MODELING GREEN SUPPLY CHAIN IN A MANUFACTURING ENVIRONMENT

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Abstract

In recent years, the importance of waste reduction and efficient use of resources has led companies to focus more on eco-friendly processes at different stages of the manufacturing process, such as acquiring raw materials, production, assembly, distribution and recycling. Additionally, manufacturers in many countries have been either under governmental pressure to follow eco-friendly guidelines in their production process, or have chosen to do so to benefit from governmental incentives such as tax reductions. Furthermore, the public interest in environmentally friendly goods has been on the rise as a result of growing awareness towards the negative consequences of industrial activities and practices that harm the environment. All of these factors have made it imperative for industries to adopt green practices in order to gain or maintain their competitive edge. However, staying green is not easy, as green production lines, products and practices are often more costly than their regular non-green counterparts. Therefore, in this study, we have developed a mathematical model based on supply chains and manufacturing facilities of all sizes producing various products with two distinct goals. First, our mathematical model helps companies maximize their profit and second it allows them stay green while the profit is maximized. This mathematical model is then solved for two scenarios in three different companies to (1) evaluate the effects of customer sensitivity towards eco-friendliness of the products and (2) the effects of changing CO_2 emissions and transportation costs. The results of the calculations performed by the mathematical model shows the profit that the company stands to gain based on an allowed production volume that does not exceed the defined green criteria and the amount of raw materials to be purchased from suppliers that offer different degrees of greenness. In practice, this mathematical model can be expanded to include more constraints and can also be implemented in commercial software solutions to provide managers with valuable data to facilitate the decision making processes within the companies and among connected commercial entities.

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Chapter 1. Introduction

1.1. Foreword

In recent years, firms have worked harder than ever to develop their organizational structure and strategies in order to be able to flourish in an increasingly competitive world market. One of the most important challenges that companies are faced with is how to maximize profits through the efficient use of resources and waste reduction by pursuing eco-friendly processes (Azzone and Noci 1998, Nouira, Frein et al. 2014). According to Kress (2013), in a recent trend, customers tend to buy environmentally friendly green products although they may cost a little more than those products that are not green (Krass, Nedorezov et al. 2013). This is partially due to the fact that, customers' awareness about green products has increased dramatically as a result of the many advertising campaigns (Seman, Zakuan et al. 2012, Nouira, Frein et al. 2014). Evidently, people are now more concerned about the effects and side-effects of using non-green products on the environment and the implications of non-eco-friendly processes on their present living conditions and that of future generations (Mollenkopf, Stolze et al. 2010). The companies that actually desire to survive and excel in this newly formed market should therefore apply green principles in their manufacturing processes (Galeazzo, Furlan et al. 2014). In addition to these advertising campaigns, in most countries, governments have implemented new policies that are aimed at protecting the environment (Dornfeld 2012). It seems that, in the current climate, moving towards green in firms is more of necessity rather than an option (Simons and Mason 2003).

1.2. Supply Chain Management

The concepts of Supply Chain (SC) and Supply Chain Management (SCM) have become one of the most important managerial aims within the last two decades. These concepts were introduced for the first time in the middle of the 1980s (Jones and Riley 1985) and later became more common in the 1990's (Min and Kim 2012).

A supply chain can be defined as follows: "A supply chain consists of all stages involved, directly or indirectly, in fulfilling a customer request. The supply chain not only includes the manufacturer and suppliers, but also transporters, warehouses, retailers, and customers themselves.” (Chopra and Meindl 2007)

We can define SCM as the set of processes that an organization performs to control its SC behaviors and achieve its predefined aims (Min and Kim 2012). The Supply Chain Council (2007) (www.supply-chain.org) defined SCM as a process which “encompasses every effort involving producing and delivering a final product or service, from the supplier’s supplier to the customer’s customer. Supply Chain Management includes managing supply and demand, sourcing raw materials and parts, manufacturing and assembly, warehousing and inventory tracking, order entry and order management, distribution across all channels, and delivery to the customer.”

1.3. The Concept of Green Supply Chain Management and Its Origins

Nowadays along with the fast development of global industrialization and an increase in demand for the reduction of the environmental impacts of consumer products, it seems necessary that SC managers try to consider environmental aspects in their decision-making process (Nouira, Frein et al. 2014). Green supply chain management (GSCM) attempts to increase productivity and profit while considering the environment in SC decision making processes. GSCM tends to minimize the unwanted environmental impacts of supply chain processes within participating organizations and the supply chain itself. Srivastava (2007) defined GSCM as “integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life.” (Srivastava 2007)

There are two origins from which GSCM has emerged. The first one is the environmental managers who tried to use life cycle assessment (LCA) techniques for evaluating the products’ environmental impacts. This technique considers many logistical activities such as material handling, packaging, distribution and disposal besides the usual product design and manufacturing processes. In addition, by integrating environmental issues with SCM practices, creative supply chain managers and analyzers aimed to improve and optimize supply chain processes (Srivastava 2007).

There are many advantages recorded for the GSCM such as its environmental importance and necessity, and financial and operational advantages. For green companies, some aspects of green practices such as waste elimination, resource saving, and productivity improvement can lead to competitive advantages (Porter and Van der Linde 1995, Porter and Linde 1999). Greening different phases of the supply chain can lead to an integrated GSCM which can lead to competitiveness and better economical and operational performance.

1.4. The Concept of Sustainable Supply Chain Management

The concept of Sustainable Supply Chain Management (SSCM) was first proposed in the 1980s when the World Commission on Environment and Development (WCED) considering the threats of deteriorating natural resources to human beings, animals, and environment, presented the two concepts of "sustainable use" and "sustainable development" (Jones and Riley , Beamon 1999, Ahi and Searcy 2013). WCED defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Economic, social and environmental dimensions are three dimensions of sustainable development which are highly rooted in political and social scenes. In addition, they are also related to industrial fields. (Preschey 2005, Muduli, Govindan et al. 2013).

In recent years, the concept of sustainability has been applicable to many fields such as economics, technology, agriculture and SCM. In general, SSCM focuses on the internal and external factors in the management of a supply chain and integrates different aspects of sustainable development. Therefore, the SSCM approach considers environmental, economic and social issues in supply chain management. Although, in SCM literature, GSCM and SSCM are used interchangeably, they are not similar. In fact, because SSCM covers economic, social and environmental sustainability whereas GSCM is largely the environment part of SSCM. (Srivastava 2007, Kumar, Teichman et al. 2012, Ahi and Searcy 2013)

1.5. Goals and Advantages of Green Supply Chain Management

Although it seems that environmental management has higher initial costs and imposes certain limits on design and manufacturing activities, there are many advantages in implementing GSCM practices for the companies (Hervani, Helms et al. 2005). One of the biggest advantages of GSCM is cost reduction. For example, reducing costs of raw material, energy costs and insurance costs can help reduce the overall production costs (El Saadany, Jaber et al. 2011, Ahi and Searcy 2013).

Also, following GSCM guidelines can reduce the risk of waste bills and pollution fines, or water or energy shortages (El Saadany, Jaber et al. 2011).

Implementing GSCM can also improve the public image of a company and increase sales, and community support (Beamon 1999, Lee, Tae Kim et al. 2012). Increasing property value by lowering operating costs and creating a healthier environment – through decreasing or responsible management of environmentally hazardous materials – are some other advantages of the GSCM (Beamon 1999, de Sousa Jabbour, Jabbour et al. 2013).

In addition, GSCM directly affects SCM practices. SC efficiency and flexibility will be increased by integrating environmental and supply chain management and through minimizing the amount of waste generated in SC, the entirety SC can be made lean. Moreover, GSCM increases adaptability and GSC analysis often leads to innovative processes and continuous improvements (Wilkerson 2005). Finally, since GSCM involves policy negotiation among manufacturers, suppliers and customers, it will lead to a better "alignment" of business processes and principles and as a result create new markets and a great competitive advantage for green companies (Hervani, Helms et al. 2005, Zhu, Sarkis et al. 2005, Ahi and Searcy 2013).

1.6. Green Supply Chain Management Barriers

There are four main groups of barriers of GSCM: (1) environmental requirement costs, (2) lack of green awareness, (3) technological barriers, and (4) lack of environmental information, knowledge and training (Walker, Di Sisto et al. 2008, Murillo-Luna, Garcés-Ayerbe et al. 2011, de Sousa Jabbour, Jabbour et al. 2013).

The environmental requirement costs and investments are one of the major obstacles to green purchasing programs. Involving customers and partnership with suppliers in green projects and taking advantage of governmental loans for these kinds of projects are a few ways to tackle this issue and help companies move towards green (Min and Kim 2012).

Some barriers such as lack of government involvement and participation and lack of management support in higher level are caused by lack of green awareness. Hence all managers, end customers and especially governments are responsible for the promotion of GSCM awareness (Massoud, Fayad et al. 2010, Murillo-Luna, Garcés-Ayerbe et al. 2011).

Overcoming technological limitations is only possible through inter-organizational cooperation and investment from both governments and large companies with widespread influence (Das 2002, Min and Kim 2012). One of the best ways to spark interest in these areas in order to encourage technological development is to provide more training for government personnel and those who are involved in the decision-making processes of influential companies (Zhu, Sarkis et al. 2005, Lee 2008). Finally, establishment and publicizing environmental information databases and knowledge transfer networks can also increase environmental information and knowledge (Kumar, Teichman et al. 2012).

1.7. Green Supply Chain Management Initiatives

There are many factors that can motivate companies to adopt GSCM. These factors can be categorized in four main groups. One of the main factors is customer requirements. This factor has an important effect on design and specifications of the products, and most suppliers try to respect and follow these requirements. The green thinking and demand of the major customers can stimulate companies and suppliers to apply green practices in their organizations. This demand has a huge influence and goes through the entire supply chain (Eltayeb and Zailani 2009).

Another main factor is governmental and international laws and regulations. Passing laws and regulations and monitoring the industries to execute these laws by governments, national standard institutes, and local authorities have a great impact on industries and can facilitate moving towards green practices. Some laws and regulations from international organizations such as UN and EU, are particularly important in this regard (Das 2002, Min and Kim 2012).

Governments in many countries have new policies about eco-friendly manufacturing which has forced firms to apply green practices in their structures and activities. Companies are trying to be more cautious about the impact of their activities on the environment. For example, a recent law in the United States Congress demands decreasing CO_2 emissions by 80% before 2050 (Dornfeld 2012).

There are some tools that help firms in the implementation of green practices. For example, Sustainable Value Stream Mapping (SVSM) considers CO_2 emissions as an additional source of waste and helps planning to decrease CO_2 emissions (Simons and Mason 2003).

Using old, second hand and worn products for the purposes of repairing, reusing, reassembly and recycling has positive economic impacts on reducing costs and improving organizational productivity which is an important initiative for the companies to develop GSCM practices (Zhu, Sarkis et al. 2007, Eltayeb and Zailani 2009). For example, Texas Instruments (TI) in 2005 and 2006, initiated more than 200 new resource preservation projects for which the initial investment was $9.7 million. In just 15 months, it led to $7.7 million annual savings. The results of these projects were the reduction of the company's environmental impacts and the efficient use of natural resources such as water and fossil fuels (http://focus.ti.com/general/docs/gencontent.tsp Texas Instruments 2007).

There are some non-governmental organizations and groups which have environmental activities and try to spread green awareness within both the society and the industries. They inform people about green products and encourage them to buy green products instead of their non-green counterparts. Although they are mostly not experts in technical fields, environmental activists and NGOs can have great influence on industries by improving green awareness about the adoption of green practices in industries and promoting green awareness among people (Kong, Salzmann et al. 2002). They believe that end customers have the power to make a difference through their behavior by adopting green products which eventually will improve their quality of life.

According to the results of many surveys and interviews, in recent years the demand for green products has steadily increased. For example, the results of a survey conducted by the European Commission (2008-2009) have shown that more than 80% of people in Europe are concerned about the impact of the consumer products on the environment (Nouira, Frein et al. 2014).

1.8. The Concept of Green Manufacturing

There are many ways to encourage manufacturing facilities to improve the environmental outcomes of their production processes. Green manufacturing is a good example of a workplace practice that involves implementing new technology (Porter and Van der Linde 1995, Deif 2011). Green Manufacturing is usually defined as the elimination of negative impacts of the production and resource consumption on the environment (Deif 2011). The Center for Green Manufacturing at Alabama University defines green manufacturing as follows: "To prevent pollution and save energy through the discovery and development of new knowledge that reduces and/or eliminates the use or generation of hazardous substances in the design, manufacture, and application of chemical products or processes" (https://engineering. Dartmouth.edu/~d30345d/ courses/engs37/GreenManufacturing.pdf).

Generally, green manufacturing encompasses production processes which use materials and inputs with low environmental effects that generate little or no waste and pollution (Deif 2011). Green manufacturing deals with minimization and prevention of waste and pollution which is also known as the source reduction, recycling, and green product design (Tan, Liu et al. 2002, Eltayeb and Zailani 2009). Recycling involves using waste as components in a process or as an effective substitute for a new product, or returning the waste as the constitutive ingredients to the original process which produced it as a replacement for raw material (Jayal, Badurdeen et al. 2010, Deif 2011). In this regard, green product design addresses the issues with the systematic features of design that affect environmental health and safety over the product life cycle and aims at solving this problem through suggesting new product designs and generating improved design processes (Fiksel and Fiksel 1996).

There are two types of green manufacturing practices regarding pollution control: pollution prevention technologies and pollution control technologies. Pollution prevention technologies change the infrastructure of the manufacturing system and promote the use of more eco-friendly resources. Pollution control technologies include all the "end-of-pipeline" equipment that eliminates emissions that are made during the production process (Rusinko 2007, Galeazzo, Furlan et al. 2014).

Most industrial facilities have already begun, expanded or adopted source reduction and recycling activities (Sarkis 2001, Sidique, Lupi et al. 2010). Based on the 1995 survey of over 200 U.S industrial facilities, 90% of them cited source reduction and more than 80% cited recycling as main elements in their plans related to the pollution prevention (Florida and Atlas 1997).

1.9. Advantages of Moving Towards Green Manufacturing

In green, processes consume less material and energy, input materials from non-recyclable sources are replaced with those from recyclable sources. Reducing unwanted outputs, especially CO_2 emissions, is one of the main goals. Also, waste is generally considered as an unnecessary use of

resources which pollutes the air, water and land. Green also tries to eliminate the activities which may harm human health or nature (Mollenkopf, Stolze et al. 2010, Deif 2011).
Lowering raw material costs, for example by replacing virgin material by recycled waste, gaining production efficiency, for example by using less energy and water, improving corporate image by reducing perceived environmental effects on the public are some of the most important advantages that green manufacturing offers (Porter and Van der Linde 1995).

1.10. Steps Needed for Moving Towards Green Manufacturing

There are actions that essentially enable a manufacturing plant to become more environmental friendly (Florida and Atlas 1997):

- Improving maintenance program, record keeping and processes
- Modifying equipment, layout, piping and inter-transportation
- Changes in the mode of operation (not necessarily equipment)
- Replacing raw material
- Separating hazardous and chemical waste from non-hazardous and non-chemical waste
- Monitoring and controlling the conditions of organizations
- Changing detergents and cleaners used in manufacturing facilities
- Monitoring the length of time for which materials can remain usable

Most of these actions are related to improving the mode of operation or monitoring it, or are basic ideas that workers can easily implement; and the actions that actually require new technology are not that many. Therefore, it seems that the initial steps towards green manufacturing is organizing production operations, managing the functions, and training the personnel for green manufacturing to ease the identification and development of both technical and waste minimization ideas (Dillon and Fischer 1992).

There are several requirements for this process. First, it is important to have an accounting system for inputs, wastes and their related costs in all parts of the production processes. Analyzing costs will help track them back to specific production processes and a good understanding of these costs will improve future planning (Allenby and Richards 1994, Florida and Atlas 1997).

Second, the facility should be well-informed about the environmental rules with which it must comply now and the changes that probably may happen in the future. The information about the environmental laws should be up-to-date in case of certain changes or restrictions on using specific chemicals. For example, maybe in particular cases, government permits are required for the use of certain chemicals at the time or in the future (Winter and May 2001).

Third, involving the production workers in green manufacturing will be very helpful. When they are involved in this program personally, they often make a significant effort to uphold the standards, specially improvement in industrial housekeeping, internal recycling and limited changes in production processes(Hart and Ahuja 1996, Theyel 2000).

Fourth, manufacturers that want to be green need easy access to the technical and environmental information about cleaner technology options. It is also a good idea to involve the facility's suppliers and customers in this effort. Sometimes they can suggest solutions that the facility has overlooked (Georg, Røpke et al. 1992).

Finally, to create an effective green manufacturing operation, it can be helpful for the facility, to have challenging objectives and check the progress towards achieving them (Florida and Atlas 1997). The objectives can be financial (e.g., decreasing costs), legal (e.g., producing fewer emissions to avoid the need for an environmental permit), personnel (e.g., less harmful processes or materials that workers encounter) and physical (e.g., input reduction).

1.11. Green (Environmental) Waste

Green waste can be defined as the unnecessary use of resources or solid elements which pollute air, water or land and are harmful for humans and the environment. When manufacturing plants produce products or perform services for their customers, or when customers dispose of the used products, they produce environmental wastes (Porter and Van der Linde 1995, Hicks, Heidrich et al. 2004).

According to the EPA (the United States Environmental Protection Agency), environmental wastes are not only non-value added issues for customers but also they make additional costs for the society in general (Hicks, Heidrich et al. 2004).

Environmental wastes affect time, quality, and especially cost of a production system. Moreover, costs from waste water, energy and raw materials are also to be considered in many cases. In addition, often times, the existence of environmental wastes is a sign of inefficient production and may cause extra cost and time to mend (Corbett and Van Wassenhove 1993, Melnyk, Sroufe et al. 2003).

Environmental wastes are produced in many processes such as painting and metal finishing. Furthermore, the chemicals and dangerous materials which are used in production processes are sometimes harmful for the health and safety of the workers. This in turn results in additional costs for their medical treatment (Ho, Shalishali et al. 2009). Environmental wastes (Beamon 1999, Hicks, Heidrich et al. 2004) typically include:

- Energy, water, or raw material used in quantities more than what is required to satisfy the customers' needs.
- Air emissions, wastewater discharges, solid materials, such as trash or scrap which are released into the environment.
- Chemical and dangerous materials which are used in production and cause health and safety hazards for the workers when contaminating the work environment.

Some of the most common negative environmental effects that need to be closely monitored and contained occur in the following processes in a facility (Kutz 2007):

- Processes on metals such as milling, stamping, machining, welding, etc.
- Metal Finishing
- Cleaning parts
- Washing the surfaces
- Coating the surfaces
- Chemical Formulation
- Hazardous materials usage
- Molding

Reducing hazardous waste that is produced during production and operations, and post-production treating, storing or disposing wastes can lead to efficient waste minimization (Marguglio 1991).

1.12. Choosing Options for Green Manufacturing

There are five steps in choosing options for green manufacturing. When a suitable organizational method is identified, the first step is the creation of an inventory of the inputs used, for example raw material, water, energy, etc., alongside the wastes that are generated. These wastes can be products which did not meet the specified standards, inputs returned to the suppliers, solid wastes, and other outputs which had not meet the prescribed specifications and were assigned to the treatment or disposal facilities or even discharged into the environment (Melnyk, Sroufe et al. 2001, Deif 2011).

