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An optimization model for a monopolistic firm serving an environmentally conscious market: Using Chemical Reaction Optimization Algorithm

Abstract

This research considers a monopolist firm which faces the following twin challenges of serving an environmentally sensitive market. The first challenge is the demand's elasticity to emissions and price. To entice its environmentally conscious customers and generate higher demand, the firm incrementally invests in cleaner production technologies. It also adopts a voluntary limit on its emissions from transportation. However, such investments and penalty lead to the second challenge of reduced net profit. In order to address these challenges and establish a trade-off, this research develops a Non-Linear Programming (NLP) model with a maximization quadratic profit function. Furthermore, a Chemical Reaction Optimization algorithm, with superior computational performance, has been applied to solve the developed NLP models. The output results of the model provide near optimal monopolistic price, best attainable reduction in manufacturing emissions through proportional investment and a choice of suitable mode of transportation for each type of product offered by the firm. Three types of sensitivity analyses were performed by varying contextual parameters: customers' emission elasticity, penalty charged per unit emission and investment coefficient. The results underpin the importance of investments in cleaner technologies and the need of financial aids for profit maximizing firms operating in cleaner markets. This research provides a decision making model to determine the near optimal degree of each of the above dimensions in multiple business fronts.

Keywords: Emission elasticity; Chemical Reaction Optimization; Non-Linear Programming; Cleaner technologies

1. Introduction

World-wide environmental campaigns for a cleaner and safer environment have initiated the implementation of stringent regulatory norms. Simultaneously, an environmentally conscious market has evolved towards desiring eco-friendly products and services. Furthermore, recent trends in the stock market suggest that firms with strong environmental management practices have better market value. These developments have motivated organizations to map, monitor and manage their carbon emissions. For example, proactive players like FedEx, UPS, Wal-Mart, PepsiCo, Coca-Cola have publicly committed to a self-imposed carbon emission targets.

The developing countries, which were once heavily polluted, have now started raising their environmental compliance standards. Multi-nationals that outsource their polluting manufacturing units to these countries are increasingly facing resistance from organized local communities. For example, Chinese activists accused Taiwan-based Apple's suppliers for releasing toxic metals into their rivers (The Wall Street Journal 2013). Environmental awareness has even changed the market's supply-demand dynamics. Contemporary consumers are now more sensitive about the emission levels which are assigned to their consumption habits. Carter et al. (2000) revealed that 75% of U.S. consumers made their purchasing decisions considering the enterprises' environmental reputation in mind and 80% of the consumers were willing to pay more for environmental friendly products and services. Even consumers in developing countries are increasingly opting for green

products (Harris, 2006). Such changing consumers' ethical values and ecological thinking exert normative pressure on manufacturers to implement environmental friendly practices.

In recent times, ease of communication and reduction in transportation cost have opened up demand of the remote locations of the world. In addition, technological breakthroughs have resulted in the multiplication of variety of products and reduction of per unit cost of goods. However, producers and customers are less sensitive to the downside of such trends. The result of such advancements is the rise of CO_2 emissions arising from the world wide transportation of the low priced goods. If these emissions can be included as costs, for example by a CO_2 emission tax (Peters and Hertwich, 2008) or if the consumers change their demand based on the total emission levels (Yalabik and Fairchild, 2011), then producers will be bound to include an "environmental friendly" label that informs consumers how "clean" the production process of a product is and how much it has travelled around the world (Cadarso et al., 2010; Sundarakani et al., 2010).

Consumers and regulators continuously exert pressure on firms to reduce their carbon emissions (Kleindorferetal.,2005; O'Brien, 1999; Sarkisetal., 2011). Organizations now face two-fold challenges. First, they experience reduced customer demands for their products, if their manufacturing practices have severe impact on environment (KassinisandSoteriou,2003;K lassenandMcLaughlin,1996). Second, they are penalized by regulators if they violate environmental standards. Busch and Hoffmann (2007) state that carbon emissions and carbon constraints can financially affect a company even if they do not occur in the company itself, but within the value chain of the company. Two important domains that largely contribute to emissions are: energy-intensive manufacturing, and transportation of finished products. While adoption of technological developments can significantly curtail emissions in production; multiple transportation modes need to be explored for a greener supply chain.

