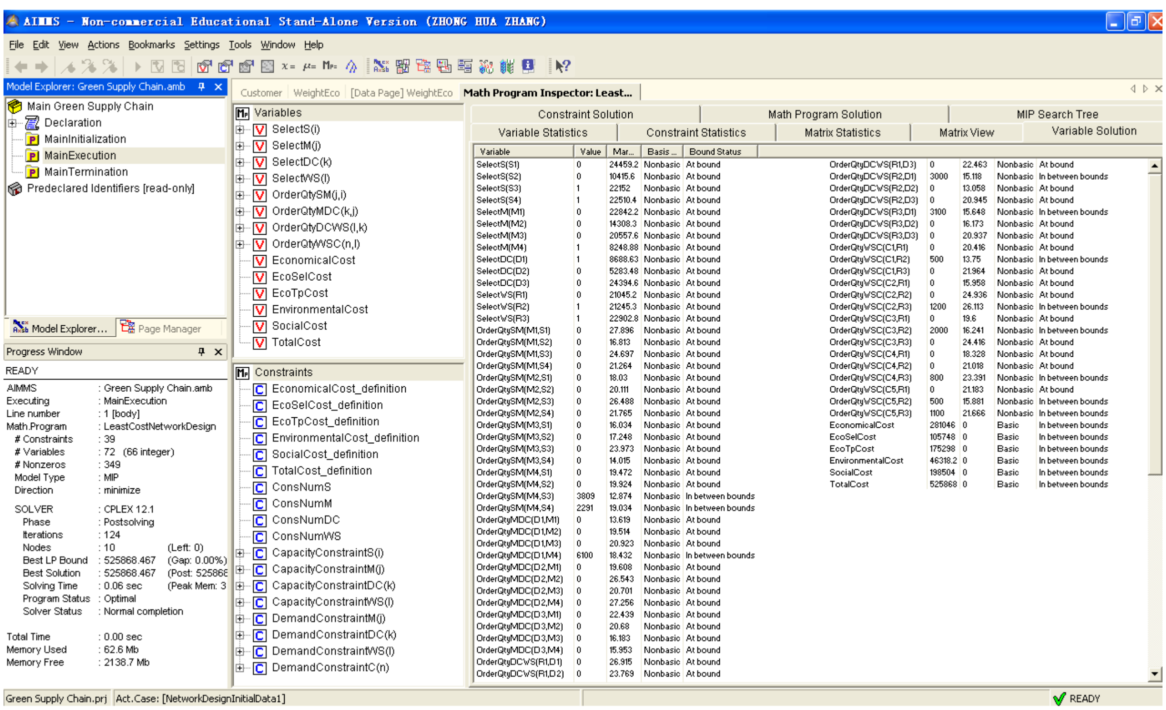


Figure 6.4: Model results from AIMMS

The solution details for the numerical example are presented in Figure 6.5. The suppliers, manufacturers, distributors, retailers finally selected in the sustainable network design have a ‘1” in the column called “value”. The order quantities allocated to them can also be seen in the same column towards the bottom. The final solution has been graphically represented in Figure 6.6.

Variable Statistics | Constraint Statistics | Matrix Statistics | Matrix View

Variable Solution | Constraint Solution | Math Program Solution | MIP Search Tree

Variable	Value	Mar...	Basis ...	Bound Status
SelectS(S1)	0	24459.2	Nonbasic	At bound
SelectS(S2)	0	10415.6	Nonbasic	At bound
SelectS(S3)	1	22152	Nonbasic	At bound
SelectS(S4)	1	22510.4	Nonbasic	At bound
SelectM(M1)	0	22842.2	Nonbasic	At bound
SelectM(M2)	0	14308.3	Nonbasic	At bound
SelectM(M3)	0	20557.6	Nonbasic	At bound
SelectM(M4)	1	8248.88	Nonbasic	At bound
SelectDC(D1)	1	8688.63	Nonbasic	At bound
SelectDC(D2)	0	5283.48	Nonbasic	At bound
SelectDC(D3)	0	24394.6	Nonbasic	At bound
SelectWS(R1)	0	21045.2	Nonbasic	At bound
SelectWS(R2)	1	21245.3	Nonbasic	At bound
SelectWS(R3)	1	22902.8	Nonbasic	At bound
OrderQtySM(M1,S1)	0	27.896	Nonbasic	At bound
OrderQtySM(M1,S2)	0	16.813	Nonbasic	At bound
OrderQtySM(M1,S3)	0	24.697	Nonbasic	At bound
OrderQtySM(M1,S4)	0	21.264	Nonbasic	At bound
OrderQtySM(M2,S1)	0	18.03	Nonbasic	At bound
OrderQtySM(M2,S2)	0	20.111	Nonbasic	At bound
OrderQtySM(M2,S3)	0	26.488	Nonbasic	At bound
OrderQtySM(M2,S4)	0	21.765	Nonbasic	At bound
OrderQtySM(M3,S1)	0	16.034	Nonbasic	At bound
OrderQtySM(M3,S2)	0	17.248	Nonbasic	At bound
OrderQtySM(M3,S3)	0	23.973	Nonbasic	At bound
OrderQtySM(M3,S4)	0	14.015	Nonbasic	At bound
OrderQtySM(M4,S1)	0	19.472	Nonbasic	At bound
OrderQtySM(M4,S2)	0	19.924	Nonbasic	At bound
OrderQtySM(M4,S3)	3809	12.874	Nonbasic	In between bounds
OrderQtySM(M4,S4)	2291	19.034	Nonbasic	In between bounds
OrderQtyMDC(D1,M1)	0	13.619	Nonbasic	At bound
OrderQtyMDC(D1,M2)	0	19.514	Nonbasic	At bound
OrderQtyMDC(D1,M3)	0	20.923	Nonbasic	At bound
OrderQtyMDC(D1,M4)	6100	18.432	Nonbasic	In between bounds
OrderQtyMDC(D2,M1)	0	19.608	Nonbasic	At bound
OrderQtyMDC(D2,M2)	0	26.543	Nonbasic	At bound
OrderQtyMDC(D2,M3)	0	20.701	Nonbasic	At bound
OrderQtyMDC(D2,M4)	0	27.256	Nonbasic	At bound
OrderQtyMDC(D3,M1)	0	22.439	Nonbasic	At bound
OrderQtyMDC(D3,M2)	0	20.68	Nonbasic	At bound
OrderQtyMDC(D3,M3)	0	16.183	Nonbasic	At bound
OrderQtyMDC(D3,M4)	0	15.953	Nonbasic	At bound
OrderQtyDCWS(R1,D1)	0	26.915	Nonbasic	At bound
OrderQtyDCWS(R1,D2)	0	23.769	Nonbasic	At bound
OrderQtyDCWS(R1,D3)	0	22.463	Nonbasic	At bound
OrderQtyDCWS(R2,D1)	3000	15.118	Nonbasic	In between bounds
OrderQtyDCWS(R2,D2)	0	13.058	Nonbasic	At bound
OrderQtyDCWS(R2,D3)	0	20.945	Nonbasic	At bound
OrderQtyDCWS(R3,D1)	3100	15.648	Nonbasic	In between bounds
OrderQtyDCWS(R3,D2)	0	16.173	Nonbasic	At bound
OrderQtyDCWS(R3,D3)	0	20.937	Nonbasic	At bound
OrderQtyWSC(C1,R1)	0	20.416	Nonbasic	At bound
OrderQtyWSC(C1,R2)	500	13.75	Nonbasic	In between bounds
OrderQtyWSC(C1,R3)	0	21.964	Nonbasic	At bound
OrderQtyWSC(C2,R1)	0	15.958	Nonbasic	At bound
OrderQtyWSC(C2,R2)	0	24.936	Nonbasic	At bound
OrderQtyWSC(C2,R3)	1200	26.113	Nonbasic	In between bounds
OrderQtyWSC(C3,R1)	0	19.6	Nonbasic	At bound
OrderQtyWSC(C3,R2)	2000	16.241	Nonbasic	In between bounds
OrderQtyWSC(C3,R3)	0	24.416	Nonbasic	At bound
OrderQtyWSC(C4,R1)	0	18.328	Nonbasic	At bound
OrderQtyWSC(C4,R2)	0	21.018	Nonbasic	At bound
OrderQtyWSC(C4,R3)	800	23.391	Nonbasic	In between bounds
OrderQtyWSC(C5,R1)	0	21.183	Nonbasic	At bound
OrderQtyWSC(C5,R2)	500	15.881	Nonbasic	In between bounds
OrderQtyWSC(C5,R3)	1100	21.666	Nonbasic	In between bounds
EconomicalCost	281046	0	Basic	In between bounds
EcoSelCost	105748	0	Basic	In between bounds
EcoTpCost	175298	0	Basic	In between bounds
EnvironmentalCost	46318.2	0	Basic	In between bounds
SocialCost	198504	0	Basic	In between bounds
TotalCost	525868	0	Basic	In between bounds

Figure 6.5: Variable Values for the SSCND Numerical Example

It can be seen in Figure 6.6 that two suppliers (S3, S4), one manufacturer (M4), one distributor (D1), and two retailers (R2, R3) are finally chosen to meet an overall customer demand of 6100. The numbers in dark represent the capacities of the respective facilities whereas the numbers in light color represent the order quantities allocated to them. It can be seen that capacities and demand constraints are respected at each stage of the supply chain.

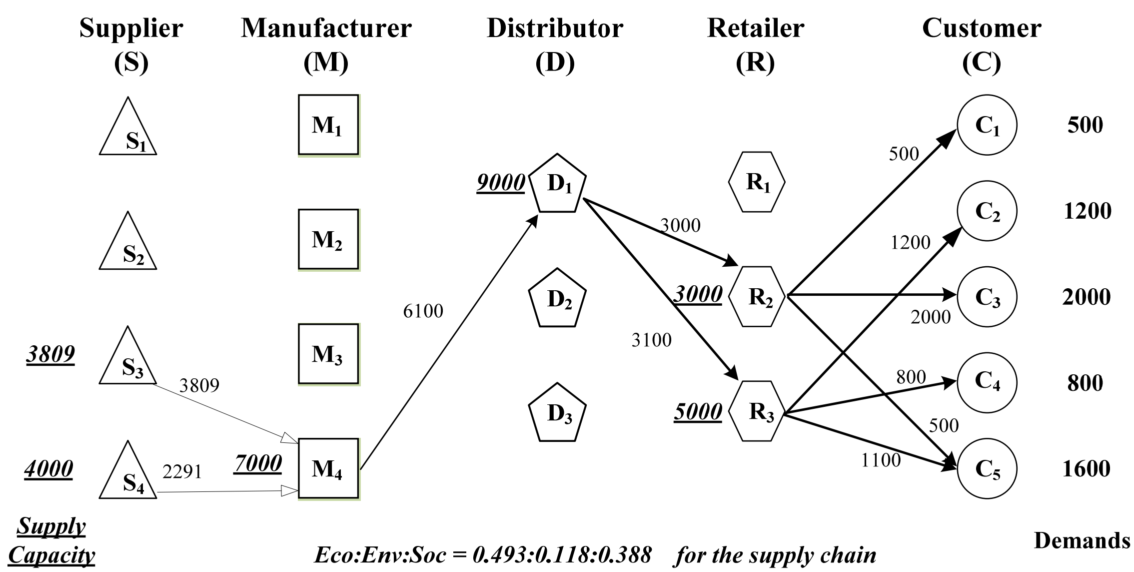


Figure 6.6: The Topology of SSCN for the Numerical Example

Table 6.6: Costs Distribution of SSCND for Numerical Example

AIMMS Outputs

The Costs:	Economical Costs	Environmental Costs	Social Costs	The Total Costs
AIMMS Optimal Results:	281046	46318	198504	565828
The Weight Used:	×0.493	×0.118	×0.388	

Table 6.6 presents the results for the objective function or total costs incurred in designing the sustainable supply chain network. The overall costs are 565828 out of

which 281046 is attributed to Economic category, 46318 to the environmental category and 198504 to the social category.