Selecting the most important outputs which are non-standard products or waste streams is the second step. This selection process depends upon the costs, environmental impacts, legal requirements, customers' demands, or a mixture of all these important factors (Franchetti, Bedal et al. 2009).

The third step is attempting to reduce or remove these non-standard products or waste stream outputs at their origins. This can be achieved through product changes, process changes, input changes, increased internal reuse of wastes and even better housekeeping (Walton, Handfield et al. 1998, Franchetti, Bedal et al. 2009).

The assessment of the options for their environmental benefits, technical practicability, economic adequacy and employee acceptability is the fourth step. An important factor to consider when assessing economic adequacy is calculating the pay-back period (Bergmiller and McCright 2009, Chuang and Yang 2014, Govindan, Diabat et al. 2015).

Finally, the fifth step is to implement one or some of the options which resulted from the assessment in the previous step. Some of these options such as improvements in housekeeping and changes in input are not only eco-friendly and advantageous, but also easy to implement, and economically viable (Hart and Ahuja 1996, Rao and Holt 2005, Deif 2011).

1.12. Role of Governments and International Organizations in Promoting Green Manufacturing and Green Supply Chain Management

Governments and international organizations play an important role as the leaders in promoting GSCM and green manufacturing. One reason is that governments themselves are very influential customers in some nationwide markets. A good example of the immense power of governmental legislations is well-demonstrated in a study conducted for the European Commission in 2004 (http://europa.eu/scadplus/leg/en/s15000.htm). According to this study, the EU can save more than

800,000 tons in CO_2 emissions if all public authorities across the continent required more energy-efficient computers, and the market tried to satisfy that need.

Also, governments and international organizations can play subtler and yet more crucial roles regarding the environmental issues. Balancing green criteria, developing high-quality standards for green products, supporting the private sector in developing green practices, supporting scientific institutes for developing new green technologies are some of these major activities (Diabat and Govindan 2011). Improving green awareness through media, creating official eco-labeling systems, and encouraging companies to apply green practices by tax exemption and service discounts are some other beneficial roles that the governments can take on (Beamon 1999, Handfield, Walton et al. 2002).

1.13. The Objective of the Thesis

In this research we have developed a mathematical model that considers different types of costs along with constraints such as energy usage and transportation emissions to produce a specific product during the manufacturing process. Our model calculates production amount, and total amount of raw material that should be acquired from different suppliers in order for the company to maximize its profit while staying green. In addition, we have included case studies and several scenario setups which can be used for validating the mathematical model that is proposed.

1.14. Roadmap of the Thesis

This thesis is divided into five chapters. The next chapter provides a brief literature review of green supply chain and manufacturing studies that are more directly related to the work presented in this thesis. Chapter 3 presents the problem description and the formulation of the mathematical model, as well as the descriptions for each part of the model. In chapter 4, the linearized model is solved using IBM ILOG CPLEX® Optimization Studio, six case studies and numerical examples are presented, and the results are analyzed. Finally, chapter 5 presents the conclusion of the study as well as future avenues of research.

Chapter 2. Literature Review

In this chapter, we cover some important studies that are pertinent to the development of the ideas in the current research. Some of these articles focus more on the solution methods rather than formulating the model.

2.1. Green Supply Chain Management and Its Definitions

The rise of environmental issues, public awareness regarding these issues and the possibility of incorporating cost saving methods in the manufacturing process has led manufacturing supply chains to move towards green supply chain management (GSCM) (Sheu, Chou et al. 2005, Xu, Hu et al. 2013). Therefore, the emergence of GSCM has helped companies develop strategies for improving their profits and market share while adhering to environmental conservation standards (Hoek 1999). Although GSCM is different from environmental or sustainable supply chain management, these terms are often used interchangeably throughout the literature (Ahi and Searcy 2013). The most important area that distinguishes GSCM from similar concepts is that in addition to the products and production processes, GSCM is also involved in factors such as sourcing (as a direct factor that demonstrates the supplier's green initiative), buyer's taste and requirements in the framework of green supply chain and even the way returns from customers are handled. In this way, GSCM has aligned its concepts more thoroughly with the green initiative compared to the other similar concepts (Wu, Tseng et al. 2011, Brindley and Oxborrow 2014).

Various authors have characterized GSCM in different ways and in general, the focus has been the integration of forward and reverse supply chain activities with green practices while the detailed properties of the concept are modified to fit the needs of different industries (Hu and Hsu 2010, Shang, Lu et al. 2010, Olugu, Wong et al. 2011).

2.2. Advantages of GSCM and Impediments

In the past, the resources used in the process of manufacturing were only associated with cost; however, in the new paradigm of GSCM the environmental impact of using the resources is also considered in addition to money. Therefore, GSCM considers both ecology and economy as its objectives whereas the sole objective of conventional supply chain management is economy (Marchi, Maria et al. 2013, Luthra, Qadri et al. 2014). In fact, it was the inevitable need for a sustainable environment that led to the gradual change in innovations and strategies of conventional supply chain management that ultimately gave birth to GSCM (Srivastava 2007). The superiority of GSCM over conventional supply chain management lies in its power to incorporate a wide range of green performance criteria such as efficiency (operational and economic as well as social and environmental), adherence to green regulations, improved use of resources and waste management techniques. GSCM is also capable of accounting for customer value and creating public awareness of green (Hervani, Helms et al. 2005, Rao and Holt 2005, Büyüközkan and Çifçi 2012, Toke 2012, Verma and Gangele 2012, Zhu, Sarkis et al. 2012). Since many of GSCM criteria offer a strong competitive edge, important companies such as Apple, IBM, Sony, General Motors, Ford Motor Company, Coca-Cola, Adidas, and Nike have made it their priority to follow those guidelines (Sarkis 2003, Zhu and Sarkis 2006, Ageron, Gunasekaran et al. 2012, Kumar, Teichman et al. 2012). Although it is feasible and rather easy for such industrial giants to incorporate GSCM into their strategies on their way towards green, it might prove to be more challenging in the case of small and medium-sized companies (Lee, Kim et al. 2012). Planning and executing GSCM is particularly challenging for small-scale companies that operate within developing companies where factors such as emphasis on reducing costs, lack of regulations and public awareness and even corruption often make it impractical for companies to pursue green and GSCM (Berliner and Prakash 2013).

2.3. The Challenges in Transforming Supply Chains from Conventional to Green

For many companies, transforming their supply chains from conventional to green presents some difficulties the most important of which is inevitable increase in costs (Kim and Rhee 2012). In most cases, however, this cost increase occurs because the areas that are chosen for implementing GSCM are selected incorrectly and furthermore green practices are applied improperly (Ho and Choi 2012).

In their study, Ho and Choi (2012) analyzed the initiation, implementation and institutionalization of GSCM in a Hong Kong fashion company. They used the five-R framework to conduct their analysis (i.e. recycle, reuse, reduce, re-design and re-imagine). They concluded that fashion companies can, in fact, greatly increase their competitive advantage by addressing environmental challenges throughout the process of product development and management of the lifecycles of products. They also suggested that the five-R framework can help understand the company's current achievements in GSCM and clarify the areas where improvement is needed.

Implementation of GSCM practices begins by purchasing green raw materials and goes all the way to integrated lifecycle management. In this way, the supply chain consists of supplier, manufacturer and customer connected in a circle with the help of reverse logistics (Büyüközkan and Çifçi 2012). The important factor is that for successful implementation of GSCM, all the stages of forward and reverse manufacturing supply chain must be centered around green concepts and need to be constantly studied and improved by innovative research. In this process, the manufacturer's responsibility is to achieve and lead the green effort to set an example for other members of the supply chain to follow which ultimately enhances the green effort all throughout the supply chain (Sarkis, Zhu et al. 2011). Thus, the level of difficulty that a company faces in implementing GSCM depends on many parameters. These parameters include (but are not limited to) the size of the company, nature of the manufacturing process and the products, capacity of the suppliers for providing green raw materials, the attitude of the customers towards using green products, the willingness of supply chain members to join the green effort, government regulations and the common practices endorsed by the competitors (Berliner and Prakash 2013, Marchi, Maria et al. 2013, Brindley and Oxborrow 2014, Luthra, Qadri et al. 2014).

Following, some of the important studies in the area of GSCM that have facilitated the development of ideas in the current study are briefly discussed.

2.4. The Interaction Between Operational Research and Environmental Management

(Bloemhof-Ruwaard, Van Beek et al. 1995): This article aims at providing solutions for operational researchers to incorporate environmental issues when analyzing supply chains and guidelines on how operational research (OR) models and techniques can be used in the field of environmental research. In relation to supply chains, the authors propose that in each step of an environmentally friendly supply chain (from raw material acquisition to waste disposal) preventive measures at the source should replace corrective measures further down the chain. They highlight the point that the considerable effect of product recovery management on production planning, inventory control and distribution naturally prevents this factor to be incorporated into traditional planning and control models mainly because of the uncertainties that exist in time, quality and quantity of recyclable used products. Therefore, if incorporated into models, recycling, among many other factors, can have a huge impact on the greenness of the supply chain. They also identify production and consumption elements of the supply chain as the main cause of pollution and propose that using OR modeling in these areas could improve the degree to which the supply chain is environmentally friendly.

2.5. Designing the Green Supply Chain

(Beamon 1999): This study tackles the issue of transforming traditional supply chains to extended supply chains that not only contain the traditional elements such as raw material acquisition and product manufacturing and delivery, but also consider the environmental management strategies. The author achieves this goal by providing information on the environmental factors that affect the formation of an environmentally friendly supply chain. Also, performance measures and a general procedure that can help achieve and maintain the green supply chain are presented. Finally, the basic differences between the two kinds of supply chains are discussed and the challenges of establishing the green supply chain are described.

2.6. A Strategic Decision Framework for Green Supply Chain Management

(Sarkis 2003): The author states that one important area that GSCM needs to focus on is the external relationships among industries regarding environmental programs. He proposes a strategic decision framework that helps managerial decision making in evaluating technological and organizational alternatives that affect other external organizations. This decision framework, which stems from practical solutions of environmentally conscious business practices, focuses on the elements of GSCM and yields a dynamic non-linear multi-attribute decision model that aids decision making within the green supply chain. The author also discusses the difficulties that exist in the modeling approach. While the model has only incorporated internal influences and relationships, it can be expanded to include external factors such as new environmental laws or cooperation among competing supply chains.

2.7. Integrating Environmental Criteria into the Supplier Selection Process

(Humphreys, Wong et al. 2003): This study proposes a framework based on environmental criteria that can be used in the process of supplier selection. The identified factors are categorized into qualitative and quantitative environmental criteria and were used to construct a decision model. They have implemented this system into a software program that can be conveniently used by purchasing managers who seek to take advantage of the green supply chain. Finally, the use of this knowledge-based system is illustrated through an example.

2.8. An Integrated Logistics Operational Model for Green Supply Chain Management

(Sheu, Chou et al. 2005): This paper presents an optimization-based linear multi-objective programming model that can handle integrated logistics and the related used-product reverse logistics in a green supply chain. While most studies conducted in this field up to that point were applicable to specific areas of the industry, this proposed model is generalized and has the potential to be applied in a wide variety of situations. Also, the authors have included factors such as governmental subsidies for used-product recovery, return ratio, and recycle fees charged to manufacturers in their mathematical model. In a case study of a selected notebook computer manufacturer, they show that the company would be able to improve its chain-based aggregate net profits by more than twenty percent using the mathematical model proposed in this study.

2.9. A System Model for Green Manufacturing

(Deif 2011): In this paper, the authors have developed a systems model approach for green manufacturing. The open mixed architecture goes through the transformation at different stages beginning from discovering the present green level of the system, moving on to devising a plan to move towards green, optimizing the plan and ultimately put mechanisms in place that ensure sustaining the devised plan to keep the manufacturing process green. The proposed transformation occurs at the level of machines, processes, and at the system level. In the architecture of the system model, performance grades that are connected to the strategic objectives of green manufacturing control different layers of the transformation plan. Finally, this system model is demonstrated using an industrial case study of a wood products manufacturer.

2.10. Design of Sustainable Supply Chains under the Emission Trading Scheme

(Chaabane, Ramudhin et al. 2012): This study presents a mixed-integer linear model for sustainable supply chain that includes life cycle management and material balance constraints at each node. The model discriminates between solid and liquid waste and gaseous emissions, therefore in can be an effective tool in designing supply chains based on different environmental policies that focus on recycling or greenhouse gas emissions reduction. The authors also present an experimental evaluation of the model conducted in the aluminum industry and propose that although only economic and environmental factors were incorporated into their mathematical model, the methodology has the potential to incorporate social dimensions, as well.

2.11. A Product-Mix Decision Model Using Green Manufacturing Technologies under Activity-Based Costing

(Tsai, Chen et al. 2013): This paper presents a mathematical model that analyzes whether a certain product mix is profitable based on activity-based costing and the theory of constraints in a mixed-integer programming model. The authors assert that the proposed model can facilitate decision making about product-mix using green manufacturing technologies. The model is demonstrated using a numerical example of a car metal component parts manufacturer. Although the authors acknowledge that their proposed model selects a product mix with higher pollution when the sole objective is maximizing the profit, they argue that one can use the constraints to limit emission quantity within the imposed limits. Their goal has been to maximize the operating profit while deviation from the target emission is minimized.

2.12. A Multicriteria Framework to Evaluate Supplier's Greenness

(Falatoonitoosi, Ahmed et al. 2014): This paper provides multilevel causal framework for selecting the most effective green suppliers based on their influential characteristics in two main areas of green supply chain management: green logistics and environmental protection. The authors have analyzed factors, dependencies and feedbacks of the elements in these two areas and have proposed an impact relationship map which can be used to determine the most influential elements that can improve the green supply chain. The authors suggest that enterprises can use their model to determine the degree of greenness of different suppliers and prioritize their raw material purchase based on the resulting data. A case study of the automotive industry is presented, as well.

2.13. Integrated Evaluation of Green Design and Green Manufacturing Processes Using a Mathematical Model

(Tseng and Lin 2014) This study proposes a mathematical model which minimizes the cost of manufacturing while it considers the traditional criteria of manufacturing costs and environmental criteria of green related costs. The authors develop a model to find the green design and the associated green manufacturing processes. The model demonstrates that different design alternatives which can satisfy the same product requirements and design concepts can affect the manufacturing process and the green supply chain. The authors implemented and tested their model through an example of a mobile phone manufacturing process using the CPLEX software and the results show that the model is practical and useful for integrated evaluation of green design and green manufacturing.

2.14. The Contribution of This Study to the Literature

The literature review in this chapter covered the research that focused on the important studies in the field of GSCM. These can be divided into two main groups. First, the work that dealt with concepts of green supply chain and manufacturing in general and second, the studies that provided various models and analytical tools which investigate the green supply chain. However, there are few papers that have suggested mathematical models for developing GSCM. In this thesis, we aim to contribute to the latter by proposing a mathematical model that considers both financial and environmental criteria as the objective functions. It aims at maximizing profit while considering the main costs of manufacturing and environmental impacts of the operation. In our model, we have put more emphasis on beginning with the purchase of raw materials from suppliers, moving on to the manufacturing process and finally arriving at the finished-goods delivered to the wholesale buyers. One of the main factors that is considered in our model is the raw material and suppliers which were not considered in similar models previously discussed. There are more detailed and specific costs that we consider in our model such as the costs of recycling, disposal and disassembly. In addition, our model develops more constraints and criteria to control manufacturing conditions so that the process is more eco-friendly. Additionally, the model imposes limitations on CO_2 emissions both in the manufacturing process and in transportation. This limitation encourages companies to use eco-friendly materials and transport them in a way that produces less CO_2. Transportation cost and transportation emissions of raw material are two other factors that we consider in our model which were not mainly mentioned in previous former models. Using fuel-efficient vehicles which are more environmentally friendly, can have significant influences on the total profit of the company. The next chapter provides the description of the problem investigated in this thesis along with the problem formulation.

Chapter 3. Methodology

3.1. Problem Description and Formulation

This research aims to study green supply chain and manufacturing in order to generate optimized production schedules in production systems of all sizes. Production planning and choosing the best supplier may have uncertainties related to initial production time, customer demand and some costs of manufacturing. The mathematical programming model, which is developed here, is based on supply chains and manufacturing facilities of all sizes producing various products.

In this chapter, our model is presented. The objective function of this mathematical model is maximizing profit while considering the main costs of manufacturing and environmental impacts of the operation. In Chapter 4, two case studies used for performing experiments along with their results are presented and various solutions are compared.

3.1.1 Model Assumptions

The following assumptions are made in order to model the green supply chain and manufacturing problem:

- All parameters of the model are deterministic.
- Each transportation vehicle has a fixed capacity.
- Different time periods (such as years, months or days) can be defined based on the type of the product. In the present study, we consider one workweek as the unit time period.
- The storage capacity of the company is known and fixed.
- Set up and development costs are known and fixed.
- The capacity of the suppliers is known and fixed.
- Total manufacturing time is known and fixed.
- The maximum capacity of production is known and fixed.
- The minimum quantity of production is known and fixed.

- Maximum energy consumption of the company is known and fixed.
- The permitted amount of CO_2 emission is known and fixed.

3.1.2 Description of Indices, Parameters and Decision Variables

The following chart shows the parameters and decision variables used for the formulation of the problem:

Indices

t	Period of time
i	Products
j	Manufacturing machine
m	Material
c	Connection (Assembly or Disassembly)
s	Suppliers

Parameters

C^V	Vehicle capacity
B_{imj}	If raw material m on machine j is used for product i
T_i	Manufacturing time of product i
T_t^T	Total manufacturing time in period t
C_{mt}^S	The capacity of each supplier
C_t^{St}	The capacity of store in period t
P_t^{Min}	Minimum production in period t
P_t^{Max}	Maximum production in period t
M_{im}^{Con}	Amount of raw material m consumed for manufacturing product i
L_t^{Em}	Limitation of total emission in period t
L_t^W	Limitation of total energy usage in period t
U_{it}^W	Energy usage of manufacturing product i in period t
D_{it}	Maximum demand of product i in period t
G_i	Price of product i

m_i^e	Sensitivity rating of customers towards manufacturing emission for product *i*
t_i^e	Sensitivity rating of customers towards transportation emission for product *i*
J_{mt}^{Em}	Emission of transportation of material *m* in period *t*
F_{ijt}^{Em}	Emission of manufacturing product *i* on machine *j* in period *t*
F_{mjt}^{Co}	Unit cost of manufacturing process using material *m* on machine *j* in period *t*
J_{st}^{Co}	Unit cost of transportation from supplier *s* in period *t*
M_{st}^{Co}	Unit cost of raw material from supplier *s* in period *t*
A_{cti}^{Co}	Unit cost of assembly of two parts of product *i* with connection *c* in period *t*
R_{jit}^{Co}	Unit cost of disassembly of product *i* on machine *j* in period *t*
Z_{it}^{Co}	Unit cost of disposal of product *i* in period *t*
W_{jit}^{Co}	Unit cost of energy of manufacturing product *i* on machine *j* in period *t*
I_{jit}^{Co}	Unit cost of recycling of product *i* on machine *j* in period *t*
E_{mj}^{Co}	Unit cost of environmental impact cost of material *m* on machine *j*
L_{it}^{CO2}	CO_2 emission limitation for product *i* in period *t*
l	Rate of production amount which goes for disassembly
u	Rate of production amount which goes for disposal
e	Rate of production amount which goes for recycling
A	Other one-time production costs such as set up cost, design cost, development cost, etc.