This research considers a monopolist firm which faces the following twin challenges of serving an environmentally sensitive market. The first challenge is the demand's elasticity to emissions and price. The optimal price of each product is dependent on its demand. The firm strives to derive a best attainable carbon emission level for profit maximization. To entice its emission conscious customers and generate higher demand, the firm incrementally invests in cleaner production technologies. The firm delivers its products through a third party logistic provider which operates on three different modes with different per unit transportation costs and emissions. The firm also adopts a voluntary limit on its emissions from transportation. However, such investments, transportation mode choice and penalty lead to the second challenge of reduced net profit. To address above trade-off a Non-Linear Programming (NLP) model with a maximization quadratic profit function has been formulated in this research as discussed in section 3.

A recently developed Chemical Reaction Optimization (CRO) algorithm has been applied to solve the NLP model. The results are tested for different parameters using sensitivity analysis and this method is proved to provide robust results. A detailed explanation of CRO algorithm is provided in Section 4. To illustrate the implementation of the CRO algorithm, a numerical example is considered and demonstrated in Section 5. The output of the model provides near optimal monopolistic price, best attainable reduction in manufacturing

emissions through proportional investment and makes a choice of suitable mode of transport for each type of product offered by the firm. Three types of sensitivity analyses by varying contextual parameters like customers' emission elasticity, penalty charged per unit emission and investment coefficient, are performed in sub-sections 5.1, 5.2 and 5.3. The results underpin the importance of investments in cleaner technologies and the need of financial aids for profit maximizing firms operating in cleaner markets.

This research contributes to the body of knowledge by incorporating various dimensions of sustainability suggested in the extant literature: emission sensitive customers, green supply chain, and cleaner manufacturing technologies (each of these dimensions are discussed in Section 2), in a single holistic model. It provides a decision making tool to determine the near optimal degree of each of the above dimension in multiple business scenario.

2. Literature review

This research builds up the problem statement on following three broad sub-topics of environmental concerns: 1) impact of adoption of environmental friendly practices on a firm's market value and demand, 2) investment in eco-friendly manufacturing practices and 3) emission reduction in supply chain based on the choice of transportation mode. This section reviews the related research on these sub-topics and tried to identify a research gaps.

Greenhouse Gas Protocol (GHG, 2011) categorizes emissions into three broad scopes. Scope 1 emissions include all emissions by assets owned by the reporting company. For a manufacturing company, this typically includes on-site fuel consumption for production or heating. Scope 2 emissions are related to emissions caused by the production of electricity generally consumed by various assets. Scope 3 emissions include all remaining emissions by other companies e.g. suppliers from which products or services are bought, directly or indirectly. Manufacturing companies also include the emissions from their third party logistics providers under scope 3. This research mainly focuses on scope 1 and scope 3 emissions of a manufacturing firm.

2.1 Market value and demand

The extant literature significantly supports the impact of superior environmental performance on financial performance. Dowell et al. (2000) analysed a sample of U.S. based multi-national enterprises and have statistically validated that firms adopting a single stringent global environmental standard, have much higher market values than those defaulting the local standards. Jacobs et al. (2010) examine the stock market reaction associated with announcements of corporate environmental initiatives and environmental awards and certifications. Their findings reveal that the environmental philanthropy is viewed positively by the market. It generates positive publicity and goodwill among various stakeholders and also creates value through loyal customers and highly motivated employees.

In recent times, ease of communication and reductions in transportation costs have spurred up off-shoring practices. This has led to the fragmentation of production processes and increase in the total distance travelled by the final goods to reach customers. The net result is the rise in CO_2 emissions (Weber and Matthews, 2008;

van Veen-Groot et al. 2001). However, the allocation of the responsibility for the environmental consequences of international trade is debatable. On one hand, the producer responsibility principle states that the country where production of goods or services takes place is responsible for the pollutant emissions regardless of where those commodities are consumed (domestic or foreign market). IPCC and Kyoto Protocol (IPCC, 1997) follow producer responsibility principle. On the other hand, the consumer responsibility principle allocates responsibility for emissions to the final consumers of the products (Gay and Proops, 1993; Munksgaard and Pedersen, 2001). Cadarso et al. (2010) defined the Broad Consumer Principle (BCP) which assigns CO_2 emissions due to international transport to the country which finally consumes the product.