6.5 Scenario Analysis

To verify the model results, we conducted scenario analysis. These scenarios are related to change in weights of socio-economic-environmental objectives, change in supply capacities of facilities and demands of customers and change in the size of the supply chain network. The details of the different scenarios along with the results obtained are presented as follows:

6.5.1 Scenario 1 (Change in Weights of Objective Functions)

The first scenario addresses the change in weights of social, economic and environmental costs used in the objective function. From SFD, we obtained the weights 0.493:0.118:0.388 for the Economic:Environmental:Social category. The different weight categories that will be addressed in the scenario analysis are shown in Table 6.7.

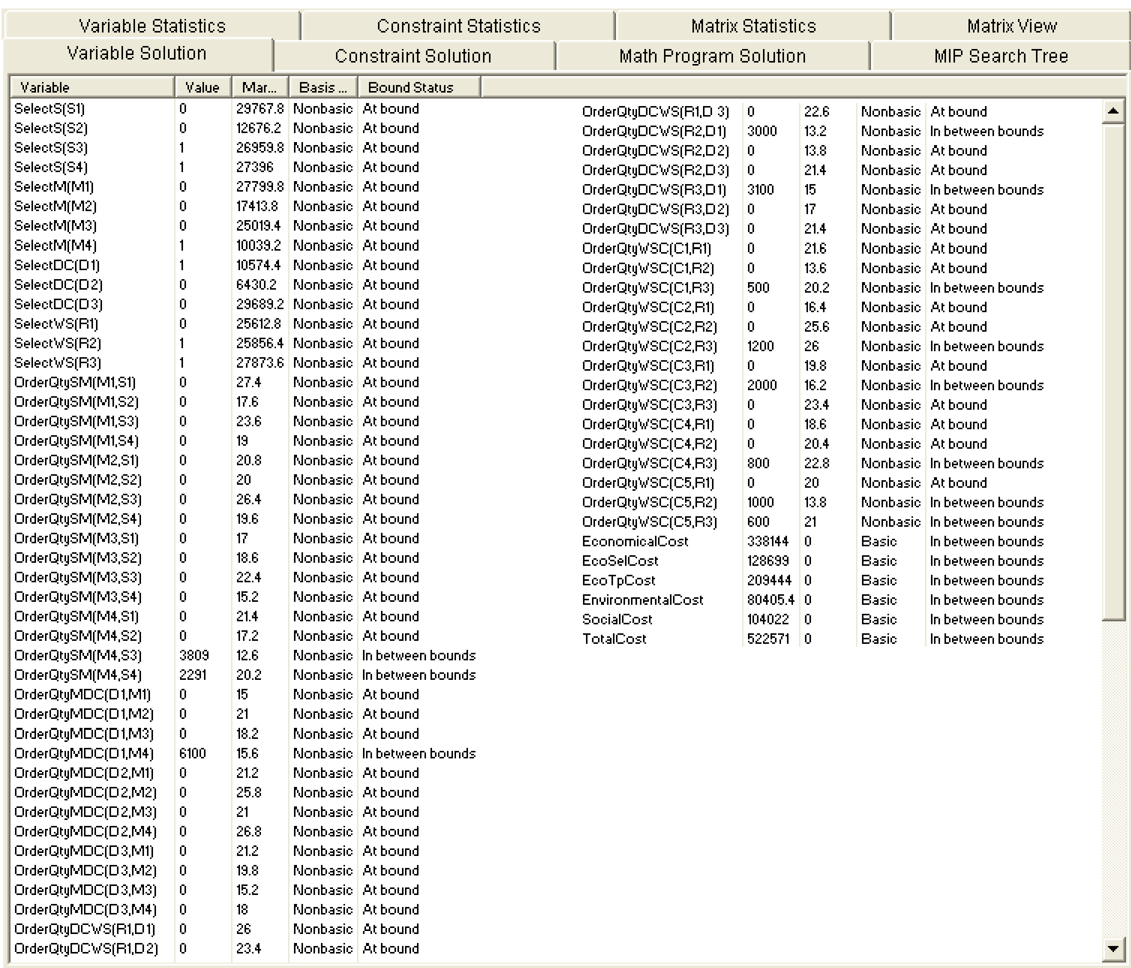
Table 6.7: Weights for Scenario Analysis

	w^{ec}	w^{en}	w^{so}
Test 1	0.6	0.2	0.2
Test 2	0.2	0.6	0.2
Test 3	0.2	0.2	0.6
Test 4	0.333	0.333	0.333

It can be seen in Table 6.7 that there are four categories of tests. In Test 1, the economic costs have highest weight; in Test 2 the environmental costs have the highest weight whereas in Test 3, the social costs have highest weight. In Test 4, all the three costs have equal weights. The results for the different tests are presented as follows:

1. Test 1 (Weight ratio 0.6:0.2:0.2 (Eco:Env:Soc)).

The outputs from AIMMS for Test 1 scenario are shown in Figure 6.7. It can be seen that suppliers S3 and S4, manufacturer M4, distributor D1, and retailers R2 and R3 are finally selected.



Variable	Value	Mar...	Basis ...	Bound Status
SelectS(S1)	0	29767.8	Nonbasic	At bound
SelectS(S2)	0	12676.2	Nonbasic	At bound
SelectS(S3)	1	26959.8	Nonbasic	At bound
SelectS(S4)	1	27396	Nonbasic	At bound
SelectM(M1)	0	27799.8	Nonbasic	At bound
SelectM(M2)	0	17413.8	Nonbasic	At bound
SelectM(M3)	0	25019.4	Nonbasic	At bound
SelectM(M4)	1	10039.2	Nonbasic	At bound
SelectDC(D1)	1	10574.4	Nonbasic	At bound
SelectDC(D2)	0	6430.2	Nonbasic	At bound
SelectDC(D3)	0	29689.2	Nonbasic	At bound
SelectWS(R1)	0	25612.8	Nonbasic	At bound
SelectWS(R2)	1	25856.4	Nonbasic	At bound
SelectWS(R3)	1	27873.6	Nonbasic	At bound
OrderQtySM(M1,S1)	0	27.4	Nonbasic	At bound
OrderQtySM(M1,S2)	0	17.6	Nonbasic	At bound
OrderQtySM(M1,S3)	0	23.6	Nonbasic	At bound
OrderQtySM(M1,S4)	0	19	Nonbasic	At bound
OrderQtySM(M2,S1)	0	20.8	Nonbasic	At bound
OrderQtySM(M2,S2)	0	20	Nonbasic	At bound
OrderQtySM(M2,S3)	0	26.4	Nonbasic	At bound
OrderQtySM(M2,S4)	0	19.6	Nonbasic	At bound
OrderQtySM(M3,S1)	0	17	Nonbasic	At bound
OrderQtySM(M3,S2)	0	18.6	Nonbasic	At bound
OrderQtySM(M3,S3)	0	22.4	Nonbasic	At bound
OrderQtySM(M3,S4)	0	15.2	Nonbasic	At bound
OrderQtySM(M4,S1)	0	21.4	Nonbasic	At bound
OrderQtySM(M4,S2)	0	17.2	Nonbasic	At bound
OrderQtySM(M4,S3)	3809	12.6	Nonbasic	In between bounds
OrderQtySM(M4,S4)	2291	20.2	Nonbasic	In between bounds
OrderQtyMDC(D1,M1)	0	15	Nonbasic	At bound
OrderQtyMDC(D1,M2)	0	21	Nonbasic	At bound
OrderQtyMDC(D1,M3)	0	18.2	Nonbasic	At bound
OrderQtyMDC(D1,M4)	6100	15.6	Nonbasic	In between bounds
OrderQtyMDC(D2,M1)	0	21.2	Nonbasic	At bound
OrderQtyMDC(D2,M2)	0	25.8	Nonbasic	At bound
OrderQtyMDC(D2,M3)	0	21	Nonbasic	At bound
OrderQtyMDC(D2,M4)	0	26.8	Nonbasic	At bound
OrderQtyMDC(D3,M1)	0	21.2	Nonbasic	At bound
OrderQtyMDC(D3,M2)	0	19.8	Nonbasic	At bound
OrderQtyMDC(D3,M3)	0	15.2	Nonbasic	At bound
OrderQtyMDC(D3,M4)	0	18	Nonbasic	At bound
OrderQtyDCWS(R1,D1)	0	26	Nonbasic	At bound
OrderQtyDCWS(R1,D2)	0	23.4	Nonbasic	At bound
OrderQtyDCWS(R1,D3)	0	22.6	Nonbasic	At bound
OrderQtyDCWS(R2,D1)	3000	13.2	Nonbasic	In between bounds
OrderQtyDCWS(R2,D2)	0	13.8	Nonbasic	At bound
OrderQtyDCWS(R2,D3)	0	21.4	Nonbasic	At bound
OrderQtyDCWS(R3,D1)	3100	15	Nonbasic	In between bounds
OrderQtyDCWS(R3,D2)	0	17	Nonbasic	At bound
OrderQtyDCWS(R3,D3)	0	21.4	Nonbasic	At bound
OrderQtyWSC(C1,R1)	0	21.6	Nonbasic	At bound
OrderQtyWSC(C1,R2)	0	13.6	Nonbasic	At bound
OrderQtyWSC(C1,R3)	500	20.2	Nonbasic	In between bounds
OrderQtyWSC(C2,R1)	0	16.4	Nonbasic	At bound
OrderQtyWSC(C2,R2)	0	25.6	Nonbasic	At bound
OrderQtyWSC(C2,R3)	1200	26	Nonbasic	In between bounds
OrderQtyWSC(C3,R1)	0	19.8	Nonbasic	At bound
OrderQtyWSC(C3,R2)	2000	16.2	Nonbasic	In between bounds
OrderQtyWSC(C3,R3)	0	23.4	Nonbasic	At bound
OrderQtyWSC(C4,R1)	0	18.6	Nonbasic	At bound
OrderQtyWSC(C4,R2)	0	20.4	Nonbasic	At bound
OrderQtyWSC(C4,R3)	800	22.8	Nonbasic	In between bounds
OrderQtyWSC(C5,R1)	0	20	Nonbasic	At bound
OrderQtyWSC(C5,R2)	1000	13.8	Nonbasic	In between bounds
OrderQtyWSC(C5,R3)	600	21	Nonbasic	In between bounds
EconomicalCost	338144	0	Basic	In between bounds
EcoSelCost	128699	0	Basic	In between bounds
EcoTpCost	209444	0	Basic	In between bounds
EnvironmentalCost	80405.4	0	Basic	In between bounds
SocialCost	104022	0	Basic	In between bounds
TotalCost	522571	0	Basic	In between bounds