Decision Variables

X_{it}	Quantity of manufacturing product i in period t
H_{mt}	Amount of raw material m consumed in period t
Y_{it}	Binary variable for production. Takes value 1 if product i is produced in period t, 0 otherwise

3.1.3 Description of the Objective Function

The objective function of this problem is to maximize the profit of the company while considering the minimum cost for a green supply chain and manufacturing. We also maximize the eco-friendliness of the finished products. In this way, businesses that implement the model will gain maximum revenues and stay in the green zone.

The objective function is comprised of costs subtracted from revenues. Revenues include sales revenue while costs include production cost (material cost, manufacturing cost, assembly cost, energy cost, environmental impact cost), recycling (recycling cost, disassembly cost, disposal cost) and transportation cost.

Revenue

The revenue can be obtained by multiplying the price of product i (G_i) by the quantity of product i in period t (X_{it}).

$\sum_t \sum_i G_{\,i} * \, X_{\,it}$

Material Cost:

Material cost can be obtained by multiplying unit cost of material m (M_{st}^{Co}) by the quantity of material m that is consumed in manufacturing product i (M_{im}^{Con}).

$$\sum_m \sum_t \sum_i M_{st}^{Co} * M_{im}^{Con}$$

Manufacturing Cost:

The manufacturing cost of the items includes the cost of the manufacturing process, environmental impact costs (i.e. costs such as environmental taxes, cost of obtaining environmental permits or certificates, raised insurance cost due to environmental impact, etc.), energy usage cost and assembly cost.

The cost of the manufacturing process can be obtained by multiplying the unit manufacturing cost of the product using material *m* on machine *j* in period *t* (F_{mjt}^{Co}), quantity of product *i* in period *t* (X_{it}), and parameter (B_{imj}) to show whether material *m* on machine *j* is used for product *i*.

B_{imj} designation of material *m* on machine *j* used for product *i* is important because it takes into account the effects of the amount of the CO_2 emissions of that particular piece of machinery at the time of manufacturing and some costs for example the cost of manufacturing and energy costs of different machines.

$$\sum_{i}\sum_{m}\sum_{j}\sum_{t} F_{mjt}^{Co} * X_{it} \; * B_{imj}$$

Environmental Impact Cost:

The environmental impact cost is the total expenses imposed on the company due to environmental reasons. This cost can be different for various products and in different regions and might include such expenses as environmental taxes, cost of obtaining environmental permits or certificates, raised insurance cost due to environmental impact, etc. In the present model, the environmental impact cost can be obtained by multiplying unit environmental impact cost of material *m* on machine *j* (E_{mj}^{Co}), quantity of product *i* (X_{it}) in period *t*, and parameter (B_{imj}) to show if material *m* on machine *j* is used for product *i*.

$$\sum_{i}\sum_{j}\sum_{m}\sum_{t} E_{mj}^{Co} * X_{it} \; * B_{imj}$$

Energy Usage Cost:

Energy cost can be obtained by multiplying the unit cost of energy consumed in manufacturing product *i* on machine *j* in period *t* (W_{jit}^{Co}), quantity of product *i* in period *t* (X_{it}), and parameter (B_{imj}) to show if material *m* on machine *j* is used for product *i*.

$$\sum_{i}\sum_{j}\sum_{t}\sum_{m} W_{jit}^{Co} * X_{it} \; * B_{imj}$$

Assembly cost:

Assembly cost is obtained by multiplying the unit cost of assembly of connection parts c for product i in period t (A_{cti}^{Co}) and quantity of product i in period t (X_{it}).

$$\sum_{c}\sum_{t}\sum_{i} A_{cti}^{Co} * X_{it}$$

Recycling cost:

Normally companies install a set of machines for the purpose of recycling and assign a group of workers for separating usable components from the waste. These usable components will come back to the manufacturing process and other parts will be disposed of. For a high quality returned product, a higher percentage of the components are sent to remanufacturing and/or part harvesting. Meanwhile, for low quality returned product, the recycling percentage is greater.

The recycling cost can be obtained by multiplying unit cost of recycling or separating product i on machine j in period t (I_{jit}^{Co}), quantity of product i in period t (X_{it}), and parameter (B_{imj}) to show if material m on machine j is separated from product i, and the rate of the products which are recyclable.

$$\sum_{i}\sum_{j}\sum_{t}\sum_{m} I_{jit}^{Co} * X_{it} \; * B_{imj} * e$$

Disassembly Cost:

Disassembly is an organized method of removing desired parts from a product, without any damage to the parts(Giudice, La Rosa et al. 2006). Disassembly cost can be obtained by multiplying the unit cost of disassembling connection c of product i in period t (R_{jit}^{Co}) and quantity of product i in period t (X_{it}).

$$\sum_{c}\sum_{i}\sum_{t} R_{jit}^{Co} * X_{it} * l$$

Disposal Cost:

Disposal cost can be obtained by multiplying unit cost of disposal of product i in period t (Z_{it}^{Co}), quantity of product i in period t (X_{it}), and the rate of products which are disposable.

$$\sum_{i}\sum_{t} Z_{it}^{Co} * X_{it} * u$$

Transportation Cost:

Transportation cost, which is paid to the transportation services, is the expense involved in shipping raw materials from the suppliers to the manufacturing facilities. They come as fixed and variable costs depending on a variety of conditions related to geography, type of materials, distances traveled, and how materials should be transported.

Transportation cost can be obtained by multiplying unit cost of transportation of material m in period t (J_{st}^{Co}), amount of material that each vehicle can transport in period t (H_{mt} / C^V).

$$\sum_{m}\sum_{t} \frac{H_{mt}}{C^V} * J_{st}^{Co}$$

There are some other costs such as set up cost, labor cost, design cost, development cost, package cost, etc., which are considered fixed values in our model and are shown as a fixed parameter A that is the summation of these costs.

Mathematical representation of the Objective function:

Max

$(\sum_t \sum_i G_i * X_{it}$

- $\sum_i \sum_m \sum_j \sum_t MfgCost_{mjt} * X_{it} * B_{imj}$

- $\sum_m \sum_t \frac{H_{mt}}{C^V} * J_{st}^{Co}$

- $\sum_m \sum_t \sum_i M_{st}^{Co} * M_{im}^{Con}$

- $\sum_c \sum_t \sum_i A_{cti}^{Co} * X_{it}$

- $\sum_c \sum_i \sum_t R_{jit}^{Co} * X_{it} * l$

- $\sum_i \sum_t Z_{it}^{Co} * X_{it} * u$

- $\sum_i \sum_j \sum_t \sum_m W_{jit}^{Co} * X_{it} * B_{imj}$

- $\sum_i \sum_j \sum_t \sum_m I_{jit}^{Co} * X_{it} * B_{imj} * e$

- $\sum_i \sum_j \sum_m \sum_t E_{mj}^{Co} * X_{it} * B_{imj}$

- A

3.1.4 Description of the Constraints

Volume Requirement Constraints

The volume of material *m* should be at least equal to the quantity of product *i* in period *t* (X_{it}) multiplied by the quantity of material *m* that is consumed in manufacturing product *i* (M_{im}^{Con}) if material *m* on machine *j* is used to manufacture product *i*. Also, the volume of material *m* should at most be equal to the supplier capacity.

$$H_{mt} \geq \sum_{ij} X_{it} * M_{im}^{Con} * B_{imj} \qquad \forall t, m \quad (1)$$

$$H_{mt} \leq C_t^{St} \qquad \forall t \quad (2)$$

The above constraints ensure that the volume of material *m* bought from each supplier does not exceed the storage capacity.
Additionally, the volume of material *m* should at most be equal to the supplier capacity.

$$H_{mt} \leq C_{mt}^{S} \qquad \forall m, t \quad (3)$$

Constraint of Time capacity:

The manufacturing time of all products on all machines should be less than the total time capacity of the company.

$$\sum_i \sum_m X_{it} * T_i * B_{imj} \leq T_t^T \qquad \forall t, j \quad (4)$$

Constraints of Production Amount:

The production amount has upper and lower limitations.

$$X_{it} \geq P_t^{Min} \qquad \forall t \quad (5)$$

$$X_{it} \leq P_t^{Max} \qquad \forall t \quad (6)$$

Energy Usage Constraint:

The manufacturing energy usage of all products should be less than the total energy capacity of the company.

$$\sum_i X_{it} * U_{it}^{W} \leq L_t^{W} \qquad \forall t \quad (7)$$

CO_2 Emission Constraint

In order to become eco-friendlier, the emissions of all manufacturing and transportation for all of the products should be less than the total CO_2 emission that the company is permitted to have.

$$\sum X_{it} * B_{imj} * (F_{ijt}^{Em} + J_{mt}^{Em}) \leq L_t^{Em} \qquad \forall t \quad (8)$$

Constraints Based on the Eco-Friendliness of the Products

There is a restriction on manufacturing according to CO_2 emission limitations. A company can produce a product only if the total amount of manufacturing emissions and transportation emissions are less than the CO_2 limitation that the company is permitted to have. These constraints ensure that the product is not manufactured unless its carbon limitation is less than the amounts allowed by the regulations.

$$\sum_m \sum_j B_{imj} * \left(F_{ijt}^{Em} + J_{mt}^{Em}\right) - L_{it}^{CO2} \leq P_t^{Max} * (1\text{-}Y_{it}) \qquad \forall i,t \quad (9)$$

$$X_{it} \leq P_t^{Max} * Y_{it} \qquad \forall i,t \quad (10)$$

$$L_{it}^{CO2} - \sum_m \sum_j B_{imj} * \left(F_{ijt}^{Em} + J_{mt}^{Em}\right) \leq P_t^{Max} * Y_{it} \qquad \forall i,t \quad (11)$$

Constraints Related to the Production Quantity

The production quantity depends on the demand for the product in the markets. The degree of eco-friendliness of a product depends on the amount of CO_2 emission that is caused by manufacturing and transportation emissions. There is a maximum demand for one period that the company predicts. Therefore, the production quantity can be determined as the demand subtracted by the quantities that produce production and transportation emissions.

$$X_{it} \leq D_{it} - m * TC^{Em} \qquad \forall i,t \quad (12)$$

where

$TC^{Em} = T_F^{Em} + T_J^{Em}$

$T_F^{Em} = m_i^e * \sum_m \sum_j B_{imj} * F_{ijt}^{Em}$

$T_J^{Em} = t_i^e * \sum_m \sum_j B_{imj} * J_{mt}^{Em}$

$m = \frac{A^D}{A^{Em}}$

m : Annual Emission Ratio

A^D : $Annual\ Demand\ Prediction\ (Unit\ Product)$

A^{Em} : $Annual\ CO2\ Emission\ Index\ (kg)$

Annual Emission Ratio (AER) is used by Iranian national governmental organizations and R&D departments of manufacturing plants. It is calculated as a ratio of predicted demand for a particular manufacturing plant's product or group of products to the annual CO_2 emission index of the industrial zone where the manufacturing plant resides. The annual CO_2 emission index is determined by the Institute of Standards and Industrial Research of Iran (www.standard.ac.ir) for different national industrial zones.

Formulation of the Constraints:

Our objective function is subject to the following constraints:

$$H_{mt} \geq \sum_i \sum_j \; X_{it} * M_{im}^{Con} * B_{imj} \qquad \forall t, m \; (1)$$

$$\sum_m H_{mt} \leq C_t^{St} \qquad \forall t \quad (2)$$

$$H_{mt} \leq C_{mt}^{S} \qquad \forall m, t \; (3)$$

$$\sum_i \sum_m X_{it} * T_i * B_{imj} \leq T_t^T \qquad \forall t, j \; (4)$$

$$\sum_i X_{it} \geq P_t^{Min} \qquad \forall t \quad (5)$$

$$\sum_i X_{it} \leq P_t^{Max} \qquad \forall t \quad (6)$$

$$\sum_i X_{it} * U_{it}^{W} \leq L_t^{W} \qquad \forall t \quad (7)$$

$$\sum \mathrm{X}_{it} * B_{imj} * (F_{ijt}^{Em} + J_{mt}^{Em}) \leq L_t^{Em} \qquad \forall t \quad (8)$$

$$\sum_m \sum_j \mathrm{B}_{imj} * \left(F_{ijt}^{Em} + J_{mt}^{Em}\right) - L_{it}^{CO2} \leq P_t^{Max} * (1 - Y_{it}) \qquad \forall i, t \; (9)$$

$$X_{it} \leq P_t^{Max} * Y_{it} \qquad \forall i, t \; (10)$$

$$L_{it}^{CO2} - \sum_m \sum_j B_{imj} * \left(F_{ijt}^{Em} + J_{mt}^{Em}\right) \leq P_t^{Max} * Y_{it} \qquad \forall i, t \; (11)$$

$$X_{it} \leq D_{it} - m * TC^{Em} \qquad \forall i, t \; (12)$$

Chapter 4. Numerical Examples and Discussion

4.1 Introduction

In this chapter, we present case studies based on three companies in Iran. These case studies were used to validate the model and the results. Here, we study various scenarios. The scenarios presented in this chapter are designed to carry out the experiments in three companies: Pars PVC Pipe Company, Nab Stainless Steel Company and Pars Plastic Company.

Pars PVC Pipe Company is one of Iran's leading suppliers of plastic pipe systems. It currently exports its products to ten neighboring countries. Pars PVC Pipe Company has been a trusted manufacturer of plumbing systems since 1980. This company has been producing polyvinyl chloride (PVC) pipes for residential, agricultural, commercial and municipal markets.

This company is one of the largest PVC pipe producers in south of Iran. Almost 700 well-trained staff work for this company and it produces more than 80 different types of pipes. The company's products include:

- Pipes for transmission and distribution of water
- Sewer and wastewater pipes
- Electrical conduit and fittings including telephone and communications duct and fittings
- Plumbing and industrial pipes for both pressure/drain and waste/vent

Nab Stainless Steel Company is an Iranian company providing quality stainless steel products to clients across the southern regions of the country. Nab company is conveniently located in Shiraz, Fars, almost in the heart of the industrial area of Iran, with excellent distribution channels for shipping its products. Since 1984, Nab has become a leading stainless-steel service center that provides to the specific requirements of a diverse customer base. Nab's product range comprises of Nab cutlery set, Prince cutlery set, Nab serving spoon set, Prince serving spoon set, 5-piece serving set, 3-piece serving set, 5-piece cutlery set, paper napkin holders and other stainless-steel tableware. Manufactured using high quality steel, these products find usage in establishments like hotels, clubs, caterers, party halls and restaurants. More than 150 well-trained staff work for this company.

Pars Plastic Company is one of Iran's manufacturers of plastic pipe and fittings for the residential and commercial construction industry. The company produces drainage and pressure plumbing products in all the major plastic materials such as PVC, CPVC and PEX. Pars Plastic's manufacturing plant in Shiraz, Fars, was opened in 1985 producing various plastic products, including some specialty plumbing items. In 1990, the company started to produce PVC sewer pipe and fittings and then CPVC pipe and fittings. Within the last decade PEX pipe with metallic insert fittings was added to the product line. Pars Plastic's manufacturing plants are ISO 9001:2008 certified. The company produces more than 200 different pipes and fittings and has more than 500 staff working in the plant.

Since all of the above-mentioned companies are privately-owned, they do not disclose any financial details on the public domain. The raw data sets used in this study were obtained from these companies in the form of Microsoft Excel Data Sheets and Microsoft Access Databases after having been approved by the corresponding managerial departments and following the signature of confidentiality agreements. Names of third-party businesses and individuals in these data sets were substituted with alphanumerical designations and were unknown to us.

The corresponding mathematical models were solved in IBM ILOG CPLEX® Optimization Studio 12.6.3.0, using Optimization Programming Language (OPL) on a personal computer running Microsoft® Windows® 10 64-bit operating system, 2.50 GHz Intel Core i7-6500 CPU and 8.0 GB RAM. In all cases, the objective is to determine the highest profit for the company. All scenarios were tested for various conditions. Using the above-mentioned hardware, the IBM ILOG CPLEX® takes less than 10 minutes to solve each problem.

The proposed model is tested in scenarios in which the model is solved for changing the rate of the tendency of customers towards purchasing green products, and in scenarios in which the model is solved for changing delivery companies which differ in carbon emissions and transportation costs. Each set of data is arranged based on current existing data (Table 1).

Table 1. Outline of the experimental design of case studies in Chapter 4.

Company	Product	Experiment
Pars PVC Pipe Company	90mm PVC pipes	Effects of Customer Sensitivity towards Eco-Friendliness of the Products
Pars Plastic Company	PVC elbow 90mm- 45°	Effects of Customer Sensitivity towards Eco-Friendliness of the Products
Nab Stainless Steel Company	a standard-issue stainless steel table spoon	Effects of Customer Sensitivity towards Eco-Friendliness of the Products
Pars PVC Pipe Company	90mm PVC pipes	Effects of Changing CO2 emissions and Transportation Cost
Pars Plastic Company	PVC elbow 90mm- 45°	Effects of Changing CO2 emissions and Transportation Cost
Nab Stainless Steel Company	a standard-issue stainless steel table spoon	Effects of Changing CO2 emissions and Transportation Cost

4.2 Analysis of the Effects of Customer Sensitivity Towards Eco-Friendliness of the Products at Pars PVC Pipe Company

4.2.1 PVC Pipes and Green

Pars PVC Pipe Company produces different kinds of PVC pipes in different sizes. These pipes are used for sewer and drainage systems, irrigation and securing electrical cables in place. PVC pipes are manufactured from PVC powder, glue, water and some other compounds. The various effects of PVC pipes on the environment depends on the quality of the material (mainly PVC powder) used for their manufacturing which also affects the efficiency of their recycling and disposal. For our analysis in this section, we have considered PVC powder as the main raw material, obtained from different suppliers; all the other components are of the same quality and did not change in our experiments.

4.2.2 Sample Selection and Calculation of the Sensitivity Rates

Pars PVC Pipe Company provides its products to thousands of customers and through different sales points. For the purposes of our model we focus only on those wholesale customers (mainly construction companies) that pick up the goods at the company and do not require delivery since our model does not cover any part of the delivery process. At the time period for which we obtained the data for this analysis (January 1, 2015 through December 31, 2015), they had 128 customers that fit this description. The names of these customers were not disclosed.