Although the above two principles raise debate on carbon emissions allocation front, their end results are common. Producer responsibility principle sensitizes producers to reduce carbon emissions through their production and transportation activities. Consumer responsibility principle achieves the same by sensitizing customers about the carbon footprints of their consumption habits. Companies around the world have shown interest in adopting environmentally friendly manufacturing practices. However, their success depends on their capability to market and sell their green products (Sarkis et al., 2011). Companies may seek to communicate their environmental performance to outside stakeholders particularly their customers. To enable dissemination of such information to emission sensitive customers, several authors including Roberts (2008) and Houe and Grabot (2009) have suggested eco-labelling of products.

In this research, we incorporate the effects of both the principles. While on one hand the producer strives to reduce its carbon footprints by investing on technology (refer to Section 2.2) and choosing the least emission causing transportation mode (refer to section 2.3), on the other hand, the market demands of the products vary based on the emission elasticity of the customers. Kassinis and Soteriou (2003) and Klassen and McLaughlin (1996), have established that there is a negative relationship between the firm's environmental impact and customer demand. Yalabik and Fairchild (2011) have carried out an economic analysis of an environmentally sensitive market and have formulated the following price and emission sensitive demand function.

$$D(p,E) = a - bp - kE \quad (1)$$

Where, p is the per-unit price charged by the firm, E is the amount of emissions per unit of the output produced. The parameters a, b and k capture behaviour of customers in market. a is the market size, b is the sensitivity of the customers to the product's price, and k is the sensitivity of the customers to the firm's emissions. The firm loses b units of demand for every unit increase in price, and loses k units of demand for every unit increase in emissions per unit of product produced. As the firm's emissions increase, the demand for its product decreases by an amount kE. The authors assume that k cannot be influenced by the firm and is driven by external factors such as environmental news, efforts by policymakers or groups. This research uses the similar emission and price sensitive demand function for the developed model.

2.2 Manufacturing practices

This sub-section addresses Scope 1 emissions as defined in GHG (2011). The main issue that dominates the contemporary manufacturing industry is the adoption of sustainable production practices (Christopher, 1999).

Clark (2007) opines that an economy could be maintained by sustainable consumption that includes sustainable products and industrial processes. Penkuhnet al. (1997) and Brennan et al. (1996) suggest that firms must explicitly account for new environmental pressures in their scope of capacity planning. Angell and Klassen (1999) extended the traditional production capacity planning models (of production and recycling units) by including environmental variables in both the objective functions and constraints of production planning model. Letmathe and Balakrishnan (2005) determined the optimal product mix and production quantities for a firm in the presence of different types of environmental constraints. Barber (2007) discusses production-based initiatives including life-cycle analysis, pollution prevention, cleaner production, and extended producer responsibility. Tapiero and Kogan (2008) present a partial equilibrium model for sustainable infrastructure investment in a labour-production economy. Chen and Sheu (2009) derived an optimal design and illustrate how manufacturers can adopt optimal product green design and pricing strategies to achieve maximum profit while satisfying social responsibility and demands. Hua et al. (2011) make an investment decision with an aim to maximize profit for a producer bounded by emission regulations. Benjaafar et al. (2013) consider both emissions from production, transport and inventory in a lot-sizing problem. However, most of these works did not consider market dynamics and demand.

Despite growing concerns and regulatory pressures, producers vary in the amount of investment they make in environmental innovation. Buil-Carrasco et al. (2008) describe a stream of literature that classifies firms according to their environmental practices. For example, one classification rates firms as excellent, proactive, reactive, passive, indifferent, or negative. Firms invest in cleaner technologies, to reduce emissions. According to Hart (1995) and Popp (2005) emissions reductions might be relatively inexpensive in the early stages but as the firm's environmental performance improves, more significant investments in processes and technologies are required for further reductions in emissions. Thus, further improvements will be more expensive than the initial reductions. Based on above understanding, Yalabik and Fairchild (2011) carried out an economic analysis to examine the effects of consumer, regulatory, and competitive pressure on firm's investments in environmentally friendly production. They assumed following investment function for the reduction of emissions levels from E_0 to E_1.

$$I = t(E_0 - E_1)^2 \quad (2)$$

Where, t determines the magnitude of the cost involved in making an investment.

Further, regulators penalize the firm for every unit of emission generated by the production activities. Therefore, the firm's profit margin per unit is given by

$$PM = p - c - mE \quad (3)$$

Where, c is per-unit cost of production, m is the penalty charged by regulators for per unit emission from production activities. However, most of the research in this category did not consider the overall supply chain aspects. This research uses the similar cost and price functions for the model presented in this research while considering supply chain aspects.