Figure 6.7: Results of Test 1, Scenario 1

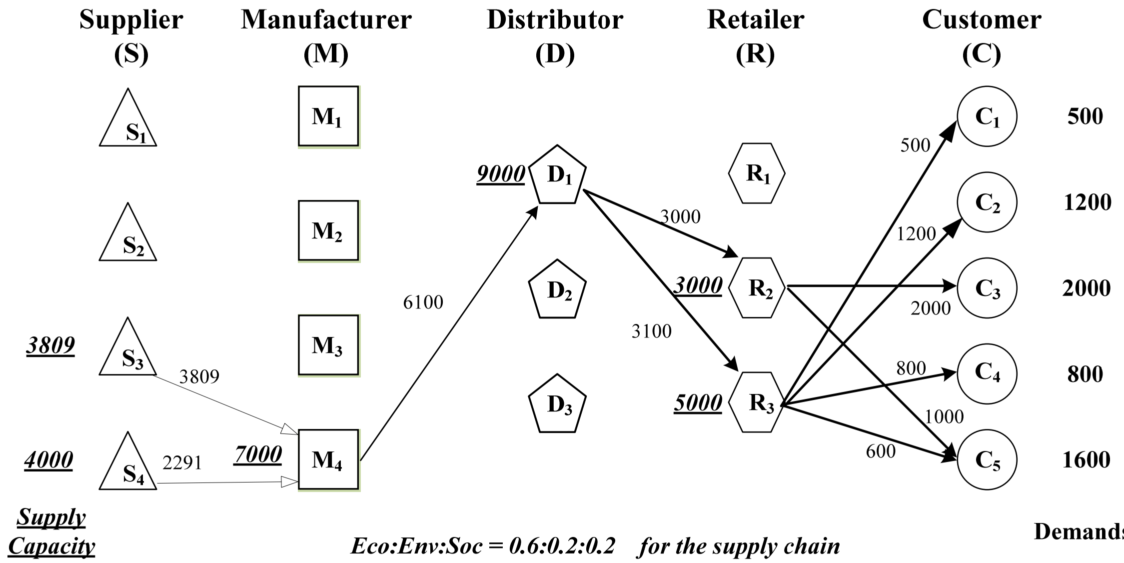


Figure 6.8: The Topology of SSCN for Test 1, Scenario 1

The results are graphically represented in Figure 6.8. The order quantity allocations for S3 and S4 are 3809 and 2291 respectively, manufacturer M4 is 6100, distributor D1 is 6100, and retailers R2 and R3 is 3000 and 3100 respectively. It can be seen that the capacity constraints are satisfied at all stages of the supply chain.

The total cost or objective function value for the network design represented in Figure 6.8 is shown in Table 6.8. The economical costs are 338144, environmental costs are 80405 and social costs are 104022 making a total cost of 522571.

Table 6.8: Costs Distribution for Test 1, Scenario 1

AIMMS Outputs

The Costs:	Economical Costs	Environmental Costs	Social Costs	The Total Costs
AIMMS Optimal Results:	338144	80405	104022	522571
The Weight Used:	×0.6	×0.2	×0.2	

2. Test 2 (weight ratio 0.2:0.6:0.2 (Eco:Env:Soc)).

The outputs from AIMMS for Test 2 scenario are shown in the Figure 6.9. It can be seen that suppliers S3 and S4, manufacturer M4, distributor D1, and retailers R2 and R3 are finally selected.

Variable Statistics | Constraint Statistics | Matrix Statistics | Matrix View
Variable Solution | Constraint Solution | Math Program Solution | MIP Search Tree

Variable	Value	Ma...	Basis ...	Bound Status
SelectS(S1)	0	9922.6	Nonbasic	At bound
SelectS(S2)	0	4225.4	Nonbasic	At bound
SelectS(S3)	1	8986.6	Nonbasic	At bound
SelectS(S4)	1	9132	Nonbasic	At bound
SelectM(M1)	0	9266.6	Nonbasic	At bound
SelectM(M2)	0	5804.6	Nonbasic	At bound
SelectM(M3)	0	8339.8	Nonbasic	At bound
SelectM(M4)	1	3346.4	Nonbasic	At bound
SelectDC(D1)	1	3524.8	Nonbasic	At bound
SelectDC(D2)	0	2143.4	Nonbasic	At bound
SelectDC(D3)	0	9896.4	Nonbasic	At bound
SelectWS(R1)	0	8537.6	Nonbasic	At bound
SelectWS(R2)	1	8618.8	Nonbasic	At bound
SelectWS(R3)	1	9291.2	Nonbasic	At bound
OrderQtySM(M1,S1)	0	23	Nonbasic	At bound
OrderQtySM(M1,S2)	0	14	Nonbasic	At bound
OrderQtySM(M1,S3)	0	17.2	Nonbasic	At bound
OrderQtySM(M1,S4)	0	19.8	Nonbasic	At bound
OrderQtySM(M2,S1)	0	23.2	Nonbasic	At bound
OrderQtySM(M2,S2)	0	21.2	Nonbasic	At bound
OrderQtySM(M2,S3)	0	24	Nonbasic	At bound
OrderQtySM(M2,S4)	0	17.2	Nonbasic	At bound
OrderQtySM(M3,S1)	0	19.8	Nonbasic	At bound
OrderQtySM(M3,S2)	0	24.2	Nonbasic	At bound
OrderQtySM(M3,S3)	0	19.2	Nonbasic	At bound
OrderQtySM(M3,S4)	0	20	Nonbasic	At bound
OrderQtySM(M4,S1)	0	20.6	Nonbasic	At bound
OrderQtySM(M4,S2)	0	17.6	Nonbasic	At bound
OrderQtySM(M4,S3)	3809	15.8	Nonbasic	In between bounds
OrderQtySM(M4,S4)	2291	16.6	Nonbasic	In between bounds
OrderQtyMDC(D1,M1)	0	22.6	Nonbasic	At bound
OrderQtyMDC(D1,M2)	0	16.2	Nonbasic	At bound
OrderQtyMDC(D1,M3)	0	18.6	Nonbasic	At bound
OrderQtyMDC(D1,M4)	6100	16.4	Nonbasic	In between bounds
OrderQtyMDC(D2,M1)	0	25.2	Nonbasic	At bound
OrderQtyMDC(D2,M2)	0	20.2	Nonbasic	At bound
OrderQtyMDC(D2,M3)	0	24.2	Nonbasic	At bound
OrderQtyMDC(D2,M4)	0	27.2	Nonbasic	At bound
OrderQtyMDC(D3,M1)	0	22.4	Nonbasic	At bound
OrderQtyMDC(D3,M2)	0	15.4	Nonbasic	At bound
OrderQtyMDC(D3,M3)	0	14	Nonbasic	At bound
OrderQtyMDC(D3,M4)	0	22.4	Nonbasic	At bound
OrderQtyDCWS(R1,D1)	0	26	Nonbasic	At bound
OrderQtyDCWS(R1,D2)	0	17.8	Nonbasic	At bound
OrderQtyDCWS(R1,D3)	0	25	Nonbasic	At bound
OrderQtyDCWS(R2,D1)	3000	14.8	Nonbasic	In between bounds
OrderQtyDCWS(R2,D2)	0	14.6	Nonbasic	At bound
OrderQtyDCWS(R2,D3)	0	22.6	Nonbasic	At bound
OrderQtyDCWS(R3,D1)	3100	18.2	Nonbasic	In between bounds
OrderQtyDCWS(R3,D2)	0	18.2	Nonbasic	At bound
OrderQtyDCWS(R3,D3)	0	25.4	Nonbasic	At bound
OrderQtyWSC(C1,R1)	0	14.4	Nonbasic	At bound
OrderQtyWSC(C1,R2)	500	12.8	Nonbasic	In between bounds
OrderQtyWSC(C1,R3)	0	26.2	Nonbasic	At bound
OrderQtyWSC(C2,R1)	0	14.8	Nonbasic	At bound
OrderQtyWSC(C2,R2)	0	23.2	Nonbasic	At bound
OrderQtyWSC(C2,R3)	1200	24.4	Nonbasic	In between bounds
OrderQtyWSC(C3,R1)	0	17	Nonbasic	At bound
OrderQtyWSC(C3,R2)	2000	15	Nonbasic	In between bounds
OrderQtyWSC(C3,R3)	0	26.6	Nonbasic	At bound
OrderQtyWSC(C4,R1)	0	22.6	Nonbasic	At bound
OrderQtyWSC(C4,R2)	500	22.8	Nonbasic	In between bounds
OrderQtyWSC(C4,R3)	300	24.4	Nonbasic	In between bounds
OrderQtyWSC(C5,R1)	0	22.4	Nonbasic	At bound
OrderQtyWSC(C5,R2)	0	14.6	Nonbasic	At bound
OrderQtyWSC(C5,R3)	1600	15.8	Nonbasic	In between bounds
EconomicalCost	115015	0	Basic	In between bounds
EcoSelCost	42899.8	0	Basic	In between bounds
EcoTpCost	72114.8	0	Basic	In between bounds
EnvironmentalCost	234616	0	Basic	In between bounds
SocialCost	102022	0	Basic	In between bounds
TotalCost	451653	0	Basic	In between bounds

Figure 6.9: Results for Test 2, Scenario 1

The results are graphically represented in Figure 6.9. The order quantity allocations for S3 and S4 are 3809 and 2291 respectively, manufacturer M4 is 6100, distributor D1 is

6100, and retailers R2 and R3 is 3000 and 3100 respectively. It can be seen that the capacity constraints are satisfied at all stages of the supply chain.

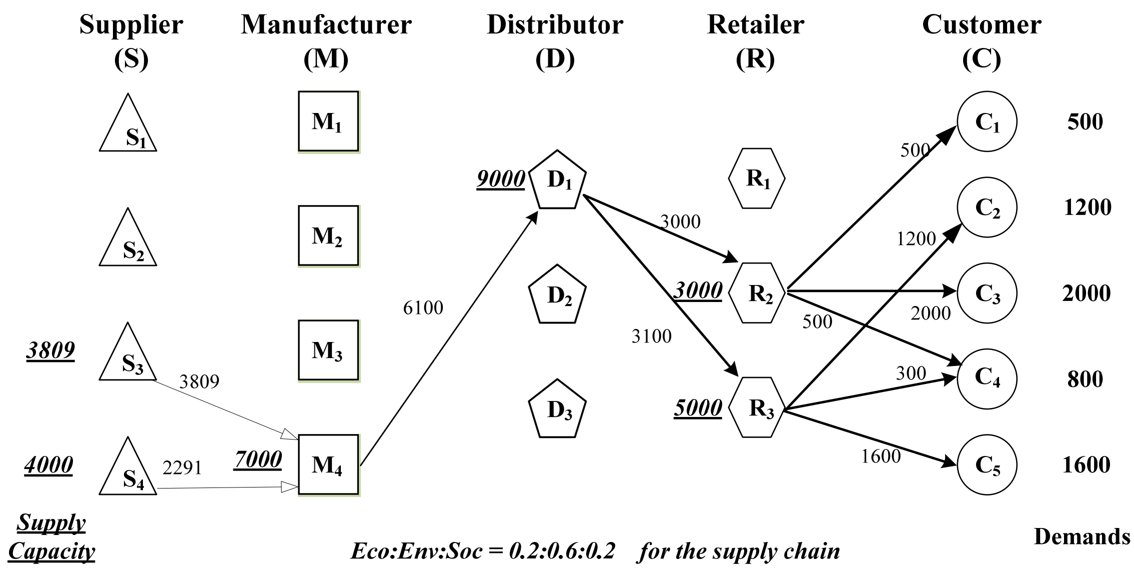


Figure 6.10: The Topology of SSCN for Test 2, Scenario 1

The total cost or objective function value for the network design represented in Figure 6.10 is shown in Table 6.9. The economical costs are 115015, environmental costs are 234616 and social costs are 102022 making a total cost of 451653.