Based on their sales data for these 128 customers, we were able to calculate the sensitivity rates of customers towards manufacturing emission (m_i^e) and transportation emission (t_i^e), using the following equation proposed for use in industrial plants within Iran by the Ministry of Industry, Mining and Commerce (www.mimt.gov.ir):

Sensitivity Rating = $\frac{O^T}{O^G \times K}$

O^T : Total number of orders from customer x

O^G : Number of orders placed by customer x with emphasis on purchasing only green products

In the equation above, value K is a constant that is defined as the percentage of orders from customer x which are significant to the analysis. For example, in calculating the sensitivity rate of customer x for manufacturing emission (t_i^e) the value of K is calculated using the following formula:

$K_{mei} = \frac{O^T \times 100}{O^R}$

O^T : Total number of orders from customer x

O^R : Total number of orders that were green mainly because of restrictions on manufacturing emissions

This method of calculating rates enables us to narrow down the analysis to the variables in which we are interested.

For example, K_{mei} for customer x in the time period of t, if:

Total number of orders from customer x for a specific product = 10,750 units

Total number of orders (for that specific product) that were green mainly because of restrictions on manufacturing emissions = 511,900 units

Therefore, K_{mei} = 2.1

Then, if the number of orders placed by customer x with emphasis on purchasing only green products in the time period of t is 2800 units, customer x's sensitivity rate will be 1.82.

The sensitivity ratings of the 128 customers were calculated. One sample with the sensitivity rating of 0 was picked for each experimental group and represents the customers who are not at all sensitive towards purchasing green products. Another 15 customers were also selected randomly from the pool. In rare cases when two randomly selected customers had exactly the same numerical rating for a given attribute, one of them was dropped and the selection process continued until we reached a total sample size of 16 which is more than ten percent of the total sample and represents an acceptable sample size for statistical analyses (Marsh, Balla et al. 1988).

The customers were sorted based on the value of their sensitivity ratings from lowest to highest and each customer was assigned a number of 1 through 16 for identification purposes. Sensitivity rates of customers for manufacturing emission (m_i^e) and transportation emission (t_i^e) for Pars PVC Pipe Company are shown in Table 2.

4.2.3 Product Selection

For the purpose of this study we selected 90mm (in diameter) PVC pipes because first, this particular size has more versatile uses and is highly in demand all the time and second, the company manufactures this pipe in three varieties. These three varieties (indicated as P1, P2 and P3 in Table 2) are exactly the same in function and form but differ in their environmental friendliness. Variety 1 (P1) is the least green and variety 3 (P3) is the most green.

Table 2. Sensitivity rates of customers for manufacturing emission (*mei*) and transportation emission (*tei*) for Pars PVC Pipe Company.

m_i^e	P1	P2	P3	t_i^e	P1	P2	P3
1	0	0	0	**1**	0	0	0
2	1.80	1.80	1.82	**2**	1.50	1.58	1.60
3	2.21	2.21	2.24	**3**	1.85	1.94	1.97
4	2.36	2.36	2.38	**4**	1.97	2.07	2.10
5	2.56	2.56	2.58	**5**	2.13	2.24	2.27
6	2.70	2.70	2.73	**6**	2.25	2.37	2.40
7	2.91	2.91	2.95	**7**	2.43	2.56	2.59
8	3.15	3.15	3.19	**8**	2.62	2.77	2.80
9	3.26	3.26	3.29	**9**	2.72	2.86	2.90
10	3.44	3.44	3.48	**10**	2.87	3.02	3.06
11	3.60	3.60	3.64	**11**	3.00	3.16	3.20
12	3.82	3.82	3.86	**12**	3.18	3.35	3.39
13	4.05	4.05	4.09	**13**	3.38	3.56	3.60
14	4.18	4.18	4.22	**14**	3.48	3.67	3.71
15	4.32	4.32	4.37	**15**	3.60	3.79	3.84
16	4.54	4.54	4.59	**16**	3.78	3.98	4.03

The sensitivity rates (m_i^e and t_i^e) along with other parameters for each of the customers were implemented in the model and the results were analyzed. Our model calculates gained profit, production amount (X_{it}), and amount of materials used in manufacturing (H_{mt}) each given product.

4.2.4 Effects on Profit

In this experiment, as the sensitivity of the customers towards purchasing green products increases, the profit made by sales of the product drops. In this sense, the company can make more profit by selling its products to customers that do not care whether they buy green products or not. The relationship between generated profit and the sensitivity of the customers towards purchasing green products and the calculated values for profit are shown in Figure 1.

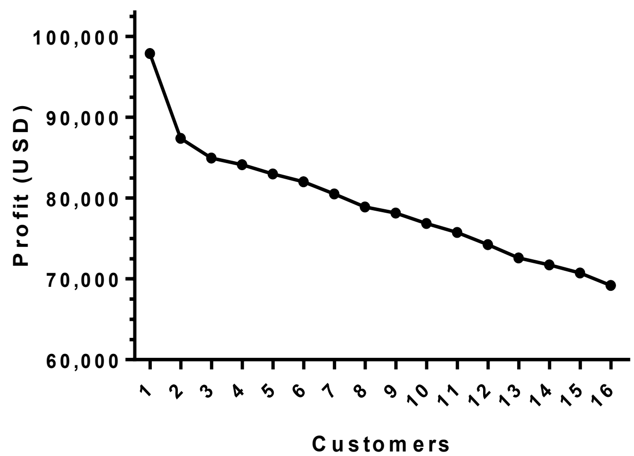

Figure 1. Relationship between generated profit and the sensitivity of the customers towards purchasing green products.

4.2.5 Effects on Production Amount

The product that we chose for this experiment (90mm PVC pipes) comes in three different varieties (P1, P2 and P3). Variety 1 is the least expensive and the least green variety and variety 3 is the most expensive and the most green variety of the three. Our model calculates the production amount per product per customer in a way that the company is able to make the most possible profit while staying within the green limits. Following these guidelines, the company management will be able to determine how many units of each product (P1, P2 and P3) and in what proportion in relation to each other need to be produced for a given customer in a defined period of time (see Figure 2).

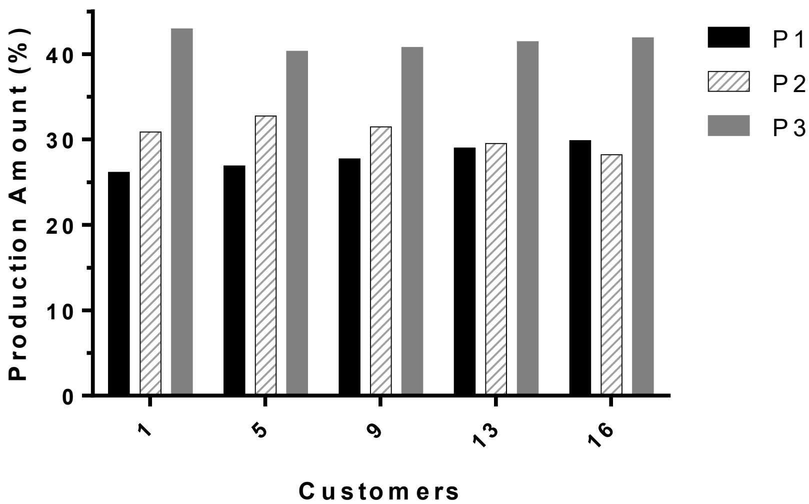

Figure 2. The effects of increased customer sensitivity towards greenness of the products on production amount.

In our experiment, the total market demand (D_{it}) is 39,700 units for 90mm PVC pipes for this defined period of time. When a customer is not sensitive towards purchasing green products, our model calculates that a total production amount of 30,707 units is permitted in order to maximize the profit, and at the same time keep the company within the boundaries of green practice (Figure 3).

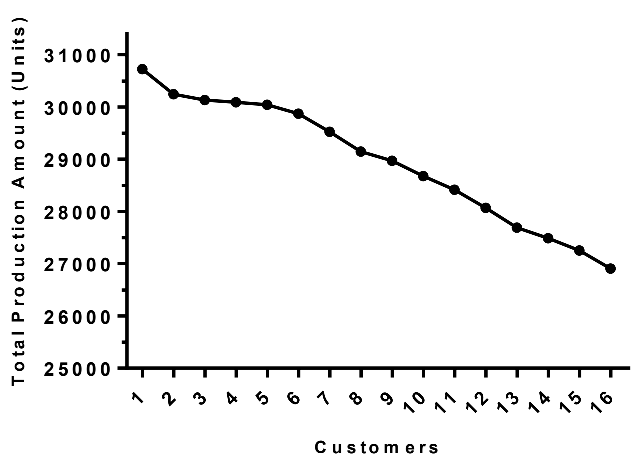

Figure 3. The effects of increased customer sensitivity on total production amount.

As more restrictions are applied to the model, such as the sensitivity of the customer towards purchasing green products, the total production amount decreases to satisfy the more stringent green standards. In case of customer 16, who has the highest sensitivity rating in this experiment, the total production amount calculated by the model falls to 26,904 units; within this limit the company is able to meet 67.77% of the demand of its most green customer and make the maximum possible profit. The effect of customer sensitivity on total production amount is shown in Figure 3.

4.2.6 Effects on the Amount of Material Purchased from Different Suppliers

The primary material used in manufacturing PVC pipes is PVC powder. In our experiment we have 3 suppliers (S1, S2 and S3) that provided this raw material for the company. Supplier 1 is located closest to the company, therefore the transportation emissions and transportation cost are the lowest for supplier 1. However, the material that supplier 1 provides for the company is more environmentally friendly and more costly than the other two suppliers.

Supplier 3 is located farthest from the company and as a result has the highest transportation emissions and transportation cost, but the raw material that supplier 3 provides is less environmentally friendly than the other two. The parameters for supplier 2 fall in the middle. Figure 4 shows the effects of customer sensitivity towards purchasing green products on the amount of material bought from different suppliers for 5 customers in our experiment. In case of customers 1,5, 9 and 13 our model prioritizes supplier 1 over the other two suppliers because first, the transportation cost is the lowest and second, the transportation emissions are the lowest due to the its closer distance to the company. These two factors help compensate for the higher cost of material and therefore contribute to maximizing the profit of the company which is the objective function of our model while the company manages to remain green.

In the case of customer 16, who has the highest sensitivity rating, our model calculates that more raw material should be bought from supplier 2 rather than supplier 1 to achieve the goal of maximizing the profit. Note that the model still does not recommend purchasing a large portion of the raw material from supplier 3 to maintain the greenness of the end product.

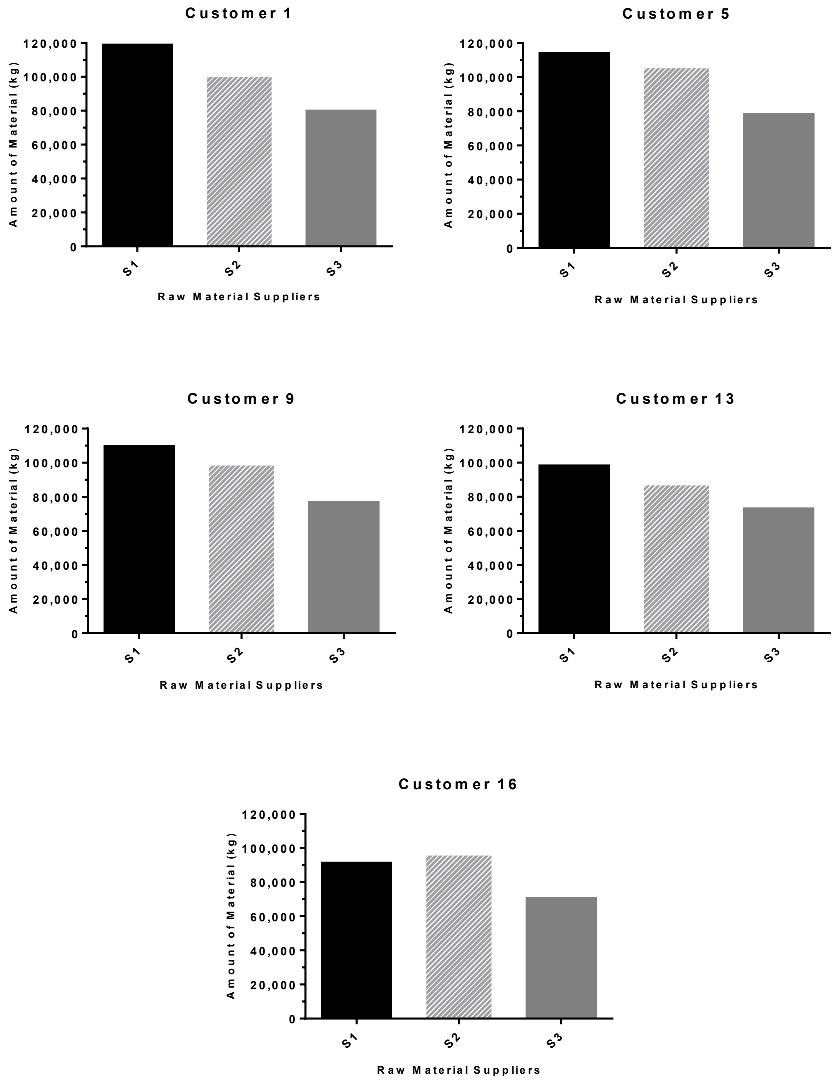

Figure 4. Effects of customer sensitivity on the amount of raw material purchased from different suppliers.

4.3 Analysis of the Effects of Customer Sensitivity towards Eco-Friendliness of the Products at Pars Plastic Company

4.3.1 PVC Elbow and Green

Pars Plastic Company is one of the best-known companies in the south of Iran for different kinds of pipe fittings. These are generally used for connecting PVC pipes. Pipe fittings should be strong enough to be able to handle the high pressure of liquid materials which pass through two pipes that are connected to one another. In these products, mainly the quality of the PVC powder determines the strength. The administrators of the company seek to purchase high quality raw materials for their manufacturing while considering the effect of these materials on the environment. Here we consider PVC powder from different suppliers as the principal raw material because all other components such as glue and water are more or less of the same quality and do not change in our experiments.

4.3.2 Sample Selection and Calculation of the Sensitivity Rates

Pars Plastic Company has thousands of customers all over Iran. For our experiments, we focused only on the construction businesses that are major customers of Pars Plastic Company and pick up their order at the factory; therefore, the company did not need to deliver the products for them. At the time period for which we obtained the data for this analysis (January 1, 2015 through December 31, 2015), they had 112 customers that fit this description. We are not allowed to publish the names of the customers. To calculate the sensitivity rates of customers for manufacturing emissions (m_i^e) and transportation emissions (t_i^e) for this experiment, we used the same method as described for Pars PVC Company (see section 4.2.2).

We calculated the sensitivity rating for 112 customers. Customer selection was performed as previously described in section 4.2.2. One sample with the sensitivity rating of 0 was randomly picked that represents the customers who are not sensitive at all towards purchasing green products. Then 15 other customers were randomly selected out of 112 customers. If two randomly selected customers had exactly the same sensitivity rating, one of them was dropped and the selection process continued until we had a total of 15 customers with various degrees of sensitivity in addition to the customer with the sensitivity rating of 0.

We sorted the customers based on the value of their sensitivity ratings from the lowest to the highest and assigned them numbers 1 to 16 for reference in our analysis. Sensitivity ratings of customers for manufacturing emission (m_i^e) and transportation emission (t_i^e) for Pars Plastic Company are shown in Table 3.

By taking into account the sensitivity rates (m_i^e and t_i^e), our model can calculate the profit, production amount (X_{it}), and the amount of materials used in manufacturing (H_{mt}) for each customer.

4.3.3 Product Selection

The pipe fitting for which we collected data was PVC elbow 90mm- 45° which performs different roles in construction processes specially for the connection of two pipes in the corners of the rectangular structures. We chose this product because it is one of the most popularly demanded pipe fitting products and it is also produced in three varieties. These three varieties (indicated as P1, P2 and P3 in Table 3) are exactly the same in function and form but differ in their environmental friendliness. Variety 1 (P1) is the least green and variety 3 (P3) is the most green one.

Table 3. Sensitivity rates of customers for manufacturing emission (*mei*) and transportation emission (*tei*) for Pars Plastic Company.

m_i^e	P1	P2	P3	t_i^e	P1	P2	P3
1	0	0	0	**1**	0	0	0
2	1.90	1.90	1.92	**2**	1.70	1.78	1.80
3	2.28	2.28	2.30	**3**	2.04	2.14	2.16
4	2.49	2.49	2.52	**4**	2.23	2.33	2.36
5	2.74	2.74	2.76	**5**	2.45	2.56	2.59
6	2.85	2.85	2.88	**6**	2.55	2.67	2.70
7	3.08	3.08	3.11	**7**	2.75	2.88	2.92
8	3.33	3.33	3.36	**8**	2.98	3.11	3.15
9	3.48	3.48	3.51	**9**	3.11	3.26	3.29
10	3.63	3.63	3.67	**10**	3.25	3.40	3.44
11	3.80	3.80	3.84	**11**	3.40	3.56	3.60
12	4.01	4.01	4.05	**12**	3.59	3.76	3.80
13	4.28	4.28	4.32	**13**	3.83	4.01	4.05
14	4.43	4.43	4.47	**14**	3.97	4.15	4.19
15	4.56	4.56	4.61	**15**	4.08	4.27	4.32
16	4.85	4.85	4.90	**16**	4.34	4.54	4.59

4.3.4 Effects on Profit

As the sensitivity of the customers towards purchasing green products increases, the profit goes down. Customers purchase less because products with lower degrees of greenness do not satisfy them when they are highly determined to purchase only green products. In Figure 5, the calculated profit from customers 1 to 16 is shown. Customer 1 has a sensitivity rating of 0, meaning that this customer does not discriminate between purchasing green and non-green products. Customer 16, on the other side of the spectrum, has the highest sensitivity rating and thus highly prefers green products over non-green products.

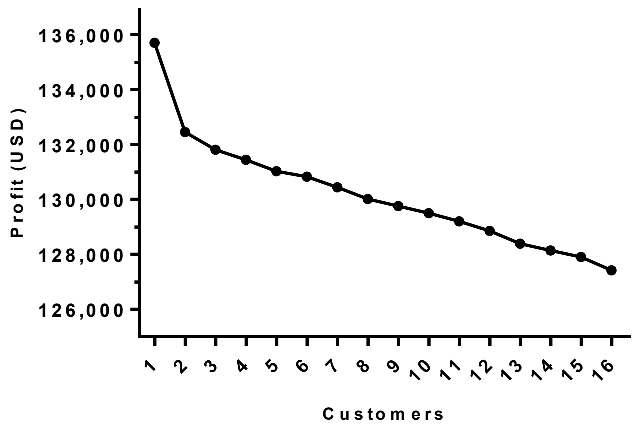

Figure 5. Relationship between total profit for each customer and the sensitivity of them towards buying green products.

4.3.5 Effects on Production Amount

The PVC elbow 90mm-45° that we chose for this experiment is manufactured in three different varieties (P1, P2 and P3). P1 is the least expensive one with the lowest degree of greenness and P3 is the most expensive one with the highest degree of greenness. We calculated the production amount per product for each customer to determine the most possible profit gain while environmental friendliness of the product is considered. According to the data generated by the model, the company can manage how many units of each verity (P1, P2 and P3) should be produced in a defined period of time for a specific customer in order to achieve maximum profit and at the same time meet the highest possible rate of demands (Figure 6). Using this model enables the company to plan the production of each product variant according to the existing demand.