2.3 Supply chain

Globalization, fragmentation of production processes and opening up of new markets have resulted in increase in international trade. This has led to the creation of global supply chains (van Veen-Groot and Nijkamp, 1999). Significant developments have taken place to address the environmental impacts of global supply chains. Research work that focuses on the environmental impact of international trade related to specific transport methods (by sea, by air, by road) has evolved over the years. Some of this research is: Corbett and Koehler (2003); Endresen et al., (2003); Eyring et al., (2005); Corbett and Winebrake(2008), on sea transport, including freight and passenger transport; Steenhof et al.(2006); Tarancón and Del Río (2007), and on land transport,

Choletteand Venkat (2009) analysed costs and emissions of wine supply chain for different types of transportation modes. Hoen et al. (2011, 2013) examined the effects of incorporating emissions as cost versus emissions as constraint on the transportation mode selection and suggested preference for constraints. Cadarso et al. (2010) developed a method to measure emissions from international freight transport and allocate emissions based on consumer responsibility. Leal Jr. and D'Agosto (2011) carried out investigation of shipping of bio-ethanol through multimodal transport and concluded that transportation of the fluid through pipelines lowers the cost and has lesser adverse environmental impacts.

This research involves the selection of appropriate transportation mode for products while satisfying a self-imposed emission limit. To compute carbon emissions from various modes, we use the method suggested by The Network for Transport and Environment (NTM). NTM (2011) specifies emissions for four types of transport: air, rail, road and water. The emissions associated with transporting one unit of product j with mode i are given by

$$e_{ij} = w_j(a_i + b_i d_{ij}) \quad (4)$$

Where, w_j is the weight of per unit of product j, d_{ij} is the distance covered for transporting per unit of product j with mode i, a_i and b_i are mode-specific emission constants. The fixed emission factor $a_i \geq 0$ is associated with the emissions generated during the beginning and end of a trip and the variable emission factor $b_i \geq 0$ is for per kilometre travelled. Both values are expressed per unit weight of load transported.

Various research mentioned in this section reveal that most of the research contributions are considered in isolation at sub-topic level (i.e. environmentally sensitive demand and price in Section 2.1, decision for investment amount in cleaner technology in Section 2.2 and transportation mode selection in Section 2.3). However, models which integrate all three concepts in a holistic model are not fully developed. This research aims to fill this research gap by developing an integrated holistic model to assist in decision making at multiple aspects of a business. Next section discusses the formation of problem under consideration in this research.

3. Problem Formulation

Various notations used in developing the model are mentioned as follows:

Let,

J be the set of types of products

j be the index for product type

I be the set of different modes of transportation available

i be the index for the mode of transportation

D_j be the market size of product type j

b_j be the price elasticity of demand of product type j

c_j be the emission elasticity of demand of product type j

$E_j^{P_0}$ be the initial emission due to production of per unit of product type j

e_{ij} be the emission due to transportation of per unit of product type j using mode i

t_j be the investment coefficient for reducing per unit of emission corresponding to production of product type j

w_j be the per unit weight of product type j

m be the penalty charged by regulators for per unit of production emission

u_{ij} be the transportation cost per unit of product type j using mode i

k_j be the cost of production per unit of product type j

λ be the pre-defined self-imposed limit on total transportation emission

Decision Variables

p_j be the price of product type j set by the monopolistic firm

Q_j be the demand of product type j fulfilled by the monopolistic firm

E_j^P be the revised emission due to production of per unit of product type j

I_j be the total investment for reduction of emissions due to production of product type j

PM_j be the profit margin per unit of product type j

PR_j be the profit generated by selling Q_j units of product type j

$NetProfit$ be the net profit of the firm

x_{ij} Binary decision variable

$$x_{ij} = \begin{cases} 1 & \text{if mode } i \text{ is selected for product type } j \\ 0 & \text{otherwise} \end{cases}$$

We develop the model for a monopolistic firm which aims to maximize its net-profit while serving an environmentally conscious market. The firm offers different types of products to the customers who are sensitive to price and emissions, as explained in Section 2.1, Equation (5) provides the function for the resultant demand Q_j fulfilled by the monopolistic firm, incorporating both the price and emission elasticity of demand. Where, b_j and c_j are the price and emission elasticity of demand of product type j, respectively and D_j is its market size. E_j^P is the emission attributed to production of per unit of product type j. e_{ij} is the emission due to transportation of per unit of product type j using transport model i.

$$Q_j = (D_j - b_j p_j - c_j E_j^P - c_j e_{ij}) \qquad (5)$$

To ensure that a non-negative quantity is sold i.e. $Q_j \geq 0$, we restrict p_j as $0 \leq p_j \leq \frac{1}{b_j}\left(D_j - c_j E_p - c_j e_{ij}\right)$

This constraint is further used in Equation (13).