Table 6.9: Costs Distribution for Test 2, Scenario 1

AIMMS Outputs

The Costs:	Economical Costs	Environmental Costs	Social Costs	The Total Costs
AIMMS Optimal Results:	115015	234616	102022	451653
The Weight Used:	×0.2	×0.6	×0.2	

3. Test 3 (Weight ratio 0.2:0.2:0.6 (Eco:Env:Soc)).

The outputs from AIMMS for the Test 3 are presented in Figure 6.11. It can be seen that suppliers S3 and S4, manufacturer M4, distributor D3, and retailers R1 and R2 are finally selected.

Variable Statistics | Constraint Statistics | Matrix Statistics | Matrix View
Variable Solution | Constraint Solution | Math Program Solution | MIP Search Tree

Variable	Value	Ma...	Basis ...	Bound Status
SelectS(S1)	0	9922.6	Nonbasic	At bound
SelectS(S2)	0	4225.4	Nonbasic	At bound
SelectS(S3)	1	8986.6	Nonbasic	At bound
SelectS(S4)	1	9132	Nonbasic	At bound
SelectM(M1)	0	9266.6	Nonbasic	At bound
SelectM(M2)	0	5804.6	Nonbasic	At bound
SelectM(M3)	0	8339.8	Nonbasic	At bound
SelectM(M4)	1	3346.4	Nonbasic	At bound
SelectDC(D1)	0	3524.8	Nonbasic	At bound
SelectDC(D2)	0	2143.4	Nonbasic	At bound
SelectDC(D3)	1	9896.4	Nonbasic	At bound
SelectWS(R1)	1	8537.6	Nonbasic	At bound
SelectWS(R2)	1	8618.8	Nonbasic	At bound
SelectWS(R3)	0	9291.2	Nonbasic	At bound
OrderQtySM(M1,S1)	0	26.6	Nonbasic	At bound
OrderQtySM(M1,S2)	0	14.4	Nonbasic	At bound
OrderQtySM(M1,S3)	0	23.2	Nonbasic	At bound
OrderQtySM(M1,S4)	0	24.2	Nonbasic	At bound
OrderQtySM(M2,S1)	0	16	Nonbasic	At bound
OrderQtySM(M2,S2)	0	20.8	Nonbasic	At bound
OrderQtySM(M2,S3)	0	25.6	Nonbasic	At bound
OrderQtySM(M2,S4)	0	23.2	Nonbasic	At bound
OrderQtySM(M3,S1)	0	16.2	Nonbasic	At bound
OrderQtySM(M3,S2)	0	18.2	Nonbasic	At bound
OrderQtySM(M3,S3)	0	24.4	Nonbasic	At bound
OrderQtySM(M3,S4)	0	14.8	Nonbasic	At bound
OrderQtySM(M4,S1)	0	17	Nonbasic	At bound
OrderQtySM(M4,S2)	0	23.2	Nonbasic	At bound
OrderQtySM(M4,S3)	3809	14.6	Nonbasic	In between bounds
OrderQtySM(M4,S4)	2291	16.2	Nonbasic	In between bounds
OrderQtyMDC(D1,M1)	0	15.4	Nonbasic	At bound
OrderQtyMDC(D1,M2)	0	15.8	Nonbasic	At bound
OrderQtyMDC(D1,M3)	0	24.2	Nonbasic	At bound
OrderQtyMDC(D1,M4)	0	22	Nonbasic	At bound
OrderQtyMDC(D2,M1)	0	19.6	Nonbasic	At bound
OrderQtyMDC(D2,M2)	0	25	Nonbasic	At bound
OrderQtyMDC(D2,M3)	0	21.8	Nonbasic	At bound
OrderQtyMDC(D2,M4)	0	28	Nonbasic	At bound
OrderQtyMDC(D3,M1)	0	24.4	Nonbasic	At bound
OrderQtyMDC(D3,M2)	0	19.8	Nonbasic	At bound
OrderQtyMDC(D3,M3)	0	16.8	Nonbasic	At bound
OrderQtyMDC(D3,M4)	6100	15.6	Nonbasic	In between bounds
OrderQtyDCWS(R1,D1)	0	28	Nonbasic	At bound
OrderQtyDCWS(R1,D2)	0	21.8	Nonbasic	At bound
OrderQtyDCWS(R1,D2)	0	21.8	Nonbasic	At bound
OrderQtyDCWS(R1,D3)	3100	23.4	Nonbasic	In between bounds
OrderQtyDCWS(R2,D1)	0	18	Nonbasic	At bound
OrderQtyDCWS(R2,D2)	0	12.6	Nonbasic	At bound
OrderQtyDCWS(R2,D3)	3000	21	Nonbasic	In between bounds
OrderQtyDCWS(R3,D1)	0	17.8	Nonbasic	At bound
OrderQtyDCWS(R3,D2)	0	15.8	Nonbasic	At bound
OrderQtyDCWS(R3,D3)	0	22.2	Nonbasic	At bound
OrderQtyWSC(C1,R1)	500	16	Nonbasic	In between bounds
OrderQtyWSC(C1,R2)	0	13.6	Nonbasic	At bound
OrderQtyWSC(C1,R3)	0	26.6	Nonbasic	At bound
OrderQtyWSC(C2,R1)	1200	14.8	Nonbasic	In between bounds
OrderQtyWSC(C2,R2)	0	23.2	Nonbasic	At bound
OrderQtyWSC(C2,R3)	0	25.6	Nonbasic	At bound
OrderQtyWSC(C3,R1)	600	18.2	Nonbasic	In between bounds
OrderQtyWSC(C3,R2)	1400	15.8	Nonbasic	In between bounds
OrderQtyWSC(C3,R3)	0	27	Nonbasic	At bound
OrderQtyWSC(C4,R1)	800	19.8	Nonbasic	In between bounds
OrderQtyWSC(C4,R2)	0	22.8	Nonbasic	At bound
OrderQtyWSC(C4,R3)	0	24.8	Nonbasic	At bound
OrderQtyWSC(C5,R1)	0	23.6	Nonbasic	At bound
OrderQtyWSC(C5,R2)	1600	18.6	Nonbasic	In between bounds
OrderQtyWSC(C5,R3)	0	20.2	Nonbasic	At bound
EconomicalCost	134093	0	Basic	In between bounds
EcoSelCost	48517.8	0	Basic	In between bounds
EcoTpCost	85574.8	0	Basic	In between bounds
EnvironmentalCost	104285	0	Basic	In between bounds
SocialCost	237965	0	Basic	In between bounds
TotalCost	476343	0	Basic	In between bounds

Figure 6.11: Results for Test 3, Scenario 1

The results are graphically represented in Figure 6.11. The order quantity allocations for S3 and S4 are 3809 and 2291 respectively, manufacturer M4 is 6100, distributor D3 is

6100, and retailers R1 and R2 is 3100 and 3000 respectively. It can be seen that the capacity constraints are satisfied at all stages of the supply chain.

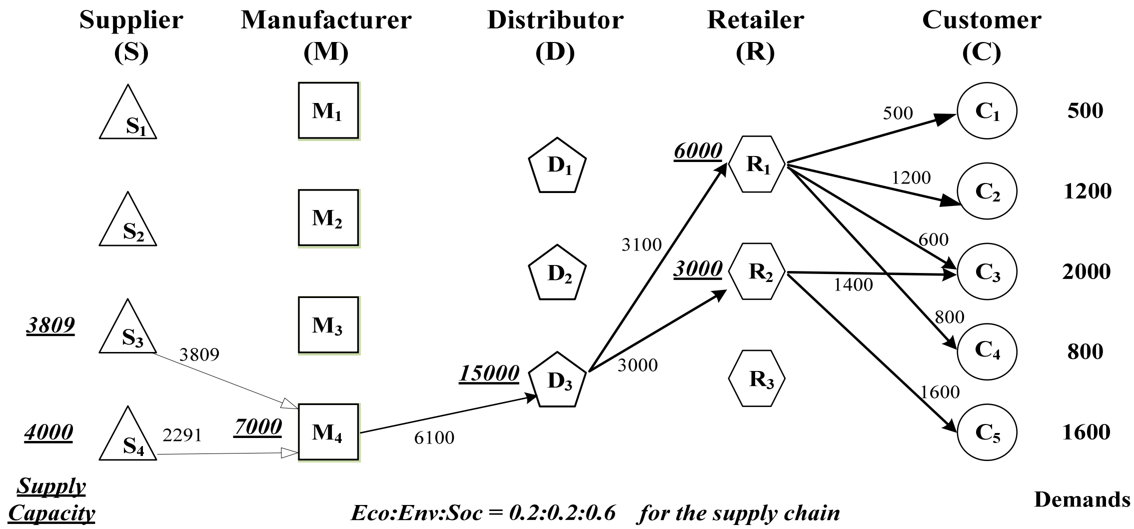


Figure 6.12: The Topology of SSCN for Test 3, Scenario 1

The total cost or objective function value for the network design represented in Figure 6.12 is shown in Table 6.10. The economical costs are 134093, environmental costs are 104285 and social costs are 237965 making a total cost of 476343.

Table 6.10: Costs Distribution for Test 3, Scenario 1

AIMMS Outputs

The Costs:	Economical Costs	Environmental Costs	Social Costs	The Total Costs
AIMMS Optimal Results:	134093	104285	237965	476343
The Weight Used:	×0.2	×0.2	×0.6	

Table 6.11 presents the differences in results obtained for Test 2 and Test 3. It can be seen that the distributors and retailers differ across the two scenarios whereas the manufacturers and the suppliers remain the same.

Table 6.11: Order Allocation and SSCND for Test 2 and Test 3, Scenario 1

	Stage One			**Stage Two**			**Stage Three**			**Stage Four**		
	Supplier	Buyer	Quantity	Supplier	Buyer	Quantity	Supplier	Buyer	Quantity	Supplier	Buyer	Quantity
Test 2:	S3	M4	3809	M4	D1	6100	D1	R2	3000	R2	C1	500
	S4	M4	2291				D1	R3	3100	R2	C3	2000
										R2	C4	500
										R3	C2	1200
										R3	C4	300
										R3	C5	1600
Test 3:	S3	M4	3809	M4	D3	6100	D3	R1	3100	R1	C1	500
	S4	M4	2291				D3	R2	3000	R1	C2	1200
										R1	C3	600
										R1	C4	800
										R2	C3	1400
										R2	C5	1600

4. Test 4 (Weight ratio 0.333:0.333:0.333 (Eco:Env:Soc)).

In this scenario weight of economical costs, environmental costs, and social costs are the same (=0.333). The outputs from AIMMS for scenario Test 4 are presented in Figure 6.13. It can be seen that suppliers S3 and S4, manufacturer M4, distributor D1, and retailers R2 and R3 are finally selected.