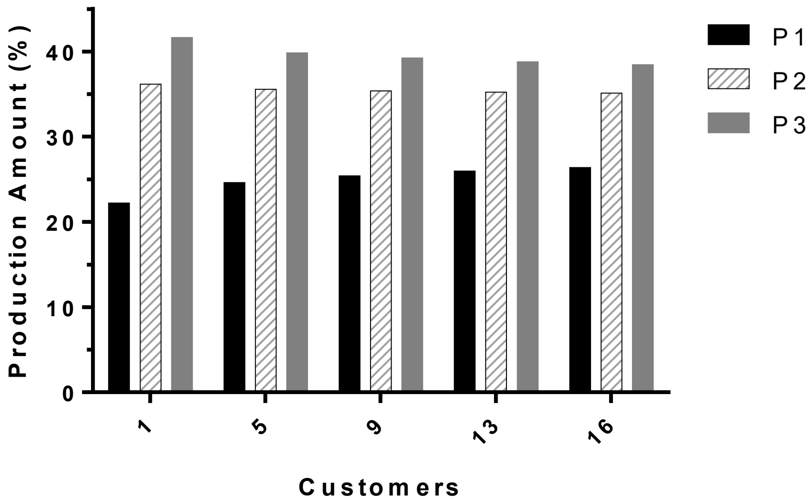

Figure 6. The effects of customer sensitivity on production amount when the sensitivity rate of customers increases.

The total market demand in this experiment is 75,900 units for PVC elbow 90mm-45° for our defined period of time. When a customer is not sensitive about the degree of greenness of the product that they purchase (customer 1), the quantity of products that the model calculates for production is 61,239 units and in the case of customer 16 with the highest degree of sensitivity, the quantity of products to be scheduled for production is 60,159 units. It is 1.76% units less than the total production amount for customer 1 in one period, which in this experiment is only one week.

The calculated total production amounts are the highest possible values per customer which give the company the highest profit considering the customers' sensitivity. All these total production amounts for each customer are shown in Figure 7.

From customer 1 to customer 16 the restrictions are increased due to the sensitivity of the customer towards buying green products. Based on these restrictions, the total amount of production diminishes slightly from customer 1 to customer 16. For customer 16, who has the highest sensitivity rating in this experiment, the model calculated total production amount 60,159 units; within the imposed limitations the company is able to meet 79.26% of the total demand of its most green customer and make the maximum possible profit. Figure 7 shows the effect of customer sensitivity on total production amount.

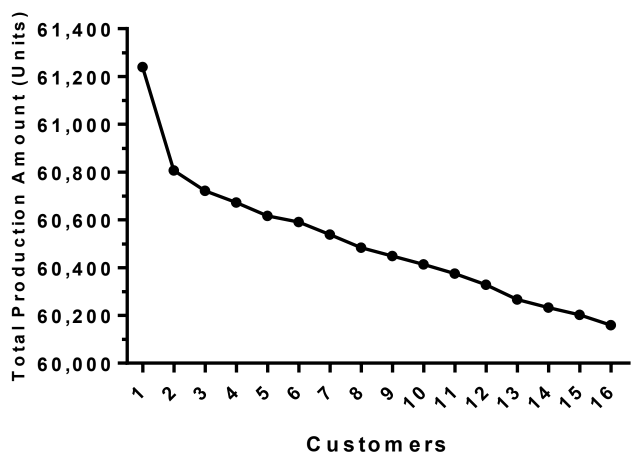

Figure 7. The total production amount for 16 different level of customer sensitivity ratings.

4.3.6 Effects on the Amount of Material Purchased from Different Suppliers

In this experiment, there are 3 suppliers (S1, S2, and S3) that provide PVC powder (the main raw material) to the company. Raw material from supplier 1 is the most environmentally friendly material and is more expensive than the others. On the other hand, as supplier 1 is located closest to Pars Plastic company, the transportation cost and transportation emission for S1 is the least compared to the other two.

Raw material from supplier 3 is the least environmentally friendly and has the lowest price. As S3 is located the farthest from Pars Plastic Company, it has the highest transportation emission and transportation cost. Supplier 2 is in the middle of S1 and S2 in case of cost of raw material and its geographical location.

Our model calculated the amount of raw material that the company needs to purchase from each supplier in order to manufacture the products for customers 1 to 16, who have different sensitivity ratings. In Figure 8 the amount of raw material that should be purchased from each supplier is shown for customers 1, 5, 9, 13 and 16 as representatives of the 16 customers in our experiment.

For each customer, the model specifies that a larger portion of raw material should be purchased from supplier 1. Supplier 1 is geographically closest to the manufacturing facility of Pars Plastic Company and therefore offers the least amount of transportation emission and transportation cost. Also, the raw material from S1 is greener compared to the other two. It is for these reasons that the model prioritizes purchasing from S1 over the other two suppliers.

In order to fulfill its objective function, the model fine-tunes the amount of raw material purchased from suppliers 2 and 3 while considering the green restrictions. In this way, the model proposes that most of the raw material for each customer has to be bought from S1 to maintain the eco-friendly status of the products in general; however, to compensate for the relatively higher cost of the raw material from S1, the model also calculates the amount of raw material that the company needs to purchase from the other suppliers in order to maximize the profit.

To emphasize the importance of this calculation in maximizing the profit, one can imagine a situation where Pars Plastic Company had to order all the raw material only from S1 to maintain greenness. In these circumstances, the incurring costs would have had reduced the profit to a great extent. By calculating the amount of raw material that can be purchased from S1 and S3 our model focuses on its objective function to prevent this from happening.

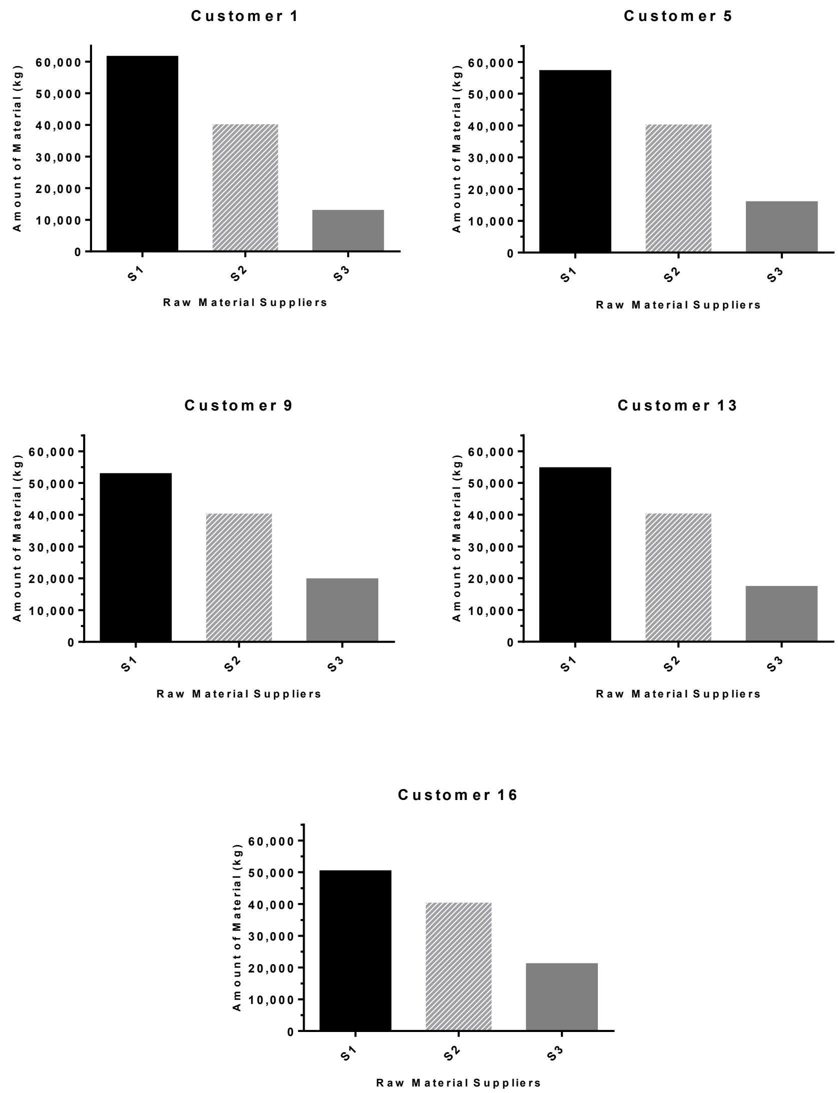

Figure 8. The effect of customer sensitivity on the amount of raw material purchased from each supplier.

4.4 Analysis of the Effects of Customer Sensitivity towards Eco-Friendliness of the Products at Nab Stainless Steel Company

4.4.1 Stainless Steel Table Spoons and Green

Nab Stainless Steel Company is a small manufacturing workshop which produces different kinds of spoons, forks and dining knives. Its products are locally well-known. Stainless steel spoons that they produce come in different sizes and designs but mostly their components are the same. Steel is the main element in this manufacturing processes. The company uses stainless steel 304 round bar for making spoons because it is highly resistant to rust. Different quality of stainless steel has different ranges of effects on the environment and the quality of raw material is the main factor in the recycling and disposal processes. For this experiment, we consider stainless steel 304 round bar as the main raw material used by Nab Stainless Steel Company which is provided by three different suppliers.

4.4.2 Sample Selection and Calculation of the Sensitivity Rates

Nab Stainless Steel Company has hundreds of customers with varying degrees of sensitivity towards purchasing environmentally friendly goods. Fifty-six of these customers were wholesalers that picked up their orders at the production facility during the time period between January 1, 2015 through December 31, 2015. The names of these wholesale customers were not disclosed to us. For this experiment, the sensitivity rates of these 56 customers for manufacturing emission (m_i^e) and transportation emission (t_i^e) were calculated as described in section 4.2.2. Among the customers with sensitivity rating of 0, only 1 was randomly selected. Ten more customers were randomly selected with varying sensitivity ratings. In case two randomly selected customers had the same sensitivity rating one of them was dropped and the random selection continued until 10 more customers were successfully selected.

The customers were sorted based on their sensitivity ratings from lowest value to the highest and they were assigned numbers 1 through 11 for the purpose of reference in this study. Sensitivity rates of customers for manufacturing emission (m_i^e) and transportation emission (t_i^e) for Nab Stainless Steel Company are shown in Table 4.

4.4.3 Product Selection

For this experiment, we selected a standard-issue stainless steel table spoon manufactured by Nab Stainless Steel Company. The company manufactures this spoon in three varieties. These three varieties (indicated as P1, P2 and P3 in Table 4) are exactly the same in shape and form but differ in their environmental friendliness. Variety 1 (P1) is the least green and variety 3 (P3) is the most green. Variety 2 (P2) falls in between P1 and P3 regarding its environmental friendliness.

Table 4. Sensitivity rates of customers for manufacturing emission (*mei*) and transportation emission (*tei*) for Nab Stainless Steel Company.

mei	P1	P2	P3	*tei*	P1	P2	P3
1	0	0	0	**1**	0	0	0
2	0.92	0.96	0.98	**2**	1.30	1.40	1.60
3	1.15	1.20	1.23	**3**	1.63	175	2.00
4	1.29	1.34	1.37	**4**	1.82	1.96	2.24
5	1.47	1.54	1.57	**5**	2.08	2.24	2.56
6	1.61	1.68	1.72	**6**	2.28	2.45	2.80
7	1.70	1.78	1.81	**7**	2.41	2.59	2.96
8	1.84	1.92	1.96	**8**	2.60	2.59	3.20
9	1.98	2.06	2.11	**9**	2.80	3.01	3.44
10	2.07	2.16	2.21	**10**	2.93	3.15	3.60
11	2.30	2.40	2.45	**11**	3.25	3.50	4.00

In this experiment, our model calculated the production amount (X_{it}), profit, and amount of raw materials used in manufacturing (H_{mt}) for each of these products (P1, P2 and P3) per customer and the resulting data were analyzed.

4.4.4 Effects on Profit

The calculated profit made by the company off the sales of P1, P2 and P3 decreases as the sensitivity of the customers towards purchasing green products increases. In this experiment, the company gains the highest profit from customer 1 with sensitivity rating of 0, i.e. customer 1 does not discriminate at all between purchasing green and non-green products. On the other hand, customer 11 is highly sensitive towards purchasing green products and contributes the least amount of profit compared to the rest of the customers. Figure 9 shows the relationship between profit and the sensitivity of the customers as calculated by our model.

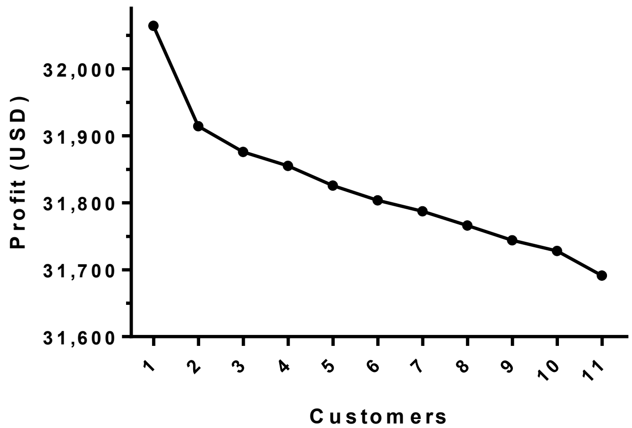

Figure 9. The effect of the sensitivity of the customers towards buying green products on profit.

4.4.5 Effects on Production Amount

In this experiment, we chose standard-issue stainless steel table spoon which comes in three different varieties (P1, P2 and P3). P1 is the least expensive one and has the lowest degree of greenness and P3 is the most expensive one with the highest degree of greenness.

The purpose of our model is to calculate the production amount per product per customer in a way that the company can have the most possible profit while the product has the highest possible degree of greenness. Based on the calculated results, the management of the company can investigate the demand of each customer to find out how many units of each product (P1, P2 and P3) and in what proportions, in relation to one another, need to be manufactured in a defined period of time (see Figure 10).

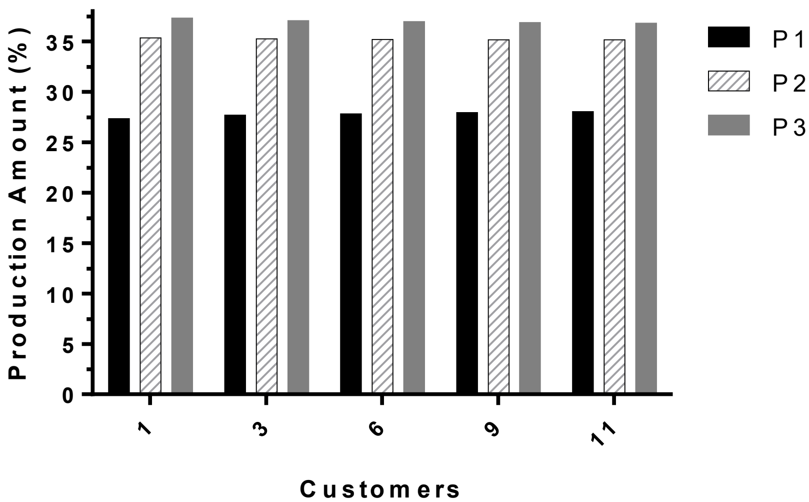

Figure 10. Relationship between production amount and the sensitivity of the customers towards purchasing green products.

The total production amount decreases as the sensitivity of the customers towards purchasing green products increases. This sensitivity acts as a limiting factor in our model. The total market demand (D_{it}) in this experiment is 27,900 units of tablespoons for this period of time. For customer 1, who is not sensitive at all about greenness of the products, our model calculates a total production amount of 25,461 units. In case of customer 11, who has the highest sensitivity rating in this experiment, the total production amount calculated by the model is 25,348 units. This is only 0.4% lower than the calculated production amount for customer 1. The effect of customer sensitivity on total production amount is shown in Figure 11.

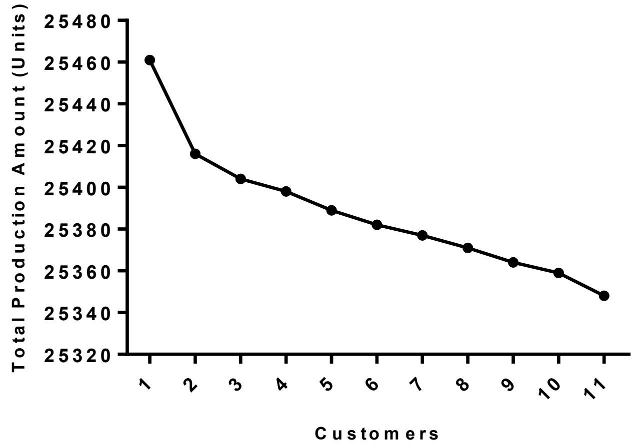

Figure 11. The effects of increased customer sensitivity on total production amount of table spoons at Nab Stainless Steel Company per customer.

4.4.6 Effects on the Amount of Material Purchased from Different Suppliers

For this experiment, the main raw material of the tablespoon is stainless steel 304 round bar. Nab stainless steel company has three suppliers (S1, S2 and S3) that provide this raw material for the company. Supplier 1 is geographically the closest supplier to the company, so the transportation emissions and transportation costs are at their lowest for S1. However, the material that supplier 1 provides for the company has the highest degree of greenness and it is slightly more expensive. Supplier 3 is located the farthest from the company and it has the highest transportation emissions and transportation cost. The raw material from supplier 3 is less environmentally friendly than the other two. The parameters for supplier 2 fall in the middle of S1 and S3.

The effect of customer sensitivity on the amount of material bought from different suppliers for 5 of the customers is shown in Figure 12. Our model prioritizes supplier 1 over the other two suppliers because it is closer to the manufacturing facility and therefore incurs the lowest transportation cost and transportation emissions making it more green compared to the other two. Also, the lower transportation cost of S1, at least partially, compensates for the slightly higher price of the raw material. Our model, seeking to maximize the profit and maintain the green status of the product keeps a balance between profit and greenness by prioritizing raw material purchase from S1 over the other two suppliers while calculating the maximum amount of raw material that can be purchased from S2 and S3 to keep the costs as low as possible and thus yield the highest amount of profit in these circumstances.