Since, there is a trade-off between the price p_j of the product and the resultant fulfilled demand Q_j, the first decision that the firm needs to take is to set optimal price p_j for each product type depending on the price elasticity b_j of its demand. If b_j is high then customers react to price rise by consuming lesser number of products. On the other hand, if b_j is low, the monopolistic firm can afford to raise the price without suffering in volume of demand. In addition, the customers are sensitive to emissions assignable to the consumption of products. Therefore, emissions due to production and transportation proportionately reduce the demand. Higher value of emission elasticity c_j suggests that the consumer is more responsive towards the changes in emission and a lower value of c_j suggests that the consumer is indifferent to the amount of the emissions generated by the firm. This research considers the assumption that c_j is solely determined by external factors.

To entice its environmentally sensitive customers for higher demand and profit, the firm builds up a “green” image. It incrementally invests in cleaner technologies to reduce emissions from production. Let us assume that the initial emission corresponding to production of per unit of product type j is $E_j^{P_0}$. Now, the firm wants to invest on cleaner technologies to reduce emission corresponding to production of per unit of product type j to E_j^P. Therefore, the second decision that the firm has to take is to decide how much investment should be made on adoption of cleaner technologies. Equation (6) refers to the investment function I_j based on diminishing rate of returns, as explained in Section 2.2 where, t_j is the investment coefficient for reducing per unit of emission corresponding to production of product type j.

$$I_j = t_j (E_j^P - E_j^{P^0})^2 \quad (6)$$

The firm also adopts a voluntary limit λ on emissions from transportation. It distributes its products through a third party logistic (3PL) provider who can operate on three different modes. Therefore, the third decision to be made by the firm is to select an appropriate mode of transport for each type of product j. Total Carbon emissions E_{ij}^T due to transportation of product type j using mode i is calculated using equation (7), as explained in Section 2.3. Equation (11) refers to the self-imposed emission constraint. It bounds the sum of transportation emissions of all types of products to a pre-defined value λ.

$$E_{ij}^T = e_{i,j}(D_j - b_j p_j - c_j E_j^P - c_j e_{ij}) \qquad (7)$$

Furthermore, regulators charge the firm by a penalty m for every unit of emission generated by the production activities. Therefore, the cost incurred due to production emissions of product type j is mE_j^P. In addition, the firm incurs per unit production cost k_j for product type j and transportation cost u_{ij} through mode i. Therefore, the firm's profit margin per unit of product type j is given by equation (8).

$$PM_j = (p_j - k_j - mE_j^P - u_{ij}) \qquad (8)$$

Furthermore, the profit generated by selling Q_j units of product type j can be given by equation (9).

$$PR_j = Q_j * PM_j - I_j = (D_j - b_j p_j - c_j E_j^P - c_j e_{ij})(p_j - k_j - mE_j^P - u_{ij}) - t_j(E_j^P - E_j^{P^0})^2 \quad (9)$$

The final objective (10) is to maximize the net profit generated by the firm after incurring costs in production, penalty, transportation and investment in cleaner technology. We formulate following Non-Linear Programming Model considering all three aspects.