Constraint Solution | Math Program Solution | MIP Search Tree

Variable Statistics | Constraint Statistics | Matrix Statistics | Matrix View | Variable Solution

Variable	Value	Mar...	Basis ...	Bound Status
SelectS(S1)	0	16521.1	Nonbasic	At bound
SelectS(S2)	0	7035.29	Nonbasic	At bound
SelectS(S3)	1	14962.7	Nonbasic	At bound
SelectS(S4)	1	15204.8	Nonbasic	At bound
SelectM(M1)	0	15428.9	Nonbasic	At bound
SelectM(M2)	0	9664.66	Nonbasic	At bound
SelectM(M3)	0	13885.8	Nonbasic	At bound
SelectM(M4)	1	5571.76	Nonbasic	At bound
SelectDC(D1)	1	5868.79	Nonbasic	At bound
SelectDC(D2)	0	3568.76	Nonbasic	At bound
SelectDC(D3)	0	16477.5	Nonbasic	At bound
SelectWS(R1)	0	14215.1	Nonbasic	At bound
SelectWS(R2)	1	14350.3	Nonbasic	At bound
SelectWS(R3)	1	15469.8	Nonbasic	At bound
OrderQtySM(M1,S1)	0	25.641	Nonbasic	At bound
OrderQtySM(M1,S2)	0	15.318	Nonbasic	At bound
OrderQtySM(M1,S3)	0	21.312	Nonbasic	At bound
OrderQtySM(M1,S4)	0	20.979	Nonbasic	At bound
OrderQtySM(M2,S1)	0	19.98	Nonbasic	At bound
OrderQtySM(M2,S2)	0	20.646	Nonbasic	At bound
OrderQtySM(M2,S3)	0	25.308	Nonbasic	At bound
OrderQtySM(M2,S4)	0	19.98	Nonbasic	At bound
OrderQtySM(M3,S1)	0	17.649	Nonbasic	At bound
OrderQtySM(M3,S2)	0	20.313	Nonbasic	At bound
OrderQtySM(M3,S3)	0	21.978	Nonbasic	At bound
OrderQtySM(M3,S4)	0	16.65	Nonbasic	At bound
OrderQtySM(M4,S1)	0	19.647	Nonbasic	At bound
OrderQtySM(M4,S2)	0	19.314	Nonbasic	At bound
OrderQtySM(M4,S3)	3809	14.319	Nonbasic	In between bounds
OrderQtySM(M4,S4)	2291	17.649	Nonbasic	In between bounds
OrderQtyMDC(D1,M1)	0	17.649	Nonbasic	At bound
OrderQtyMDC(D1,M2)	0	17.649	Nonbasic	At bound
OrderQtyMDC(D1,M3)	0	20.313	Nonbasic	At bound
OrderQtyMDC(D1,M4)	6100	17.982	Nonbasic	In between bounds
OrderQtyMDC(D2,M1)	0	21.978	Nonbasic	At bound
OrderQtyMDC(D2,M2)	0	23.643	Nonbasic	At bound
OrderQtyMDC(D2,M3)	0	22.311	Nonbasic	At bound
OrderQtyMDC(D2,M4)	0	27.306	Nonbasic	At bound
OrderQtyMDC(D3,M1)	0	22.644	Nonbasic	At bound
OrderQtyMDC(D3,M2)	0	18.315	Nonbasic	At bound
OrderQtyMDC(D3,M3)	0	15.318	Nonbasic	At bound
OrderQtyMDC(D3,M4)	0	18.648	Nonbasic	At bound
OrderQtyDCWS(R1,D1)	0	26.64	Nonbasic	At bound
OrderQtyDCWS(R1,D2)	0	20.979	Nonbasic	At bound
OrderQtyDCWS(R1,D3)	0	23.643	Nonbasic	At bound
OrderQtyDCWS(R2,D1)	3000	15.318	Nonbasic	In between bounds
OrderQtyDCWS(R2,D2)	0	13.653	Nonbasic	At bound
OrderQtyDCWS(R2,D3)	0	21.645	Nonbasic	At bound
OrderQtyDCWS(R3,D1)	3100	16.983	Nonbasic	In between bounds
OrderQtyDCWS(R3,D2)	0	16.983	Nonbasic	At bound
OrderQtyDCWS(R3,D3)	0	22.977	Nonbasic	At bound
OrderQtyWSC(C1,R1)	0	17.316	Nonbasic	At bound
OrderQtyWSC(C1,R2)	500	13.32	Nonbasic	In between bounds
OrderQtyWSC(C1,R3)	0	24.309	Nonbasic	At bound
OrderQtyWSC(C2,R1)	0	15.318	Nonbasic	At bound
OrderQtyWSC(C2,R2)	0	23.976	Nonbasic	At bound
OrderQtyWSC(C2,R3)	1200	25.308	Nonbasic	In between bounds
OrderQtyWSC(C3,R1)	0	18.315	Nonbasic	At bound
OrderQtyWSC(C3,R2)	2000	15.651	Nonbasic	In between bounds
OrderQtyWSC(C3,R3)	0	25.641	Nonbasic	At bound
OrderQtyWSC(C4,R1)	0	20.313	Nonbasic	At bound
OrderQtyWSC(C4,R2)	0	21.978	Nonbasic	At bound
OrderQtyWSC(C4,R3)	800	23.976	Nonbasic	In between bounds
OrderQtyWSC(C5,R1)	0	21.978	Nonbasic	At bound
OrderQtyWSC(C5,R2)	500	15.651	Nonbasic	In between bounds
OrderQtyWSC(C5,R3)	1100	18.981	Nonbasic	In between bounds
EconomicalCost	189834	0	Basic	In between bounds
EcoSelCost	71428.2	0	Basic	In between bounds
EcoTpCost	118406	0	Basic	In between bounds
EnvironmentalCost	130711	0	Basic	In between bounds
SocialCost	170366	0	Basic	In between bounds
TotalCost	490912	0	Basic	In between bounds

Figure 6.13: Results of the SSCND for Test 4, Scenario 1

The results are graphically represented in Figure 6.14. The order quantity allocations for S3 and S4 are 3809 and 2291 respectively, manufacturer M4 is 6100, distributor D1is 6100, and retailers R2 and R3 is 3000 and 3100 respectively. It can be seen that the capacity constraints are satisfied at all stages of the supply chain.

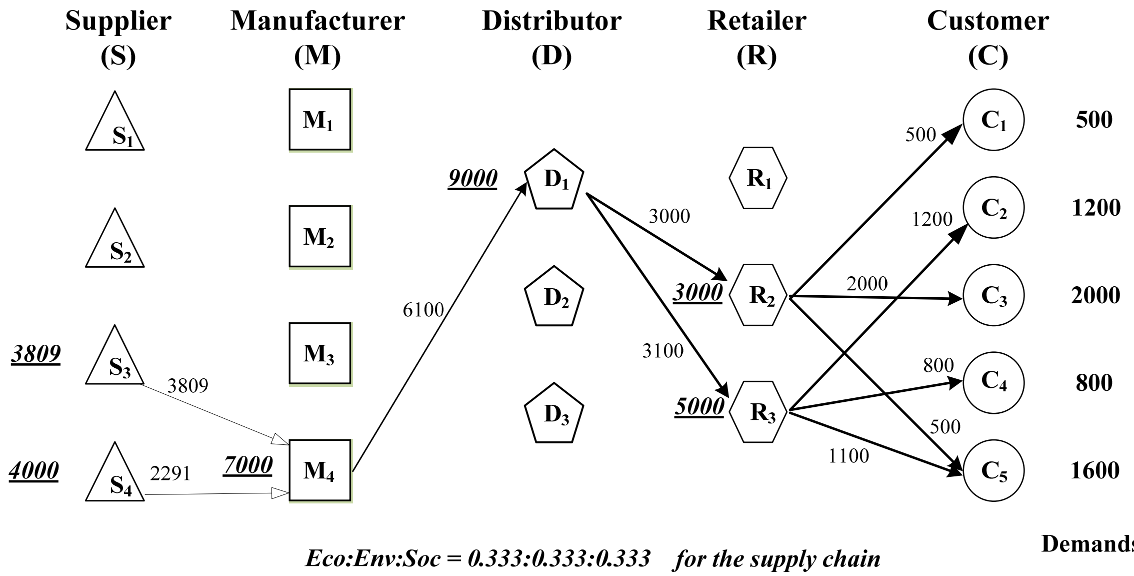


Figure 6.14: The Topology of SSCN for Test 4, Scenario 1

The total cost or objective function value for the network design represented in Figure 6.14 is shown in Table 6.12. The economical costs are 1898343, environmental costs are 130711 and social costs are 170366 making a total cost of 490912.

Table 6.12: Costs Distribution for Test 4, Scenario 1

AIMMS Outputs

The Costs:	Economical Costs	Environmental Costs	Social Costs	The Total Costs
AIMMS Optimal Results:	189834	130711	170366	490912
The Weight Used:	×0.2	×0.2	×0.6	

6.5.2 Scenario 2 (Change in Supply Capacities and Customer Demands)

Firstly, we will consider the case of change in facility capacities on network design (Test 1). Secondly, we will consider the case of change in customer demands on network design (Test 2). Table 6.13 presents the new supply capacity of each facility. It is different from the one shown in Table 6.5.

Table 6.13: New Capacities for supply chain facilities

Supply Capacity of Each Facility							
Raw Material Supplier		**Manufacturer**		**Distribution Center**		**Retailer**	
i		j		k		l	
S1	2189	M1	2400	D1	4200	R1	3250
S2	798	M2	4800	D2	5689	R2	2890
S3	1657	M3	3780	D3	7650	R3	4876
S4	3800	M4	7000				

Figure 6.15 shows the results calculated by AIMMS under the new capacities of the facilities. It can be seen that suppliers S2, S3 and S4, manufacturers M3 and M4, distributor D1 and D2, and retailers R2 and R3 are finally selected.

Variable	Value	Mar...	Basis ...	Bound Status
SelectS(S1)	0	24459.2	Nonbasic	At bound
SelectS(S2)	1	10415.6	Nonbasic	At bound
SelectS(S3)	1	22152	Nonbasic	At bound
SelectS(S4)	1	22510.4	Nonbasic	At bound
SelectM(M1)	0	22842.2	Nonbasic	At bound
SelectM(M2)	0	14308.3	Nonbasic	At bound
SelectM(M3)	1	20557.6	Nonbasic	At bound
SelectM(M4)	1	8248.88	Nonbasic	At bound
SelectDC(D1)	1	8688.63	Nonbasic	At bound
SelectDC(D2)	1	5283.48	Nonbasic	At bound
SelectDC(D3)	0	24394.6	Nonbasic	At bound
SelectWS(R1)	0	21045.2	Nonbasic	At bound
SelectWS(R2)	1	21245.3	Nonbasic	At bound
SelectWS(R3)	1	22902.8	Nonbasic	At bound
OrderQtySM(M1,S1)	0	27.896	Nonbasic	At bound
OrderQtySM(M1,S2)	0	16.813	Nonbasic	At bound
OrderQtySM(M1,S3)	0	24.697	Nonbasic	At bound
OrderQtySM(M1,S4)	0	21.264	Nonbasic	At bound
OrderQtySM(M2,S1)	0	18.03	Nonbasic	At bound
OrderQtySM(M2,S2)	0	20.111	Nonbasic	At bound
OrderQtySM(M2,S3)	0	26.488	Nonbasic	At bound
OrderQtySM(M2,S4)	0	21.765	Nonbasic	At bound
OrderQtySM(M3,S1)	0	16.034	Nonbasic	At bound
OrderQtySM(M3,S2)	0	17.248	Nonbasic	At bound
OrderQtySM(M3,S3)	0	23.973	Nonbasic	At bound
OrderQtySM(M3,S4)	3780	14.015	Nonbasic	In between bounds
OrderQtySM(M4,S1)	0	19.472	Nonbasic	At bound
OrderQtySM(M4,S2)	643	19.924	Nonbasic	In between bounds
OrderQtySM(M4,S3)	1657	12.874	Nonbasic	In between bounds
OrderQtySM(M4,S4)	20	19.034	Nonbasic	In between bounds
OrderQtyMDC(D1,M1)	0	13.619	Nonbasic	At bound
OrderQtyMDC(D1,M2)	0	19.514	Nonbasic	At bound
OrderQtyMDC(D1,M3)	890	20.923	Nonbasic	In between bounds
OrderQtyMDC(D1,M4)	2320	18.432	Nonbasic	In between bounds
OrderQtyMDC(D2,M1)	0	19.608	Nonbasic	At bound
OrderQtyMDC(D2,M2)	0	26.543	Nonbasic	At bound
OrderQtyMDC(D2,M3)	2890	20.701	Nonbasic	In between bounds
OrderQtyMDC(D2,M4)	0	27.256	Nonbasic	At bound
OrderQtyMDC(D3,M1)	0	22.439	Nonbasic	At bound
OrderQtyMDC(D3,M2)	0	20.68	Nonbasic	At bound
OrderQtyMDC(D3,M3)	0	16.183	Nonbasic	At bound
OrderQtyMDC(D3,M4)	0	15.953	Nonbasic	At bound
OrderQtyDCWS(R1,D1)	0	26.915	Nonbasic	At bound
OrderQtyDCWS(R1,D2)	0	23.769	Nonbasic	At bound
OrderQtyDCWS(R1,D3)	0	22.463	Nonbasic	At bound
OrderQtyDCWS(R2,D1)	0	15.118	Nonbasic	At bound
OrderQtyDCWS(R2,D2)	2890	13.058	Nonbasic	In between bounds
OrderQtyDCWS(R2,D3)	0	20.945	Nonbasic	At bound
OrderQtyDCWS(R3,D1)	3210	15.648	Nonbasic	In between bounds
OrderQtyDCWS(R3,D2)	0	16.173	Nonbasic	At bound
OrderQtyDCWS(R3,D3)	0	20.937	Nonbasic	At bound
OrderQtyWSC(C1,R1)	0	20.416	Nonbasic	At bound
OrderQtyWSC(C1,R2)	500	13.75	Nonbasic	In between bounds
OrderQtyWSC(C1,R3)	0	21.964	Nonbasic	At bound
OrderQtyWSC(C2,R1)	0	15.958	Nonbasic	At bound
OrderQtyWSC(C2,R2)	0	24.936	Nonbasic	At bound
OrderQtyWSC(C2,R3)	1200	26.113	Nonbasic	In between bounds
OrderQtyWSC(C3,R1)	0	19.6	Nonbasic	At bound
OrderQtyWSC(C3,R2)	2000	16.241	Nonbasic	In between bounds
OrderQtyWSC(C3,R3)	0	24.416	Nonbasic	At bound
OrderQtyWSC(C4,R1)	0	18.328	Nonbasic	At bound
OrderQtyWSC(C4,R2)	0	21.018	Nonbasic	At bound
OrderQtyWSC(C4,R3)	800	23.391	Nonbasic	In between bounds
OrderQtyWSC(C5,R1)	0	21.183	Nonbasic	At bound
OrderQtyWSC(C5,R2)	390	15.881	Nonbasic	In between bounds
OrderQtyWSC(C5,R3)	1210	21.666	Nonbasic	In between bounds
EconomicalCost	326289	0	Basic	In between bounds
EcoSelCost	142005	0	Basic	In between bounds
EcoTpCost	184284	0	Basic	In between bounds
EnvironmentalCost	55394	0	Basic	In between bounds
SocialCost	178814	0	Basic	In between bounds
TotalCost	560498	0	Basic	In between bounds