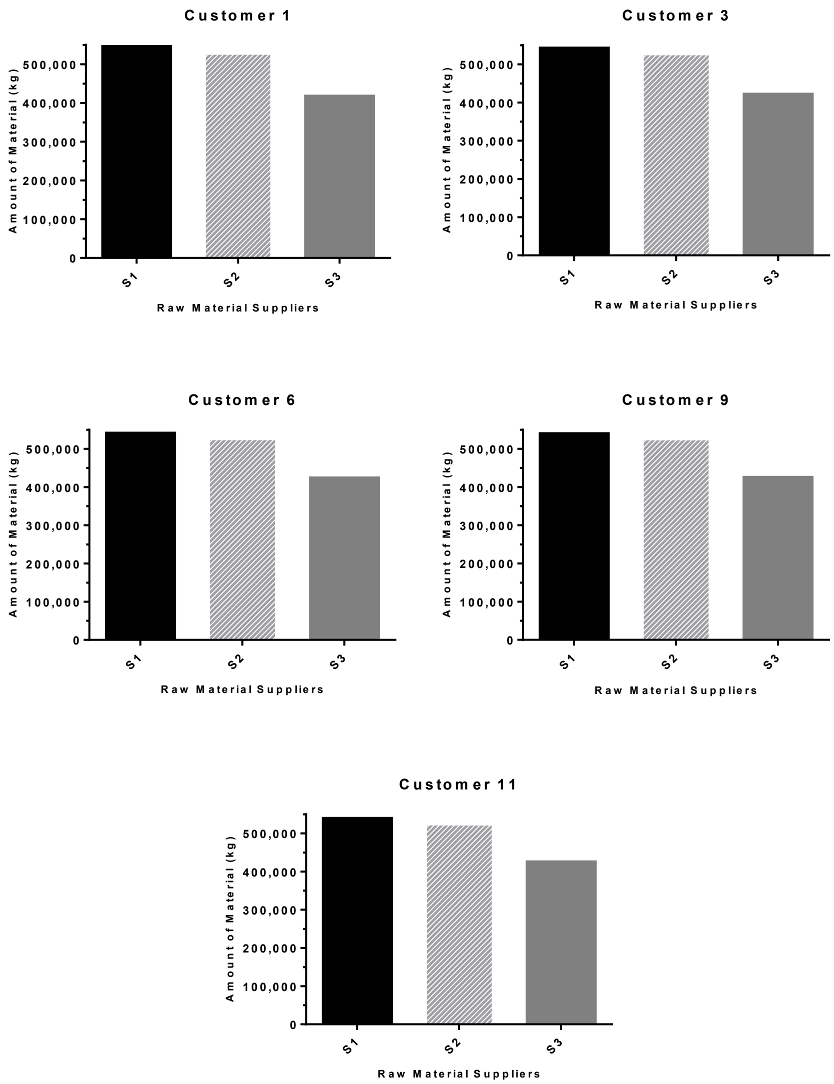

Figure 12. Effects of customer sensitivity on the amount of raw material purchased from different suppliers.

4.5 Analysis of the Effects of Changing CO_2 emissions and Transportation Cost at Pars PVC Pipe Company

Today, many companies try to buy their raw materials locally in order to decrease transportation costs and CO_2 emissions. Shipping and transportation operations are one of the factors that can decrease or increase the degree of environmental friendliness of products and need to be managed effectively. One way to reduce the level of transportation emissions is to use vehicles that emit less CO_2 compared to traditional vehicles. In our model, transportation emissions (J_{mt}^{Em}) influence the production amount; therefore, lower emissions during the transportation of raw materials translate into end products that are more environmentally friendly.

4.5.1 PVC Pipes and Green in Connection with Transportation of Raw Material

There are many delivery companies which work with Pars PVC Pipe Company to transfer raw material from suppliers to their manufacturing facility. PVC powder is the main raw material that is used in the production of the pipes and is packaged in bags, usually in 25kg or 50kg sizes so semi-trailer trucks (eighteen-wheelers) usually ship this material to the company. Various models and makes of trucks have different rates of CO_2 emissions. The amount of CO_2 emissions during the transportation of raw materials is one of the factors that determines how green the end product will be.

For our analysis in this section, we have considered CO_2 emissions (J_{mt}^{Em}) that are produced by delivery trucks in transporting raw material from supplier to Pars PVC Pipe Company and transportation cost (J_{st}^{Co}) as the parameters; all other parameters did not change in this experiment.

4.5.2 Sample Selection and Calculation of Transportation Cost and CO_2 Emissions

There are many delivery companies that deliver raw material from the suppliers to Pars PVC Pipe Company. For the purposes of our study we focused only on those delivery companies that deliver raw material from the supplier to the company without stopping at other hubs or other companies. At the time period for which we obtained the data for this analysis (January 1, 2015 through December 31, 2015), there were 20 delivery companies that fit this criterion. The names of these companies were not disclosed. Some of these delivery companies have more up-to-date fleets which are more environmentally-friendly and produce less CO_2 as a result of more efficient fuel consumption. Some other delivery companies that work with Pars PVC Pipe Company have older models of trucks that are less fuel efficient and emit more CO_2. The cost of transportation varies and is determined by the delivery company.

Based on the data for the 20 delivery companies in our study and the major types of vehicles used in their fleet, we were able to calculate the CO_2 emission of different delivery companies (by distance) using the data offered by the Iranian Research Center of Environment and Sustainable Development (www.rcesd.ac.ir).

The transportation cost and emission of 20 delivery companies for transportation of goods from three different suppliers were calculated. Five delivery companies were randomly selected and sorted based on the value of their CO_2 emissions from the lowest to the highest. Each company was assigned a number of 1 through 5 for identification purposes.

There are three different suppliers that provide raw material (PVC powder) for Pars PVC Pipe Company (S1, S2 and S3). They are located at different distances from the company so the transportation cost and transportation emissions for shipping the raw material from each of these suppliers is different per delivery company. Supplier 1 is located closest to the manufacturing facility; therefore, the transportation emissions and transportation cost are at their lowest for supplier 1. Supplier 3 is located farthest from the manufacturing facility and as a result has the highest transportation emissions and transportation cost. The parameters for supplier 2 fall in between those of S1 and S3. Transportation costs and transportation emission for different companies for one raw material (PVC powder) are shown in Table 5.

Table 5. Calculated transportation cost and CO_2 emission for 5 delivery companies that ship raw material to Pars PVC Pipe Company.

DELIVERY COMPANY	S1		S2		S3	
	CO_2e (Kg/100 units)	Cost (¢/100 units)	CO_2e (Kg/100 units)	Cost (¢/100 units)	CO_2e (Kg/100 units)	Cost (¢/100 units)
1	5.19	43.94	6.20	52.49	8.65	73.24
2	5.52	34.59	6.60	41.32	9.20	57.66
3	5.85	31.59	6.99	37.73	9.76	52.65
4	6.30	25.47	7.52	30.43	10.49	42.45
5	6.73	38.40	8.05	45.86	11.23	63.99

Transportation cost and CO_2 emission along with other parameters for each of the delivery companies were implemented in the model and the resulting data were analyzed. Our model calculates gained profit, production amount (X_{it}), and the amount of materials used in manufacturing (H_{mt}) per product for each delivery company.

4.5.3 Effects on Profit

In this experiment, the type of vehicles changes from high-tech eco-friendly models that are more fuel efficient, to models with higher CO_2 emissions. Out of the five delivery companies whose transportation emissions and transportation cost data were implemented in our model (see Table 5), the calculations show that delivery company 2 offers the most effective services in terms of maximizing the profit and maintaining the eco-friendliness of the products closely followed by delivery company 1. Delivery company 5, if used, will lead to the lowest amount of profit mainly because its high CO_2 emissions will in turn lower production amount (as seen in Figure 13) to help the company maintain the green status of its product. The relationship between using different delivery companies and profit is shown in Figure 13.

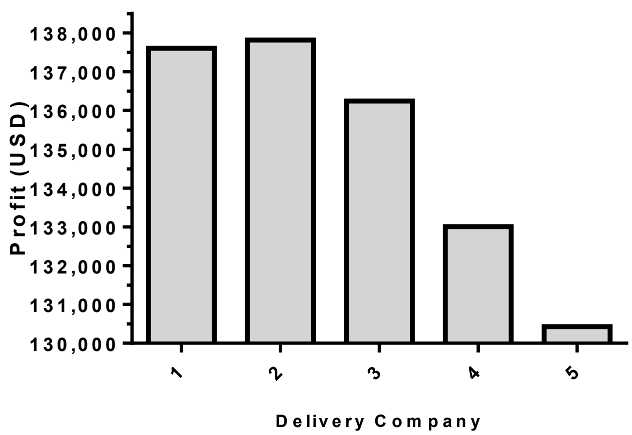

Figure 13. Relationship between generated profit and eco-friendliness of the delivery companies.

4.5.4 Effects on Production Amount

Pars PVC Pipe Company produces three variations of 90mm PVC pipes (P1, P2 and P3). These variations are similar in form and function, but have various degrees of greenness. P1 is the least expensive and the least green variety while P3 is the most expensive and the most green variety. In our sample of five delivery companies, the fleet of delivery company 1 produces the lowest amount of CO_2 emission while shipping the raw material from suppliers to Pars PVC Pipe Company. The fleet that belongs to delivery company 5 produces the highest amount of CO_2 emissions compared to other four.

One of the criteria that our model uses to determine the eco-friendliness of the product is the use of green delivery companies. Our model calculates the production amount per product per delivery company in a way that Pars PVC Pipe Company is able to make the most possible profit while staying within the green limits. Using the data generated by the model, the company management will be able to determine how many units of each product (P1, P2 and P3) and in what proportion, in relation to one another, need to be produced in a defined period of time in order to maximize the profit and stay green at the same time (Figure 14).

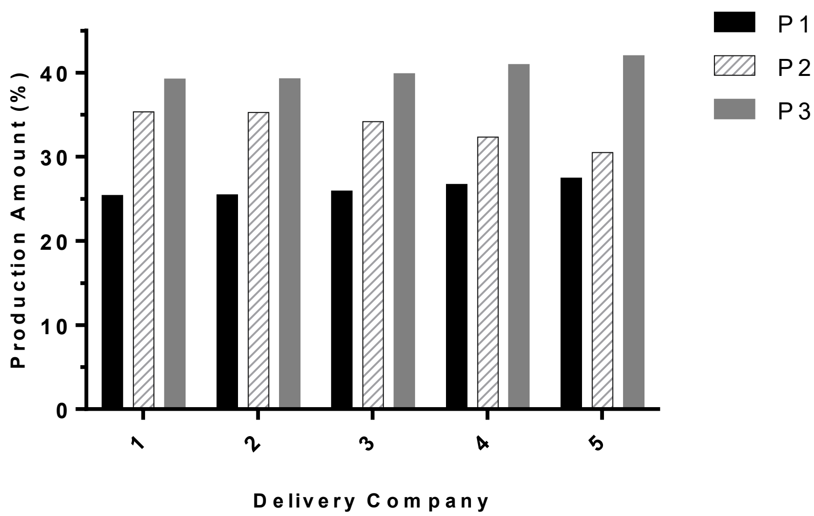

Figure 14. Effect of changing transportation cost and CO_2 emissions on production amounts of P1, P2 and P3.

In our experiment, the total market demand (D_{it}) is 39,700 units for 90mm PVC pipes for this defined period of time (one week). Our model calculates that by using the services of delivery company 2 to deliver raw materials to the manufacturing facility, Pars PVC Pipe Company can achieve the highest possible total production amount. Our model recommends delivery company 2 perhaps because despite the fact that its CO_2e (per end product) is slightly higher than that of delivery company 1, its transportation cost is significantly cheaper (Table 5).

As the amount of CO_2 emissions of the delivery companies 3–5 increase due to using vehicles that are less fuel efficient, the total production amount decreases to satisfy the more stringent green standards. In case of delivery company 5, that has the highest amount of CO_2 emissions in this experiment, the total production amount calculated by the model falls to 29,269 units. However, when the services of delivery company 1 is used, which has the lowest amount of CO_2 emissions, the total production amount rises to 31,634 units (Figure 15).

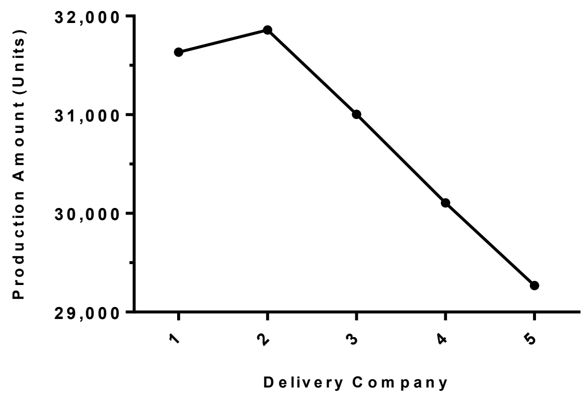

Figure 15. The effects changing transportation cost and CO_2 emission on total production amount.

4.5.5 Effects on the Amount of Raw Material Purchased from Different Suppliers

The primary material used in manufacturing PVC pipes is PVC powder. As mentioned in section 4.5.2, we have 3 suppliers (S1, S2 and S3) that provide this raw material for the company. Supplier 1 is located closest to the company; therefore, the transportation emission is the lowest for S1. Supplier 3 is located farthest from the company and as a result has the highest transportation emission.

Figure 16 shows the effects of changing the transportation cost and CO_2 emission on the amount of raw materials that need to be bought from different suppliers and delivered by the delivery companies. In all cases, our model prioritizes supplier 1 over the other two suppliers, because mainly it is located the closest to the company and therefore the transportation emissions are the lowest. The model optimizes the amount of material that can be bought from the other suppliers in order to maximize the profit and help keep the company remain green.

The reason supplier 3 is prioritized over supplier 2 is that the price of raw materials bought from supplier 3 is the lowest of the three. Thus, by managing the amount of the raw materials purchased from S3 correctly and at the same time taking into account the higher transportation cost and increased CO_2 emissions, the model balances out the cost-profit ratio and in the end maximizes profit to achieve its primary objective.

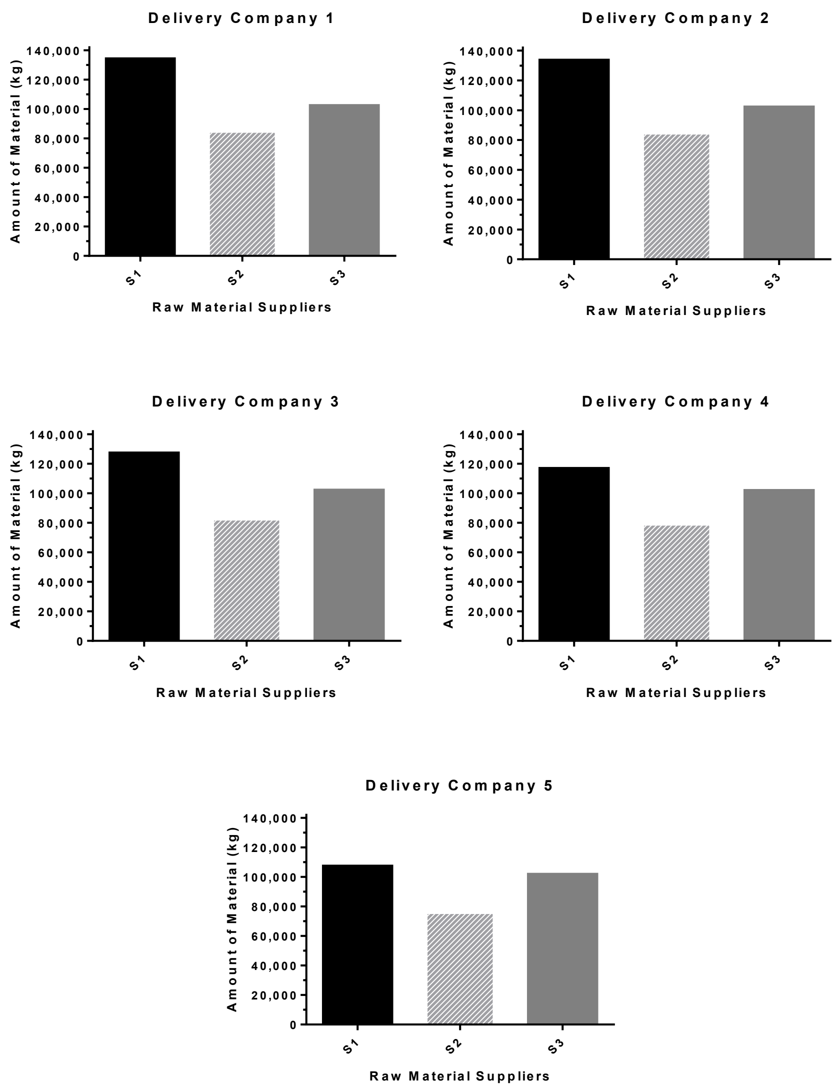

Figure 16. Effect of changing transportation cost and CO_2 emissions on the amount of raw material purchased from different suppliers.

4.6 Analysis of the Effects of Changing CO_2 emissions and Transportation Cost at Pars Plastic Company

The product that we studied at Pars Plastic Company was PVC elbows. The main raw material for this product is PVC powder. The PVC powder used at Pars Plastic Company already complies with green standards, but delivery operations have an important role in increasing or decreasing the degree of environmental friendliness of the end products, as well. Transportation emissions (J_{mt}^{Em}) is one of the factors that affect production amount in our model; therefore, lower transportation emissions while transporting raw materials to the manufacturing facility will lead to more environmentally friendly products.

4.6.1 PVC Elbows and Green in Connection with Transportation of Raw Material

There are many delivery companies which Pars Plastic Company uses for transporting raw material from suppliers to the company. Generally, the shorter the distance between the supplier and manufacturing facility, the lower the amount of transportation emissions are and the end product is considered to be greener. In this experiment, we have considered CO_2 emissions (J_{mt}^{Em}) that are produced by delivery vehicles in transporting raw material from suppliers to Pars Plastic Company and their transportation cost (J_{st}^{Co}) as the parameters; all other parameters did not change in this experiment.

4.6.2 Sample Selection and Calculation of Transportation Cost and CO_2 Emission

Delivery of raw material from suppliers to the company is one of the most important issues that influence the degree of greenness of the products. Efficiency of fuel consumption is the main factor that determines the amount of CO_2 emission. There are 25 delivery companies that deliver raw materials from the suppliers to Pars Plastic Company. The delivery companies considered for this experiment are those that deliver raw materials directly from the supplier to the company non-stop. The location of the suppliers and the distance between suppliers and Pars Plastic Company determines the amount of CO_2 emissions and transportation cost.

The values for transportation costs and CO_2 emissions of all 25 delivery companies were calculated using the method described in section 4.5.2. Out of these 25 delivery companies that deliver raw materials to the manufacturing facility of Pars Plastic Company we randomly selected 5. The transportation CO_2 emissions for these five delivery companies were sorted from the lowest to the highest values and the delivery companies were assigned numbers 1 to 5 for the purpose of reference throughout this study. Transportation costs and CO_2 emissions for different delivery companies that deliver raw materials for the production of PVC elbows are shown in Table 6.

Raw materials were provided from three different suppliers for Pars Plastic Company (S1, S2 and S3). They are located in different distances from the company, therefore the transportation cost and CO_2 emissions for transporting the raw materials from each of these suppliers is different per delivery company. Supplier 1 is located closest to the company and supplier 3 is located the farthest from Pars Plastic Company.

Table 6. Calculated transportation cost and CO_2 emission for 5 delivery companies that transport raw materials to Pars Plastic Company.

Delivery Company	S1		S2		S3	
	CO_2e (Kg/100 units)	Cost (¢/100 units)	CO_2e (Kg/100 units)	Cost (¢/100 units)	CO_2e (Kg/100 units)	Cost (¢/100 units)
1	1.29	8.57	2.00	13.29	2.71	18.01
2	1.38	9.41	2.13	14.58	2.89	19.75
3	1.46	11.82	2.26	18.32	3.06	24.82
4	1.57	6.34	2.43	9.83	3.29	13.32
5	1.68	9.56	2.61	14.82	3.52	20.08

After implementing the values for CO_2 emissions and transportation cost, our model calculates profit, production amount (X_{it}), and the amount of materials used in manufacturing (H_{mt}) per product for each delivery company.

4.6.3 Effects on Profit

Changing the type of vehicles affects the calculated profit. Delivery companies that use high-tech, fuel efficient vehicles that produce less CO_2 emissions than the older models provide more environmentally friendly services. In our model, out of the five delivery companies whose transportation emissions and transportation cost data were used (see Table 6), the calculations show that delivery company 1 offers the most effective services in terms of maximizing the profit and maintaining the eco-friendliness of the products. Using delivery company 5 will lead to the lowest amount of profit because restrictions on CO_2 emissions and the relatively high price of delivery company 5 decreases the total production amount. The relationship between using different delivery companies and profit is shown in Figure 17.

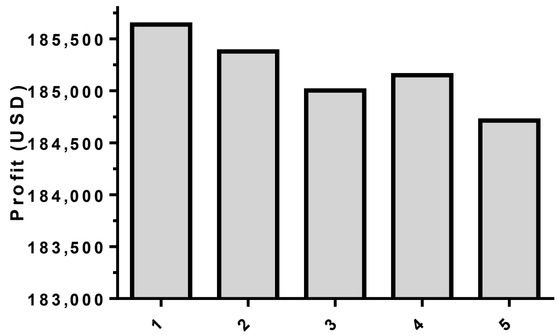

Figure 17. Relationship between profit and eco-friendliness of the delivery companies.

4.6.4 Effects on Production Amount

Pars Plastic Company produces three variations of PVC elbow 90mm-45° (P1, P2 and P3). These variations are similar in form and function, but have various degrees of greenness. P1 is the least expensive and the least green variety while P3 is the most expensive and the most green variety.

In this experiment, we chose five different delivery companies from a pool of delivery companies that provide services to Pars Plastic Company. The fleet of delivery company 1 produces the lowest amount of CO_2 emission in transferring raw material from suppliers to Pars Plastic Company because its delivery vehicles are more eco-friendly. The fleet that belongs to delivery company 5 produces the highest amount of CO_2 emissions compared to other five.

Our model calculates the maximum production amount for the three variations of PVC elbow 90mm- 45° (P1, P2 and P3) when the raw material is delivered to the manufacturing facility by each of the delivery companies (Figure 18).

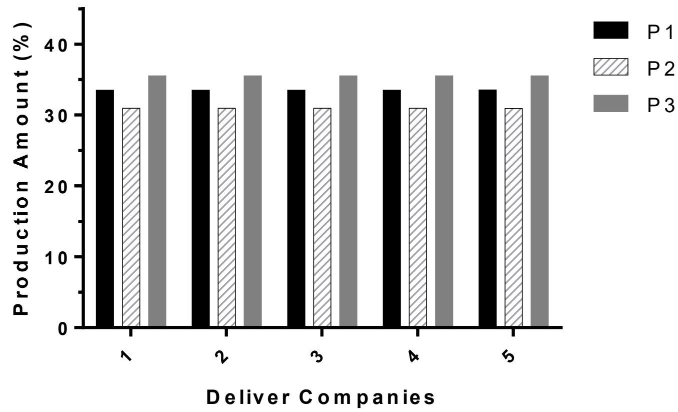

Figure 18. Effect of changing the transportation cost and CO_2 emissions on production amount of P1, P2 and P3.

In our experiment, the total market demand (D_{it}) is 75,900 units for elbow 90mm- 45° for this defined period of time (1 week). For delivery company 1 our model calculates that a total production amount of 74,422 units is permitted in order to maximize the profit, which is the objective function of the model (Figure 19).

As the amount of CO_2 emissions of the delivery increase, due to using vehicles that are less fuel efficient, the total production amount decreases in response to the green restrictions. In case of delivery company 5, which has the highest amount of CO_2 emissions in this experiment, the total production amount calculated by the model is 74,190 units. For delivery company 1, which has the lowest amount of CO_2 emissions the total production amount is 74,422. The effect of the changes in transportation cost and CO_2 emissions on total production amount of PVC elbows is shown in Figure 19.

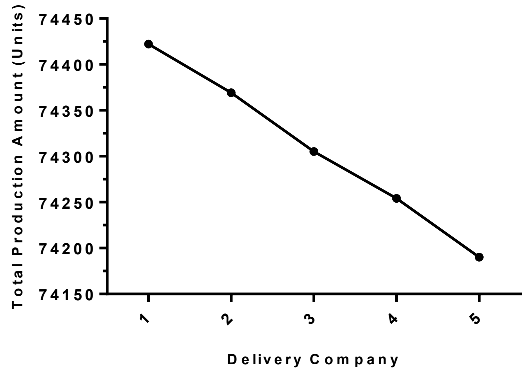

Figure 19. The effects changing the transportation cost and emission on total production amount.

4.6.5 Effects on the Amount of Material Purchased from Different Suppliers

The main material used in manufacturing PVC Elbow 90mm- 45° is PVC powder. As mentioned in section 4.6.2, we have 3 suppliers (S1, S2 and S3) that provide this raw material to the company. S1 is located closest to the company, therefore the transportation emissions and transportation costs are the lowest for S1. S3 is located farthest from the company and as a result has the highest transportation emissions and transportation costs. The geographical location of S2 is closer to the manufacturing facility than S3 but farther compared to S1.

Figure 20 shows the effects of changing transportation costs and CO_2 emissions on the amount of raw materials bought from different suppliers by five different delivery companies (1-5). Our model calculates that purchase of raw materials from supplier 1 should be prioritized over the other two suppliers because of two reasons. First, although S1 offers the most expensive raw material, its close proximity to the manufacturing facility of Pars Plastic Company causes the relatively low shipping cost of the raw materials to compensate for the higher price. In this way the model maximizes the profit. Second, because of the shorter distance between S1 and Pars Plastic Company, CO_2 emissions are the lowest for this supplier, therefore acquiring most of the raw material from S1 helps the company produce more eco-friendly products.

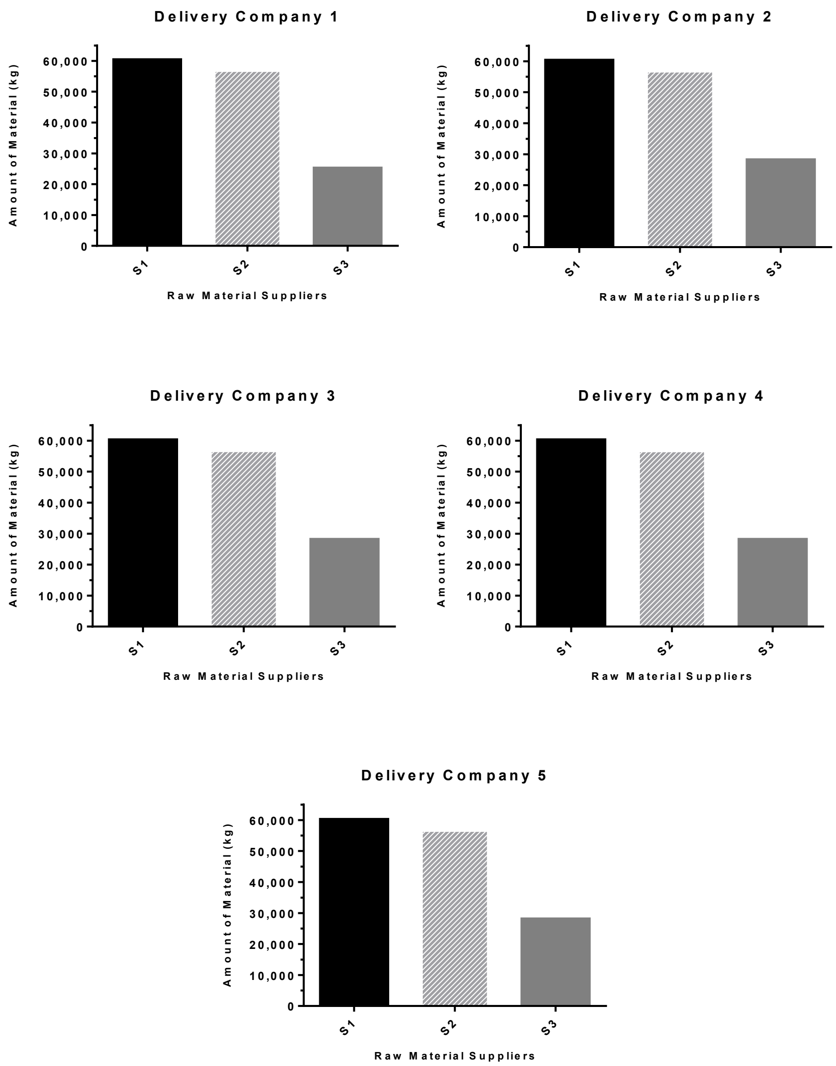

Figure 20. Effects of changing transportation cost and CO_2 emissions on the amount of raw material purchased from different suppliers.

4.7 Analysis of the Effects of Changing the Type of Transportation Vehicles at Nab Stainless Steel Company

4.7.1 Stainless Steel spoons and Green Transportation of Raw Materials

The product that we studied at Nab Stainless Steel Company was a standard-issue tablespoon. The main raw material for manufacturing the spoons is stainless steel 304 round bar. Although the raw material used at Nab Stainless Steel Company complies with green standards, delivery operations, also, have an important role in increasing or decreasing the degree of environmental friendliness of the end products. Our model considers transportation emissions (J_{mt}^{Em}) as one of the factors that affect production amount; therefore, lower transportation emissions while shipping the raw materials to the manufacturing facility will lead to more environmentally friendly end products.

For all analyses in this section, two parameters affect the calculations of the model. First, CO_2 emissions that are produced by delivery vehicles in transporting raw materials from suppliers to Nab Stainless Steel Company (J_{mt}^{Em}) and second, transportation costs of raw material per unit end product (J_{st}^{Co}). All other parameters are fixed.

4.7.2 Sample Selection and Calculation of Transportation Cost and CO_2 emission

There are 16 delivery companies that deliver raw materials from the suppliers to Nab Stainless Steel Company. The delivery companies considered for this experiment are those that deliver raw material directly from supplier to the company non-stop. The types of vehicles for different delivery companies are not the same. Some delivery companies use modern fuel-efficient vehicles that generally emit less CO_2 compared to those vehicles that are less fuel efficient as a result of using older technology.

The values for transportation costs and CO_2 emissions of all the delivery companies were calculated using the method described in section 4.5.2. Five different delivery companies were randomly chosen. If two selected delivery companies had exactly the same numerical values for transportation costs and CO_2 emissions, one of them was dropped and the selection process continued until we had successfully selected a total sample size of 5.

Based on the values for CO2 emissions, the delivery companies were sorted from the lowest (most green) to the highest (least green) and each delivery company was assigned a number of 1 to 5 for reference. Transportation costs and CO_2 emissions for the 5 delivery companies in this study are shown in Table 7.

Raw material for the production of tablespoons was provided to Nab Stainless Steel Company by three different suppliers (S1, S2 and S3). The geographical location of the delivery companies relative to the manufacturing facility is another factor that affects CO_2 emissions. Supplier 1 is located closest to the company and supplier 3 is located the farthest from the manufacturing facility.

Table 7. Calculated transportation cost and CO_2 emission for 5 delivery companies that ship raw materials to Nab Stainless Steel Company.

Delivery Company	S1		S2		S3	
	CO_2e (Kg/100 units)	Cost (¢/100 units)	CO_2e (Kg/100 units)	Cost (¢/100 units)	CO_2e (Kg/100 units)	Cost (¢/100 units)
1	0.47	5.62	0.71	8.61	1.06	12.73
2	0.52	4.57	0.80	7.01	1.19	10.36
3	0.60	7.84	0.92	12.02	1.36	17.76
4	0.73	6.83	1.11	10.47	1.66	15.48
5	0.80	7.41	1.23	11.35	1.82	16.79

Transportation costs and CO_2 emissions for each of the delivery companies were implemented in the model and the results were analyzed. Our model calculates gained profit, production amount (X_{it}), and the amount of materials used in manufacturing (H_{mt}) per product for each delivery company.

4.7.3 Effects on Profit

Changing the type of vehicles used by the delivery companies from high-tech eco-friendly models to the models with higher CO_2 emissions affects the profit gained by the company. Figure 21 shows how using 5 different delivery companies affects profit. Among these five delivery companies whose transportation emissions and transportation cost data were used in our model (see Table 7), the calculations show that delivery company 2 yields the highest amount of profit while the eco-friendliness of the products is maintained. Using delivery company 3 will produce the lowest amount of profit. The relationship between using different delivery companies and profit is shown in Figure 21.

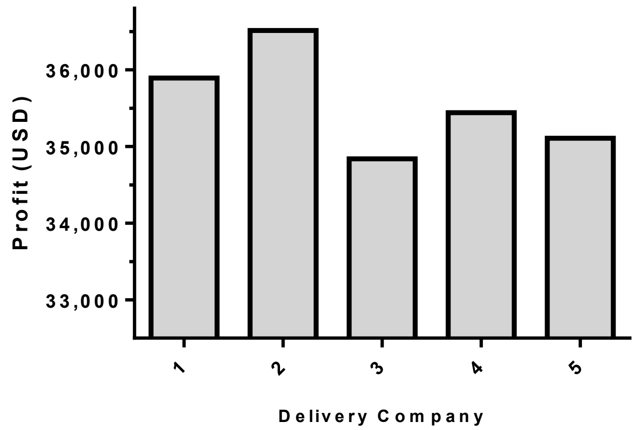

Figure 21. Relationship between generated profit and eco-friendliness of the delivery companies at Nab Stainless Steel Company.

4.7.4 Effects on Production Amount

Nab Stainless Steel Company produces three variations of standard-issue tablespoon (P1, P2 and P3). These variations are similar in form and appearance, but have various degrees of greenness. P1 is the least expensive and the least green variety while P3 is the most expensive and the most green variety. In this experiment, we chose 5 different delivery companies from a pool of delivery companies. Delivery company 1 produces the lowest amount of CO_2 emissions in transferring raw material from suppliers to Nab Stainless Steel Company. Delivery company 5 produces the highest amount of CO_2 emissions compared to the other four companies because its vehicles are less eco-friendly. Our model calculates the production amount per product per delivery company in a way that the manufacturer is able to make the most possible profit while staying within the green limits and the company management will be able to determine how many units of each product (P1, P2 and P3) should be produced (Figure 22).

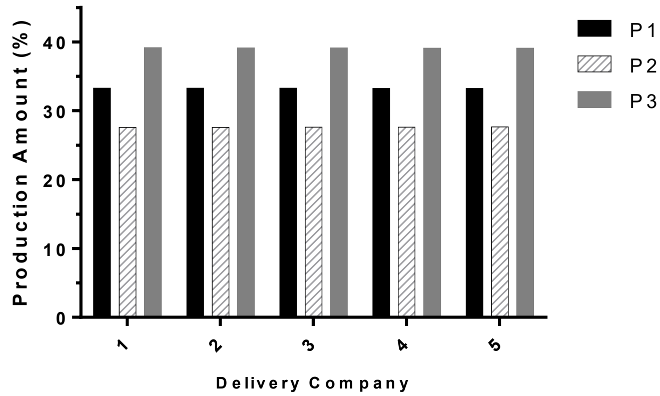

Figure 22. Effect of changing transportation cost and transportation emissions on production amounts of P1, P2 and P3.

In our experiment, the total market demand (D_{it}) is 27,900 units for the standard-issue tablespoon for this defined period of time. In case of delivery company 5, that has the highest amount of CO_2 emissions in this experiment, the total production amount calculated by the model falls to 25,409 units. However, when the services of delivery company 1 is used, which has the lowest amount of CO_2 emissions, the total production amount rises to 25,422 units. Our model calculates that by using the services of delivery company 2 to deliver raw materials to the manufacturing facility, Nab Stainless Steel Company can achieve the highest possible total production amount of 25,424 (Figure 23).

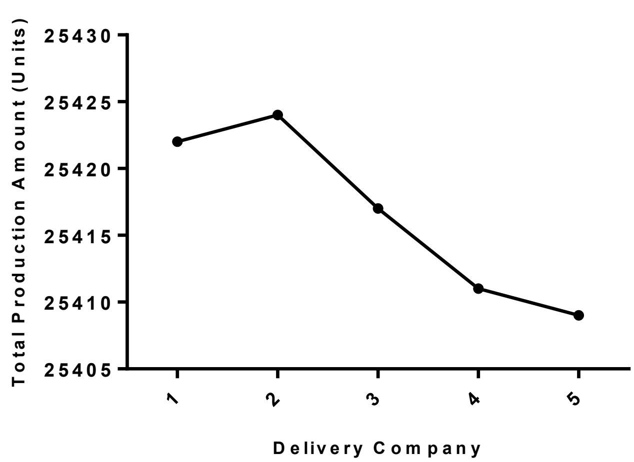

Figure 23. The effects changing transportation cost and transportation emissions on total production amount.

4.7.5 Effects on the Amount of Material Purchased from Different Suppliers

The main material used in manufacturing tablespoons is stainless steel. As mentioned in section 4.7.2, Nab Stainless Steel Company has 3 suppliers (S1, S2 and S3) that provide them with this raw material. Supplier 1 is located closest to the company; therefore, the transportation emissions and transportation costs are the lowest for supplier 1.

Supplier 3 is located farthest from the company and as a result has the highest transportation emissions and transportation cost. The parameters for supplier 2 fall in the middle. Figure 24 shows the effects changing the transportation costs and transportation emissions on the amount of raw materials bought from different suppliers and delivered by 5 different delivery companies. In all cases, supplier 1 is calculated to provide the largest amount of raw materials, closely followed by supplier 2. The model suggests that the company should acquire the least amount of its raw materials from supplier 3. This is because first, the transportation cost for supplier 1 is the lowest as a result of its close geographical proximity to the manufacturing facility and second, transportation emissions for shipping materials from supplier 1 to the company are at their lowest, hence by receiving most of the raw materials from the two most green sources, Nab Stainless Steel Company manages to achieve the highest total production amount and maximize its profit.