Figure 6.15: Outputs for Test 1, Scenario 2

The results are graphically represented in Figure 6.16. The order quantity allocations for S2, S3 and S4 are 643, 1657 and 3800 respectively, manufacturers M3 and M4 is 3780 and 2320, distributors D1 and D2 is 3210 and 2890, and retailers R2 and R3 is 2890 and 3210 respectively. It can be seen that the capacity constraints are satisfied at all stages of the supply chain.

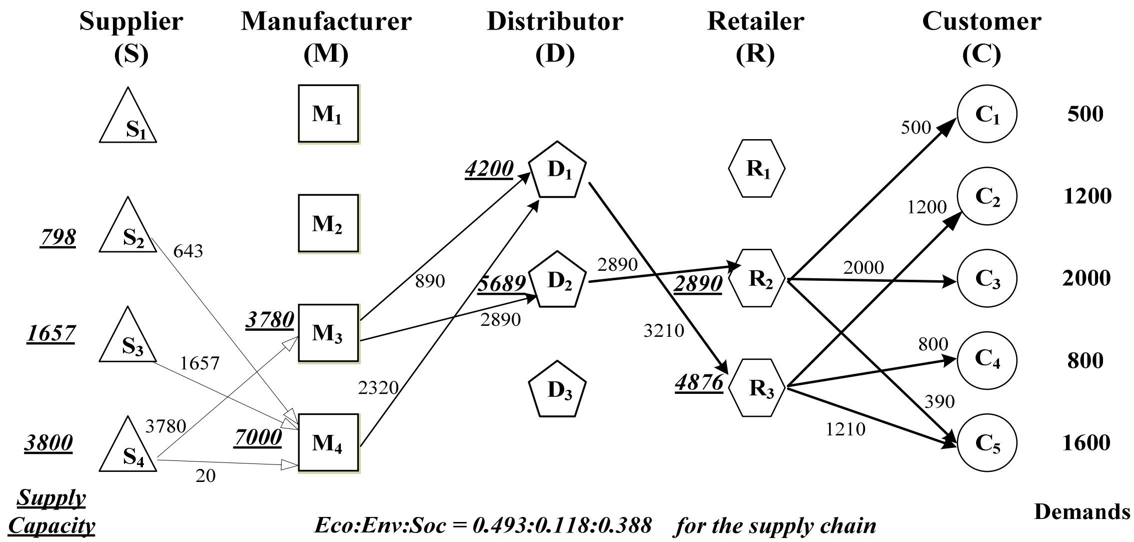


Figure 6.16: The Topology of SSCN for Test 1, Scenario 2

The total cost or objective function value for the network design represented in Figure 6.15 is shown in Table 6.14. The economical costs are 326289, environmental costs are 55394 and social costs are 178814 making a total cost of 560498.

Table 6.14: Costs Distribution for Test 1, Scenario 2

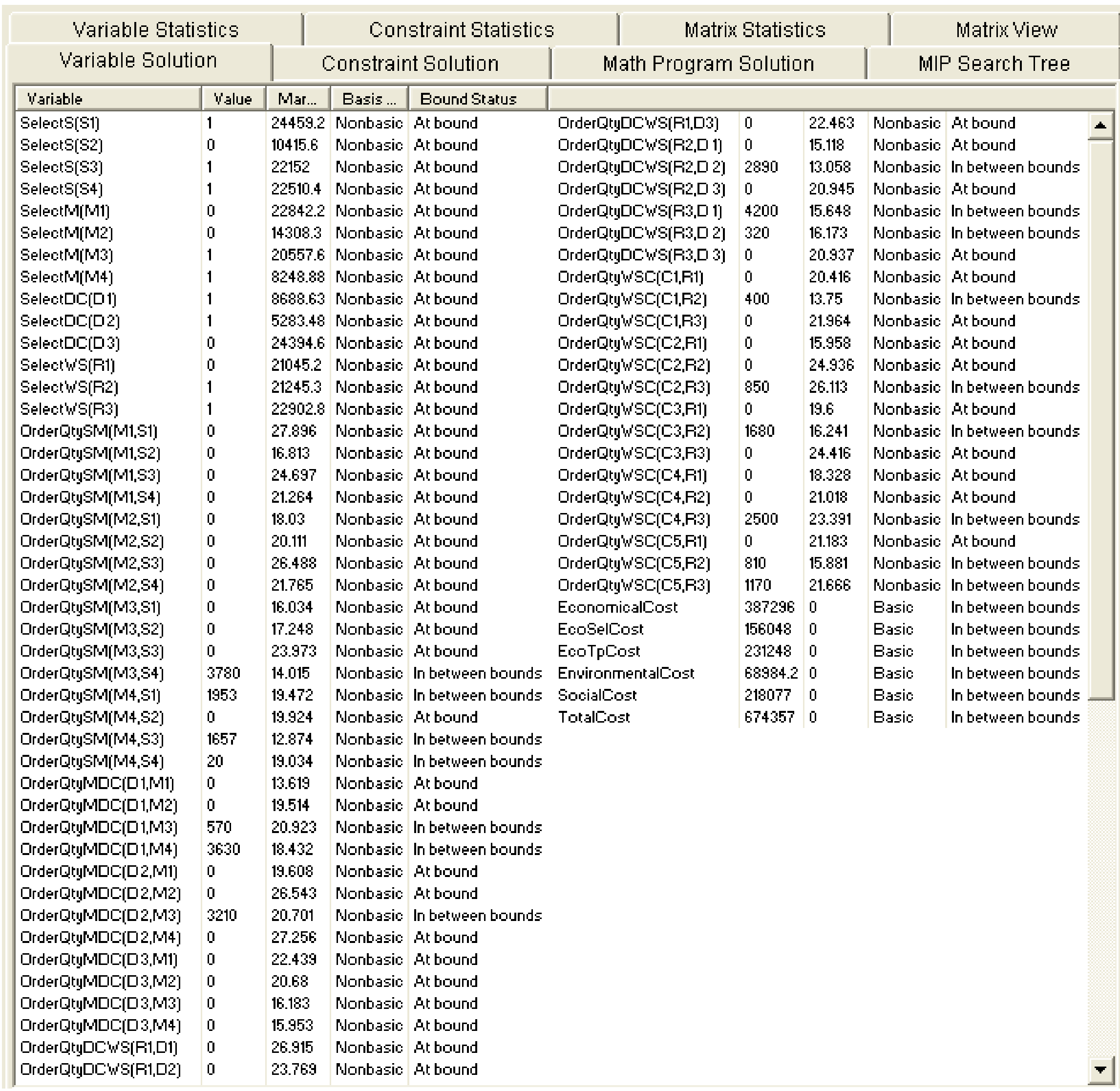
AIMMS Outputs

The Costs:	Economical Costs	Environmental Costs	Social Costs	The Total Costs
AIMMS Optimal Results:	326289	55394	178814	560498
The Weight Used:	×0.493	×0.118	×0.388	

Now, we will consider the case of change in customer demands on network design (Test 2). Table 6.15 presents the new set of customer demands. Figure 6.17 and Figure 6.18 show the outputs and the topology of SSCN.