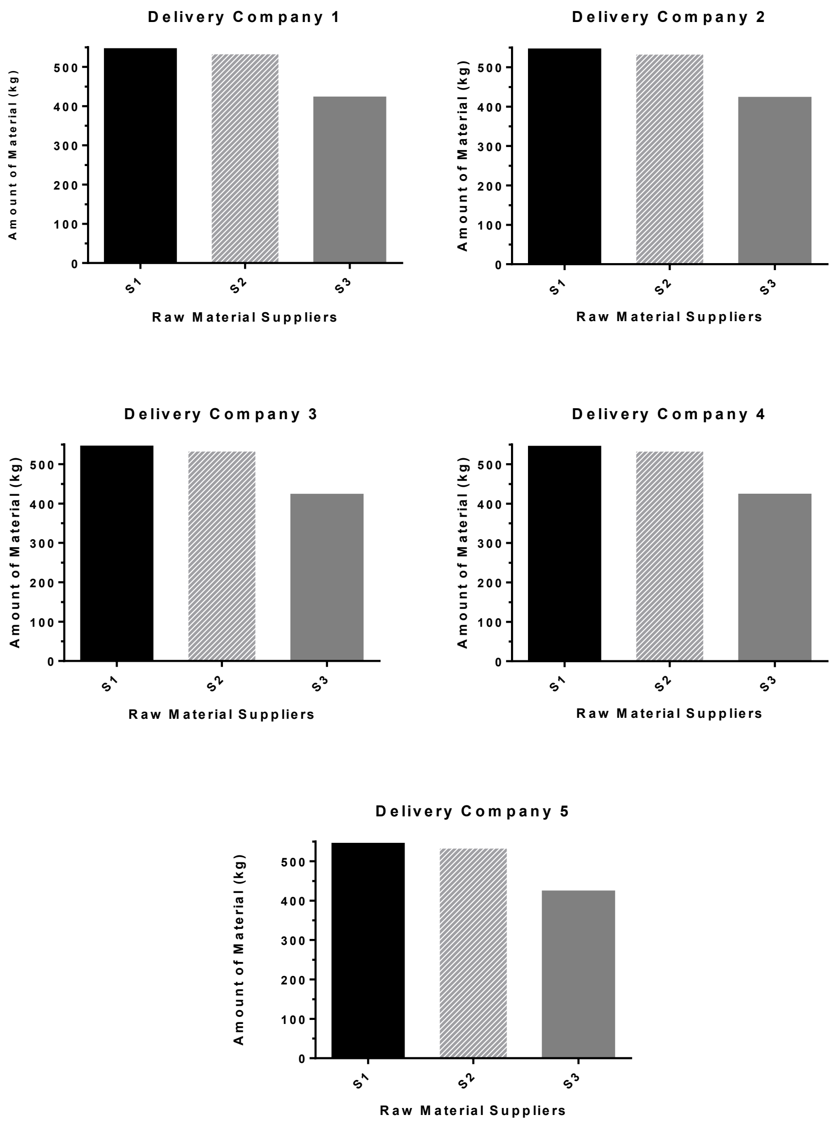

Figure 24. Effect of changing transportation costs and CO_2 emissions on the amount of raw material purchased from different suppliers.

4.8. Results and Discussion

4.8.1. Analysis of the Effects of Changing Customer Sensitivity Towards the Eco-friendliness of the Products

In the case studies presented in this chapter, we selected a specific product manufactured by each company which came in three varieties P1, P2 and P3. These products have the same shape and design but they are different in their degree of greenness. P1 is the least green product and P3 is the most green product. The sensitivity rates of the customers were calculated and the model was executed to check the effect of this factor on profit. The calculated profit made by the company for P1, P2 and P3 showed a general trend that as the sensitivity of the customers towards purchasing green products increases, the profit goes down. This is due to the fact that customers purchase less because products with lower degrees of greenness do not satisfy them when they are highly determined to purchase only green products.

For the effect of the sensitivity of the customers towards purchasing green products on production amount, as our model's objective function is to maximize the profit, it prefers to manufacture P3 over the other verities in all cases because it has the highest price and will return more profit to the company. It is also the most green product and fits the demand for the green products as the sensitivities increase. On the other hand, the total production amount decreases as the sensitivity of the customers towards purchasing green products increases. This happens because as a result of increased customer sensitivity, more rigid constraints are imposed in the model which leads to decreased total production amount to keep the manufacturing process green.

To demonstrate the effects of customer sensitivity on the amount of raw material purchased from different suppliers, our model calculates that out of the three suppliers (S1, S2 and S3), most of the purchases should be from S1 since it offers the most green raw material and its transportation costs and transportation emissions are less than the other two suppliers due to its close proximity to the manufacturing plant. However, the raw material from S1 is more costly than what can be obtained from the other two suppliers; therefore, in order to maximize the profit, the model calculates some portion of raw material to be purchased from S2 and S3 which is less costly and also less environmentally friendly.

4.8.2. Analysis of Effects of Changing CO_2 Emissions and Transportation Costs

To examine the effects of changing delivery companies, which differ in carbon emission production and transportation costs, we only focused on those delivery companies that deliver raw materials directly from the supplier to the company without making stops at any other transportation hubs or manufacturing facilities.

In our experiments, the raw material for the production of specific product was provided to the manufacturing facility by three different suppliers S1, S2 and S3 which were located at different distances from the company. Transportation emissions and transportation costs for supplier 1 is the lowest amount because it is located closest to the company. The highest transportation emissions and transportation costs are for supplier 3 because it is located farthest from the company. In each case, our model selects a supplier that allows for maximizing the profits while helping the company maintain the green status of its products.

Delivery companies are sorted based on their transportation emission, i.e. the fleet of delivery company 1 produces the least amount of CO_2 emissions, and the fleet of delivery company 5 produces more CO_2 emissions than the others.

For the production amount of the three variations of the designated product (P1, P2 and P3 that have varying degrees of greenness with P1 being the least green and P3 the most green variant), our model prioritizes the manufacturing of P3 over the other two verities in all cases because it is the most green product and the most expensive one and therefore the most profitable variety. In this way, we maximize the profit and at the same time maintain the green status of the products. Also, for each experiment, the model selects a delivery company that can help maximize profits while the company still manages to stay within the green zone.

In studying the effect of changing transportation costs and CO_2 emissions on the amount of raw material purchased from different suppliers, our model calculates the maximum amount of raw material that the company should purchase from supplier S1 to maximize profit and meet as much of the market demand as possible while staying green. S2 and S3 are the next suppliers that our model prioritizes.

4.9. A Comparison Between the Mathematical Model Presented in This Study and a Similar Study by Tseng and Lin (2014)

There are few studies which have mathematical models that mainly focus on environmental issues and costs similar to the model presented in our study. One of them is the paper that Tseng and Lin (2014) worked on. As described in section 2.13 Tseng and Lin (2014), have proposed a model that has the goal of finding a suitable design case and selection of materials and manufacturing processes to minimize the cost of manufacturing while considering the green related costs and constraints. The model presented in this study follows the same rule, however, our model puts more emphasis on following green guidelines from obtaining the raw materials from the suppliers all the way to the manufacturing of the end-product and making it available to the customers. The flow starts from the suppliers, goes through the manufacturers and then moves on to the wholesale customers at the factory.

In the study by Tseng and Lin the objective function is mainly to minimize the total cost to achieve the goal of green design and manufacturing by making decisions of design cases, materials, and manufacturing processes. They consider the material cost, manufacturing costs, energy costs, reverse logistics cost, environmental costs and costs related to pollution as “operative costs” in their mathematical model. On the other hand, the objective function in our model is maximizing the profit while considering the costs from suppliers to the manufacturing processes and sales. In our model, the profit gain is calculated based on the revenue from selling products in markets after deducing the costs. The costs that are considered in our model are raw material, manufacturing, assembly, disassembly, disposal, recycling, transportation, energy and environmental costs, which are more detailed and specific than what is used by Tseng and Lin (2014). Additionally, the goal of the objective function is to maximize the profit of the company so there should be a formula to consider the revenue of the company.

A product is made of a number of discrete parts, or components, and connections (Lambert and Gupta 2016). Companies try to maximize their usage of raw materials in a way that produce less wastes and minimize their environmental impact by recycling these reusable parts. Some of these components can be sent back to the operation process via recycling in the product life cycle. Product life cycle recycling can include material recycling and reusing parts as well as disposing of non-reusable materials in an environmentally friendly way. In general, the recycling process can be divided into main steps, including disassembly of components, recovery of reusable components and disposal of the remaining components which are not usable in the manufacturing process (Chen, Navin-Chandra et al. 1994). In addition, the use of reused materials reduces the environmental impact which is the main goal of our model; however, it incurs certain costs for companies that should also be considered. In contrast to the model by Tseng and Lin, our model takes these costs into consideration.

Some of the concepts of the constraints presented by Tseng and Lin (2014) are similar to the ones in our model. These similarities include the constraints for energy and time. But there are some more specific constraints in our model which makes it more green oriented. One of the main advantages of the model in this study is that it takes into account the direct relationship between demand for green products and the production amount while Tseng and Lin (2014) considered production amount equal to demand in general.

The production amount in our model is dependent on the demand of customers for green products. This means that the production amount of a green product is closer to the maximum demand of that product in the market which a company can produce. By increasing the eco-score of the products, the demand for that product decreases in the market.

Our model utilizes more constraints to restrict manufacturing conditions in order to be more environmentally friendly. It imposes limitations on CO_2 emission both in the manufacturing process and in transportation. This limitation encourages companies to use eco-friendly materials and transport them in a way that produces less CO_2. Based on the constraints of CO_2 limitations in our mathematical model, if the CO_2 emission in manufacturing a specific product is more than the amount permitted by the law, the company should not produce that product in excessive amounts. Fuel efficiency of the vehicles used for transportation and the distance of the suppliers from the manufacturing facility of the company influences transportation emissions. Using fuel-efficient trucks, which are more eco-friendly, can reduce transportation emissions. The location of the suppliers from the company changes the amount of CO_2 that is produced in the process of shipping materials to the company. In addition, some materials from suppliers far from the company with slightly lower green standards are cheaper. These influence the total profit of the company.

Therefore, in contrast with Tseng and Lin (2014) we consider transportation cost and transportation emissions of raw materials in our model.

In our model, there are constraints for supplier capacity and storage capacity of the company which prevent the company from buying raw materials from suppliers more than its storage capacity. Also, suppliers have limitations in their capacity to produce raw materials for a specific period of time. In their model, Tseng and Lin (2014) do not have such restrictions.

In the model proposed by Tseng and Lin (2014) there are no limits to maximum and minimum production amounts. Because of market predictions there are limitations on minimum and maximum production. Producing either less than what is permitted or more than the needs of the market does not translate into profit for the company, therefore, our model imposes constraints on production amount.

Finally, in the model presented by Tseng and Lin (2014) design is varied and for different designs the number of different variables and parameters changes. In our model, design is fixed and based on different periods of time the values of the parameters and variables change. Essentially, design is one of the main factors that was considered in Tseng and Lin model, while in our model the main factor is the period of time and the end product.

Chapter 5. Conclusions and Future Research

5.1. Summary of Experimental Design

In this thesis, a mathematical programming model was developed which is based on supply chains and manufacturing facilities of all sizes producing various products. In studying the system and developing the mathematical model, we considered two practical scenarios: one scenario focuses on the customers' tendency towards purchasing green products and the other one is centered around changing delivery companies which in turn results in changes in carbon emissions and transportation costs. We further solved a number of numerical example problems in three different companies: Pars PVC Pipe Company, Pars Plastic Company and Nab Stainless Steel Company.

The objective function of this model is to maximize the profit of the company while considering the minimum cost for a green supply chain and manufacturing. All the examples were solved to find the maximum profit while considering the environmental criteria. In each company, we tested both scenarios. In the experiment that tested for effects of customer sensitivity towards eco-friendliness of the products, one sample with the sensitivity rating of 0 was picked for each experimental group and represents the customers who are not at all sensitive towards purchasing green products as a control group. Customers were randomly selected from a pool.

5.2. Conclusions from the Experimental Data

Our mathematical programming model calculates profit, allowed production amount and the amount of raw materials to be purchased from suppliers based on input data on categories such as costs, the market value of products, market demand, and environmental constraints. For each company, the calculations aim at maximizing the profit while maintaining the green status of the company and its products. However, our case studies show that the amount of the profit in comparison to conditions prior to implementation of the model varies considerably and can increase or decrease. In other words, input data determine whether the company is going to make more profit by implementing green or its profits are going to decrease but in each case the model calculates how the company should adjust its input to gain maximum possible profit in a given scenario. In addition, because this model follows green guidelines, it may lead to incurring shortage costs and result in the cancelation of orders and losses in sales which might result in loss of the trust of a fraction of the customers and profit. However, the company takes this risk to satisfy the customers who are sensitive towards purchasing green products. Therefore, companies should consider many factors such as their competitive advantage, environmental laws and customer satisfaction before implementing this model to see how those elements influence their profits.

5.3. Future Research

In this thesis, the mathematical model was solved for several case studies and the solutions are satisfactory and can be adjusted for practical implementation. Our mathematical model can be solved by commercial solvers like IBM ILOG CPLEX® Optimizer. However, for this model to function properly in large-scale industrial applications a heuristic algorithm should be developed based on the methods presented in the model. This allows the problem to be solved in a reasonable amount of time.

In future research in this direction, further development of the main model is possible to investigate more detailed green related cost functions and explore more practical evaluations criteria. We considered a linear demand function. This study can be expanded by applying a nonlinear demand function. Additionally, the factors that change in our scenarios are sensitivity rate and changing the transportation costs and CO_2 emissions. For future studies, other factors that can have effects on profit can be considered, such as the price of the products, the changes in the source of energy and its costs and changing the technology used in the manufacturing process.

The current model can also be developed to find the efficient algorithm to incorporate the economy of scale. This is especially important when certain green products are highly in demand and manufacturers need to factor in the reduced consumer price in their calculations.

In addition, the feasibility, effectiveness and efficiencies of using such an integrated model for solving problems of larger sizes can be studied. Finally, efficient heuristic solution methods should be developed for industrial applications.

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Appendix A: Input Data for the Effects of Customer Sensitivity Towards Eco-Friendliness of the Products at Pars PVC Pipe Company (Section 4.2)

m_i^e	P1	P2	P3	t_i^e	P1	P2	P3
1	0	0	0	**1**	0	0	0
2	1.80	1.80	1.82	**2**	1.50	1.58	1.60
3	2.21	2.21	2.24	**3**	1.85	1.94	1.97
4	2.36	2.36	2.38	**4**	1.97	2.07	2.10
5	2.56	2.56	2.58	**5**	2.13	2.24	2.27
6	2.70	2.70	2.73	**6**	2.25	2.37	2.40
7	2.91	2.91	2.95	**7**	2.43	2.56	2.59
8	3.15	3.15	3.19	**8**	2.62	2.77	2.80
9	3.26	3.26	3.29	**9**	2.72	2.86	2.90
10	3.44	3.44	3.48	**10**	2.87	3.02	3.06
11	3.60	3.60	3.64	**11**	3.00	3.16	3.20
12	3.82	3.82	3.86	**12**	3.18	3.35	3.39
13	4.05	4.05	4.09	**13**	3.38	3.56	3.60
14	4.18	4.18	4.22	**14**	3.48	3.67	3.71
15	4.32	4.32	4.37	**15**	3.60	3.79	3.84
16	4.54	4.54	4.59	**16**	3.78	3.98	4.03

Pi	T_i (sec)
P1	43
P2	44
P3	43

P_t^{Min} (unit)	8000
P_t^{Max} (unit)	50000

C_t^{St} (kg)	500000

Pi	G_i (Cent)
P1	2200
P2	2220
P3	2240

T_t^T (sec)
345600

Material	Machine	Period	F_{mjt}^{Co} (cent)
1	1	1	600
1	2	1	620
2	1	1	650
2	2	1	650
3	1	1	630
3	2	1	640

Product	Material	M_{im}^{Con} (kg)
1	1	6
1	2	5
1	3	5
2	1	6
2	2	4
2	3	5
3	1	6
3	2	5
3	3	5

Product	Period	D_{it} (unit)
1	1	13500
2	1	13200
3	1	13000

Material	Period	J_{mt}^{Em} (kg)
1	1	68
2	1	75
3	1	92

Material	Period	C^{S}_{mt} (kg)
1	1	500000000
2	1	500000000
3	1	500000000

Product	Material	Machine	B
1	1	1	0
1	1	2	0
1	2	1	1
1	2	2	0
1	3	1	0
1	3	2	1
2	1	1	1
2	1	2	1
2	2	1	0
2	2	2	1
2	3	1	0
2	3	2	0
3	1	1	0
3	1	2	0
3	2	1	0
3	2	2	0
3	3	1	1
3	3	2	0

Material	Machine	Period	F^{Em}_{ijt} (kg)
1	1	1	50
1	2	1	52
2	1	1	60
2	2	1	58
3	1	1	62
3	2	1	62

L_t^W (J)
1200000

y (AER) (unit/kg)	3.25

Supplier	Period	J_{st}^{Co} (cent)
1	1	280
2	1	350
3	1	400

Supplier	Period	M_{st}^{Co} (cent)
1	1	700
2	1	640
3	1	580

Connection	Period	Product	A_{cti}^{Co} (cent)
1	1	1	20
1	1	2	20
1	1	3	20
2	1	1	20
2	1	2	20
2	1	3	20

Machine	Product	Period	R_{jit}^{Co} (cent)
1	1	1	20
1	2	1	20
1	3	1	20
2	1	1	20
2	2	1	20
2	3	1	20

Product	Period	Z_{it}^{Co} (cent)
1	1	40
2	1	42
3	1	42

L_t^{Em} (kg)
8000000

Machine	Product	Period	W_{jit}^{Co} (cent)
1	1	1	10
1	2	1	11
1	3	1	13
2	1	1	11
2	2	1	11
2	3	1	12

Machine	Product	Period	I_{jit}^{Co} (cent)
1	1	1	13
1	2	1	16
1	3	1	17
2	1	1	14
2	2	1	11
2	3	1	19

Machine	Material	E_{mj}^{Co} (cent)
1	1	40
1	2	42
1	3	50
2	1	42
2	2	44
2	3	46

Product	Period	U_{it}^{W} (J)
1	1	15
2	1	17
3	1	15

Product	Period	L_{it}^{CO2} (kg)
1	1	700
2	1	700
3	1	700

Appendix B: CPLEX® Output Data for the Effects of Customer Sensitivity Towards Eco-Friendliness of the Products at Pars PVC Pipe Company (Section 4.2)

Customers	Profit (USD)	Customers	Profit (USD)
1	97884.38	**9**	78137.37
2	87389.35	**10**	76872.11
3	84975.11	**11**	75751.28
4	84137.90	**12**	74237.55
5	82985.63	**13**	72607.46
6	82037.20	**14**	71720.20
7	80524.33	**15**	70716.59
8	78894.24	**16**	69202.86

X_{it} *(unit)*	P1	P2	P3
1	8037	9906	13000
2	8037	10257	12154
3	8037	10338	11959
4	8037	10366	11892
5	8037	10332	11801
6	8037	10170	11732
7	8037	9931	11631
8	8037	9662	11520
9	8037	9543	11469
10	8037	9340	11383
11	8037	9161	11309
12	8037	8916	11208
13	8037	8652	11099
14	8037	8209	11340
15	8037	7984	11341
16	8037	7709	11270

Customers	Total X_{it} (Units)	Customers	Total X_{it} (Units)
1	30,727	**9**	28,970
2	30,243	**10**	28,679
3	30,132	**11**	28,418
4	30,093	**12**	28,068
5	30,040	**13**	27,690
6	29,872	**14**	27,486
7	29,523	**15**	27,254
8	29,145	**16**	26,904

Raw Material(kg)	S1	S2	S3
1	118872	101185	80109
2	115184	108955	79213
3	116056	107980	79537
4	116392	107645	79649
5	115984	107190	79513
6	123040	98845	80865
7	120172	98340	79909
8	116944	98185	78833
9	115116	97530	78357
10	106080	89100	77545
11	104432	88730	76829
12	101792	88225	75849
13	98824	87680	74793
14	96708	98385	72221
15	95048	98040	71601
16	92308	97535	70621