Table 6.15: Varying the Demand Data with the Numerical Example to Test the Model

Demands from Customer	
n	
C1	400
C2	850
C3	1680
C4	2500
C5	1980



Variable	Value	Mar...	Basis ...	Bound Status
SelectS(S1)	1	24459.2	Nonbasic	At bound
SelectS(S2)	0	10415.6	Nonbasic	At bound
SelectS(S3)	1	22152	Nonbasic	At bound
SelectS(S4)	1	22510.4	Nonbasic	At bound
SelectM(M1)	0	22842.2	Nonbasic	At bound
SelectM(M2)	0	14308.3	Nonbasic	At bound
SelectM(M3)	1	20557.6	Nonbasic	At bound
SelectM(M4)	1	8248.88	Nonbasic	At bound
SelectDC(D1)	1	8688.63	Nonbasic	At bound
SelectDC(D2)	1	5283.48	Nonbasic	At bound
SelectDC(D3)	0	24394.6	Nonbasic	At bound
SelectWS(R1)	0	21045.2	Nonbasic	At bound
SelectWS(R2)	1	21245.3	Nonbasic	At bound
SelectWS(R3)	1	22902.8	Nonbasic	At bound
OrderQtySM(M1,S1)	0	27.896	Nonbasic	At bound
OrderQtySM(M1,S2)	0	16.813	Nonbasic	At bound
OrderQtySM(M1,S3)	0	24.697	Nonbasic	At bound
OrderQtySM(M1,S4)	0	21.264	Nonbasic	At bound
OrderQtySM(M2,S1)	0	18.03	Nonbasic	At bound
OrderQtySM(M2,S2)	0	20.111	Nonbasic	At bound
OrderQtySM(M2,S3)	0	26.488	Nonbasic	At bound
OrderQtySM(M2,S4)	0	21.765	Nonbasic	At bound
OrderQtySM(M3,S1)	0	16.034	Nonbasic	At bound
OrderQtySM(M3,S2)	0	17.248	Nonbasic	At bound
OrderQtySM(M3,S3)	0	23.973	Nonbasic	At bound
OrderQtySM(M3,S4)	3780	14.015	Nonbasic	In between bounds
OrderQtySM(M4,S1)	1953	19.472	Nonbasic	In between bounds
OrderQtySM(M4,S2)	0	19.924	Nonbasic	At bound
OrderQtySM(M4,S3)	1657	12.874	Nonbasic	In between bounds
OrderQtySM(M4,S4)	20	19.034	Nonbasic	In between bounds
OrderQtyMDC(D1,M1)	0	13.619	Nonbasic	At bound
OrderQtyMDC(D1,M2)	0	19.514	Nonbasic	At bound
OrderQtyMDC(D1,M3)	570	20.923	Nonbasic	In between bounds
OrderQtyMDC(D1,M4)	3630	18.432	Nonbasic	In between bounds
OrderQtyMDC(D2,M1)	0	19.608	Nonbasic	At bound
OrderQtyMDC(D2,M2)	0	26.543	Nonbasic	At bound
OrderQtyMDC(D2,M3)	3210	20.701	Nonbasic	In between bounds
OrderQtyMDC(D2,M4)	0	27.256	Nonbasic	At bound
OrderQtyMDC(D3,M1)	0	22.439	Nonbasic	At bound
OrderQtyMDC(D3,M2)	0	20.68	Nonbasic	At bound
OrderQtyMDC(D3,M3)	0	16.183	Nonbasic	At bound
OrderQtyMDC(D3,M4)	0	15.953	Nonbasic	At bound
OrderQtyDCWS(R1,D1)	0	26.915	Nonbasic	At bound
OrderQtyDCWS(R1,D2)	0	23.769	Nonbasic	At bound
OrderQtyDCWS(R1,D3)	0	22.463	Nonbasic	At bound
OrderQtyDCWS(R2,D 1)	0	15.118	Nonbasic	At bound
OrderQtyDCWS(R2,D 2)	2890	13.058	Nonbasic	In between bounds
OrderQtyDCWS(R2,D 3)	0	20.945	Nonbasic	At bound
OrderQtyDCWS(R3,D 1)	4200	15.648	Nonbasic	In between bounds
OrderQtyDCWS(R3,D 2)	320	16.173	Nonbasic	In between bounds
OrderQtyDCWS(R3,D 3)	0	20.937	Nonbasic	At bound
OrderQtyWSC(C1,R1)	0	20.416	Nonbasic	At bound
OrderQtyWSC(C1,R2)	400	13.75	Nonbasic	In between bounds
OrderQtyWSC(C1,R3)	0	21.964	Nonbasic	At bound
OrderQtyWSC(C2,R1)	0	15.958	Nonbasic	At bound
OrderQtyWSC(C2,R2)	0	24.936	Nonbasic	At bound
OrderQtyWSC(C2,R3)	850	26.113	Nonbasic	In between bounds
OrderQtyWSC(C3,R1)	0	19.6	Nonbasic	At bound
OrderQtyWSC(C3,R2)	1680	16.241	Nonbasic	In between bounds
OrderQtyWSC(C3,R3)	0	24.416	Nonbasic	At bound
OrderQtyWSC(C4,R1)	0	18.328	Nonbasic	At bound
OrderQtyWSC(C4,R2)	0	21.018	Nonbasic	At bound
OrderQtyWSC(C4,R3)	2500	23.391	Nonbasic	In between bounds
OrderQtyWSC(C5,R1)	0	21.183	Nonbasic	At bound
OrderQtyWSC(C5,R2)	810	15.881	Nonbasic	In between bounds
OrderQtyWSC(C5,R3)	1170	21.666	Nonbasic	In between bounds
EconomicalCost	387296	0	Basic	In between bounds
EcoSelCost	156048	0	Basic	In between bounds
EcoTpCost	231248	0	Basic	In between bounds
EnvironmentalCost	68984.2	0	Basic	In between bounds
SocialCost	218077	0	Basic	In between bounds
TotalCost	674357	0	Basic	In between bounds

Figure 6.17: Outputs for Test 2, Scenario 2

Figure 6.17 shows the results calculated by AIMMS under the new customer demands. It can be seen that suppliers S1, S3 and S4, manufacturers M3 and M4, distributor D1 and D2, and retailers R2 and R3 are finally selected. The results are graphically represented in Figure 6.18. The order quantity allocations for S1, S3 and S4 are 1953, 1657 and 20 respectively to manufacture M4. The raw material supplier S4 supplies 3780 units of product to M3. In second stage, manufacturer M3 supplies 570 to D1 and 3210 for D2. Manufacturer M4 supplies 3630 to distributor D1. Distributors D1 and D2 allocate total 4520 to retailer R3, and D2 supplies 2890 to R2. It can be seen that the capacity constraints are satisfied at all stages of the supply chain.

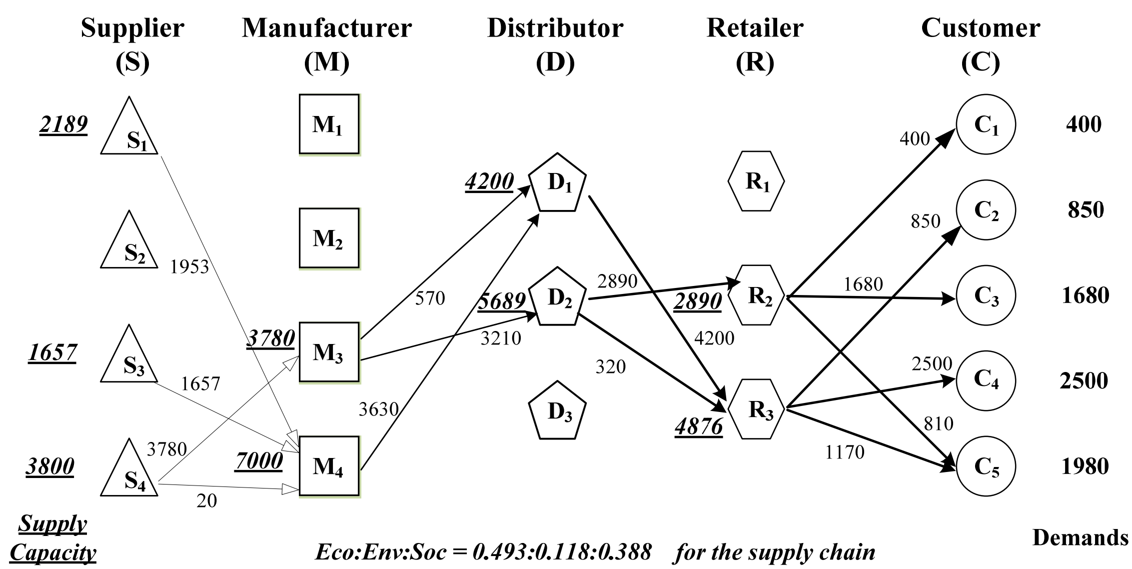


Figure 6.18: The Topology of SSCN for Test 2, Scenario 2

The total cost or objective function value for the network design represented in Figure 6.18 is shown in Table 6.16. The economical costs are 387296, environmental costs are 68984 and social costs are 218077 making a total cost of 674357.

Table 6.16: Costs Distribution for Test 2, Scenario2

AIMMS Outputs

The Costs:	Economical Costs	Environmental Costs	Social Costs	The Total Costs
AIMMS Optimal Results:	387296	68984	218077	674357
The Weight Used:	×0.493	×0.118	×0.388	

Based on the results of these two scenarios, we can say that the network design and associated order quantity allocations are different whenever a change in capacity or demand occurs.

6.5.3 Scenario 3 (Change in Size of the Supply Chain Network)

Table 6.17: Model results for Test 1-5, Scenario 3

	Supplier	Manufacturer	Distributor	Retailer	Customer	Network Design	Total Cost	Time to get the results
Test 1 (Remove S3, S4)	2	4	3	3	5	Infeasible	N/A	-
Test 2 (Remove M3, M4)	4	2	3	3	5	S2,S3,S4,M1,D1,R2,R3	554756	0.02s
Test 3 (Remove D2, D3)	4	4	1	3	5	S3,S4,M4,D1,R2,R3	525868	0.02s
Test 4 (Remove R1, R2)	4	4	3	1	5	Infeasible	N/A	-
Test 5 (Remove C1, C2)	4	4	3	3	3	S2,S3,M4,D1,R2,R3	382903	0.02s

Table 6.17 shows the details of the different network sizes used for testing in scenario 4. The different network sizes are obtained by changing the number of suppliers, manufacturers, distributors, retailers, customers etc. A total of five scenarios are

considered. The results generated from AIMMS for each of the test scenario is presented in last three columns of Table 6.17.

It can be seen from results of Table 6.17 that the network design becomes infeasible whenever demand and capacity constraints are violated (Test 1 and Test 4). For Test 2 and Test 5, we observe a change in the network design and associated costs when compared to original network design (Figure 6.6). For Test 3, the network design remains same as in Figure 6.6; however, the total costs are different. Therefore, based on the results of scenario “change in network size”, we can verify the correctness of results of our model and sensitivity to input parameters in designing sustainable supply chain networks.

Chapter 7

Conclusions and Future Work

7.1 Summary

In this thesis, we propose a mathematical programming based modeling framework for designing sustainable supply chain networks considering the economical, environmental and social objectives. Applying the method of systematical literature review, the research collects and analyzes the state-and-the-art publications about green supply chain management and sustainable supply chain management to investigate the definitions, applications, research methods, drivers and barriers about GSCM and SSCM. It was found during the literature study that most of the models on sustainable supply chains are more concerned with minimizing the costs for economical and environmental side, and social requirements are rarely integrated in the SSCND models. Considering the shortage of studies in this direction, we pursued the goal of developing a modeling framework for sustainable supply chain design considering the three dimension of "sustainability" namely social, economic and environmental.

The proposed framework comprises of three steps. In the first step, we identify the customer requirements (also called listening to Voice of the Customer (VOC)), technical requirements, and metrics for measuring the performance of sustainable supply chains using Systematic Literature Review and Questionnaire Surveys C-REQ and T-REQ. In the second step, we investigate the customer requirements and technical requirements, study their relationship and allocate weights using Priority Matrix and Sustainable Function Deployment (SFD). In the third and the last step, we develop an integer programming model for designing sustainable supply chain network in AIMMS using the weighted technical requirements and network modeling parameters.

7.2 SWOT Analysis

Figure 7.1 presents a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of the research work pursued in this thesis.

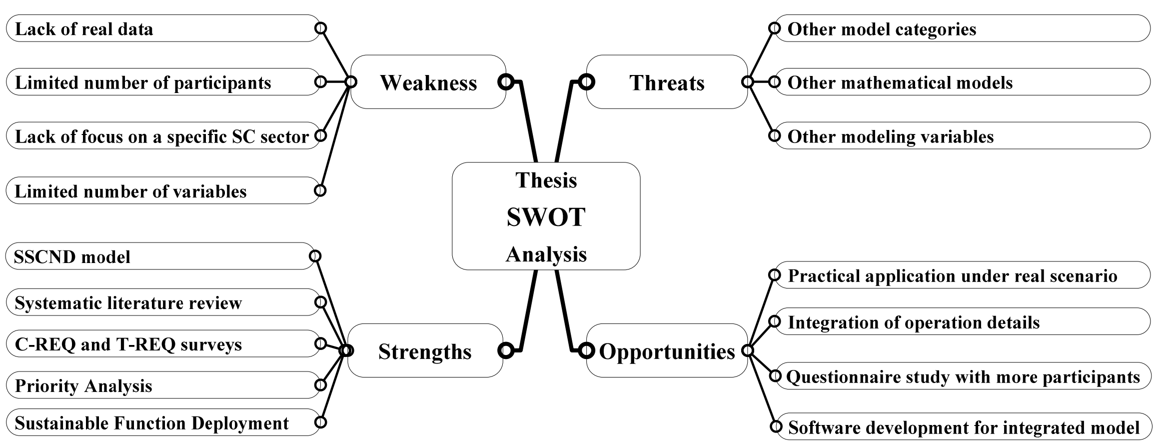


Figure 7.1: Thesis SWOT Analysis

The strengths of our work are the novelty of approaches used in SSCND. In our knowledge, this is the first work that integrates a multitude of techniques such as

Systematic literature review, C-REQ and T-REQ surveys, Priority Analysis, Sustainable Functional Deployment, and Mathematical programming based model for SSCND. The weakness of our model is lack of real data, limited number of participants, lack of focus on a specific supply chain sector, and consideration of only limited number of variables extracted from systematic literature review. These weaknesses open opportunities for improvement in these areas in future and integration of new features such as operational level planning, software development, and practical application under realistic test scenarios. The threats to our model are existence of other model categories, other mathematical models, and inclusion of more modeling variables; however, they are not yet many in number.

7.3 The Future Research

From the SWOT analysis, many opportunities emerge that can be pursued as future works in the field of sustainable supply chain network design. First, application of the proposed SSCND model on practical problems can be done and results be verified and validated under real conditions. Secondly, integration of more operational details, allocation of different weights for socio-economic-environmental dimensions at various stages of the supply chain, survey studies with increased number of participants can be done. Last but not the least, the proposed modeling framework can be used to develop an integrated modeling software for decision makers at strategic levels in supply chains for designing sustainable supply chain networks. Therefore, as future works, efforts can be directed towards planning and execution of the proposed research activities for developing sustainable supply chain networks.

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Appendix A

Customer Requirements Survey for Sustainable Supply Chain Management (C-REQ)

This questionnaire intends to collect the customer requirements for sustainable supply chain management. Questions can have multiple answers. ***Please feel free to ask surveyor(s) if you need more information about anything on the questions.***

1. Please indicate your status?

   ☐ Student ☐ Faculty ☐ Researcher ☐ Full time worker

2. Please indicate your managerial position if you are a full time employee?

   ☐ Junior manager ☐ Team leader ☐ Project manager ☐ Senior manager ☐ VIP ☐ CEO

3. Which stage of supply chain are you associated with?

   ☐ Material Supply ☐ Manufacturing/Production ☐ Distribution/Logistics
   ☐ Whole Seller/Retail ☐ Customer Service/Marketing

4. Which category of "Customer" you belong to?

   ☐ Clients of business ☐ Clients of products/services ☐ Internal employees
   ☐ Business partners ☐ All the stakeholders related your work or business

5. What should be included in "Performance" based on your work or business?

   ☐ Clients satisfy the products/services ☐ Stakeholders satisfy processes/results of work/business
   ☐ Employees satisfy the benefits ☐ Employees satisfy the work environment

6. Do you have customers in your work? How do they feel about your products/services?

   ☐ No
   ☐ Yes
   ☐ No feedbacks ☐ More complaints ☐ Satisfied ☐ Good comments

7. Does satisfaction of customer requirements impacts your work performance?

   ☐ No impact ☐ Somewhat impact ☐ Impact ☐ Remarkable impact

8. Do you think that all customer requirements should be satisfied and best fulfilled at the same time?

   ☐ All should be considered at same time ☐ All should be considered but not the same time

☐ Not all to be considered at same time ☐ Not all to be considered and not the same time

9. Do you think it is feasible and valuable to respond to every customer requirement with your efforts?

   ☐ Not feasible but valuable ☐ Feasible but not valuable

   ☐ Feasible and valuable ☐ Not feasible and also Not valuable

10. Please mark the most important factors related to the performance of your work/business. In addition, please indicate the level to each factor based on their influence on the total performance of your work/business, and how much efforts should be devoted to accomplish them.

	Impact on Total Performance	*Effort to be Devoted*
☐ High employee benefits	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Consumer safety	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Competitive advantage	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Best returns on investing	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Efficient communication	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Consumer health	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Good to be a leader	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Good in public benefits	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Effective work processes	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Compliance in product	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Good for globalization	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Legislation compliance	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Human rights protection	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Best in service	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Good for collaboration	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Good in public safety	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Least work pressures	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Least costs on product	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Least operation costs	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Good for public health	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Safe in work environment	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Good for social diversity	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10

Thank you for your time and responses.

Appendix B

Technical Requirements Survey for Sustainable Supply Chain Management (T-REQ)

The purpose of this survey is to collect the responses from managerial and technical people on most important technical requirements for sustainable supply chain management (SSCM), the relationships between customer requirements and technical requirements, and assessing correlation between them. ***Please feel free to ask surveyor(s) if you need more information about anything on the questions.***

1. Please indicate your professional level?

   ☐ Supply chain manager ☐ Senior manager in a supply chain ☐ Researcher in supply chains

2. Which stage are you involved in the supply chain?

   ☐ Material Supply ☐ Manufacturing/Production ☐ Distribution/Logistics

   ☐ Whole Seller/Retail ☐ Customer Service/Marketing

3. Please mark your expectations and perceptions for the following ***technical requirements*** associated with sustainable supply chain management.

   DEFINITIONS:

   Technical Requirements: stands for what kind of methods/activities should be conducted to satisfy the customer requirements in order to improve the performance of SSCM.

   Customer Requirements: stand for what kind of results or characteristics should be achieved in order to fulfill the customer needs and improve the performance of SSCM.

   Expectation Degree: stands for your expectations for a relevant technical requirement in improving the performance of SSCM.

   Perception Degree: stands for a judgment based on your personal experiences about a relevant technical requirement on improving the performance of SSCM.

Technical Requirements Influencing on the Performance of SSCM

Technical Requirements	*Expectation Degree*	*Perception Degree*
☐ Costs and expenses control	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Reach the high business profitability	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Widely apply new technology and integrated systems	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Efficient business process management, activity operations	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Apply the optimization techniques or methodologies in SCs	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Collaborative operations among facilities in SCs	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Good environment operation, such as pollution prevention	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ High efforts in utilizing natural resources, such as mining	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ High efforts in conserving natural resources	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Efforts in natural resource regeneration, such as reuse	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Effective energy utilization, such as use fossil/bio-energy	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Efforts in planning and conducting environment policy	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ High compliance in environment legislations	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ High satisfaction of customers and business partners in SCs	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ High efforts to manage business trust and reputation	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ High efforts in the social equity, such as salary, work load	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ High efforts in public benefits, such as training, welfare	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ High efforts in culture protection, such as respect habits	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ High efforts in business ethics and moral attempts	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ Natural environment decides the performance of SSCM	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ The politics satisfaction decides the performance of SSCM	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10
☐ The religion situation decides the performance of SSCM	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10

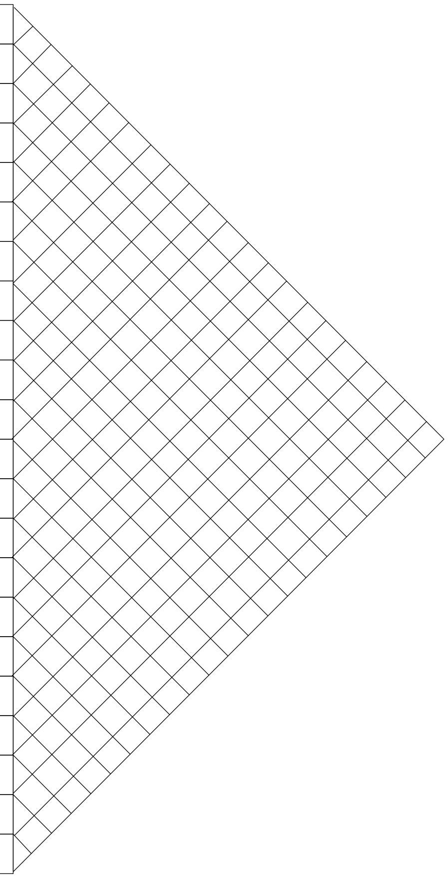
4. Please to indicate the relationships between the technical requirements?

   SYMBOL:

   - ● means there is a strong positive relationships between those two technical requirements
   - o means there is an obvious positive relationships between those two technical requirements
   - Δ means there is a weak positive relationships between those two technical requirements
   - × means there is a weak negative relationships between those two technical requirements
   - ☒ means there is an obvious negative relationships between those two technical requirements
   - ☆ means there is a strong negative relationships between those two technical requirements

● = +9 (Strong positive)
o = +5 (Positive)
Δ = +1 (Weak positive)
× = −1 (Weak negative)
⊠ = −5 (Negative)
☆ = −9 (Strong Positive)

Costs and expenses control
Reach high business profitability
Widely apply new technology and integrated systems
Efficient business process management, activity operations
Apply optimization techniques or methodologies in SCs
Collaborative operations among facilities in SCs
Good environmental operation, such as pollution prevention
High efforts in utilizing natural resources, such as mining
High efforts in conserving natural resources
Efforts in natural resource regeneration, such as reuse
Effective energy utilization, such as use fossil/bio-energy
Efforts in planning and conducting environment policy
High compliance in environment legislations
High satisfaction of customers and business partners in SCs
High efforts to manage business trust and reputation
High efforts in the social equity, such as salary, work load
High efforts in public benefits, such as training, welfare
High efforts in culture protection, such as respect habits
High efforts in business ethics and moral attempts
Natural environment decides the performance of SSCM
The politics satisfaction decides the performance of SSCM
The religion situation decides the performance of SSCM



5. Please indicate the relationships between the customer requirements and the technical requirements.

SYMBOL:

- ● means there is a strong association between the customer and technical requirements
- o means there is a somewhat association between the customer and technical requirements
- Δ means there is a weak association between the customer and technical requirements

Symbols
● = 9 (Strong association)
o = 3 (Somewhat association)
Δ = 1 (Weak association)

	Efficient communication within facilities in supply chains	Effective work processes within facilities in supply chains	Employee rights protection throughout the supply chains	Protect the safety while employees are working	Assure consumer safety while they consume products/services	Protect consumer health while they consume products/services	Provide the compliance in products/services as claimed	Minimize the cost of clients consuming products/services	Minimize managerial or operations costs throughout supply chains	Comply with the legislations on economic, environment, and society
Costs and expenses control										
Reach the high business profitability										
Widely apply new technology and integrated systems										
Efficient business process management, activity operations										
Apply the optimization techniques or methodologies in SCs										
Collaborative operations among facilities in SCs										
Good environment operation, such as pollution prevention										
High efforts in utilizing natural resources, such as mining										
High efforts in conserving natural resources										
Efforts in natural resource regeneration, such as reuse										
Effective energy utilization, such as use fossil/bio-energy										
Efforts in planning and conducting environment policy										
High compliance in environment legislations										
High satisfaction of customers and business partners in SCs										
High efforts to manage business trust and reputation										
High efforts in the social equity, such as salary, work load										
High efforts in public benefits, such as training, welfare										
High efforts in culture protection, such as respect habits										
High efforts in business ethics and moral attempts										
Natural environment decides the performance of SSCM										
The politics satisfaction decides the performance of SSCM										
The religion situation decides the performance of SSCM										

Thank you for your time and responses.