Objective Function:

$$\text{Maximize } NetProfit = \sum_{j\in J}\sum_{i\in I} x_{ij}[(D_j - b_j p_j - c_j E_j^P - c_j e_{ij})(p_j - k_j - mE_j^P - u_{ij}) - t_j(E_j^P - E_j^{P^0})^2]$$

(10)

Subject to constraints:

$$\sum_{j\in J}\sum_{i\in I} x_{ij} E_{ij}^T \le \lambda \qquad (11)$$

$$0 \le E_j^P \le E_j^{P^0} \ \forall \ j \in J \quad (12)$$

$$0 \le p_j \le \frac{1}{b_j}\left(D_j - c_j E_p - c_j e_{ij}\right) \ \forall \ j \in J \quad (13)$$

$$x_{ij} \in [0,1] \cap \mathrm{I} \ \forall \ j \in J, \ i \in I$$

$$p_j, E_j^P, E_{ij}^T \ge 0 \ \forall \ j \in J, \ i \in I$$

The objective function represents a trade-off between price, demand, investment, emissions due to production and transportation for products. The firm aims to maximize its net profit by setting higher selling price. But its negative impact on the volume of demand imposes restrictions. Further, to attract environmentally conscious customers and reduce penalty paid to the regulators, the firm aspires to reduce its production emissions. However, the corresponding higher value of investment on cleaner technologies reduces the net profit. Similarly, the firm's selection for the mode of transportation also involves trade-off between the emission levels and corresponding cost of transportation. Note, that the objective $NetProfit$ is a non-linear function. To solve this NLP model, we use a novel Chemical Reaction Optimization (CRO) algorithm (Lam and Li, 2012) developed recently. Section 4 provides an overview of this method, discusses its various steps and justifies reasons for its adoption as a solution methodology.

4. Chemical Reaction Optimization

Chemical Reaction Optimization (CRO) is a novel optimization meta-heuristic developed by Lam and Li, (2012). CRO algorithm is based on working mechanism of chemical reactions which follow two laws of thermodynamics. The first is the law of conservation of energy and the second law states that the entropy of a system always tends to increase. In a chemical reaction, unstable molecules with lower entropy and higher potential energy tend to attain stable state with higher entropy by converting potential energy into kinetic energy and by gradually losing the energy to the surroundings by colliding with each other. A chemical change of a molecule is triggered by collision. The result of collision can be any one of the following four types of elementary reactions. More details are further explained in Section 4.1.

Table 1: Characteristics of the four elementary reactions

Extent of change	**Number of molecules involved**	
	Uni-molecular	**Inter-molecular**
More	Decomposition	Synthesis
Less	On-wall ineffective collision	Inter-molecular ineffective collision

CRO algorithm captures the above phenomenon of chemical reactions to formulate its step-wise search for the optimal point. The solutions are manipulated through a random sequence of elementary reactions. The two ineffective collisions, as shown in Table 1, implement local search (intensification) while decomposition and synthesis give the effect of diversification. An appropriate mixture of intensification and diversification makes an effective search of the global optima in the solution space. CRO algorithm leverages the advantages of both Simulated Annealing (SA) and Genetic Algorithm (GA) in finding global optima. The energy conservation requirement gives similar effect of the Metropolis Algorithm used in SA. The decomposition and synthesis operations are similar to the crossover and mutation operations of GA. When the number of molecules is small, CRO algorithm resembles as SA algorithm. On the other hand, when crossover and mutation operators are implemented during decomposition and synthesis phase, CRO performs more like a GA.

Conversion of energy and transfer of energy in different entities and forms make CRO unique among other available meta-heuristics. CRO algorithm has the potential to tackle problems which have not been successfully solved. It manifests an impressive computational performance in solving real world NP-hard problems, e.g. task scheduling in grid computing, spectrum allocation in cognitive radio system and in non-convex continuous problems. It can easily deploy various arithmetic operators to suit different problem scenarios. These advantages motivate us to implement CRO algorithm as a solution methodology for the above formulated non-linear optimization problem. In the following section, we further explain the implementation of CRO algorithm in our problem context.

4.1 CRO implementation

The basic agent which is manipulated in CRO is a molecule. Each molecule is characterized by three key attributes: molecular structure (ω), potential energy (PE) and kinetic energy (KE). In our problem context, molecular structure ω is a matrix which contains continuous decision variables for price and production emissions associated with each type of product $j \in J$. Potential energy PE represents the value of the objective function $NetProfit$ corresponding to the solution represented by the molecular structure ω. Kinetic energy KE is a non-negative number that quantifies the tolerance of the system for accepting a worse solution than the existing one.

In this context, following additional attributes store the information as the molecule undergoes collision. Number of hits $(NumHit)$ records the total number of collisions a molecule has undergone. Maximum Structure $(MaxStruct)$ is that value of ω (matrix of price and emission for each product type) corresponding to which the value of Potential Energy (PE) is maximum $(MaxPE)$. Minimum Hit Number $(MinHit)$ is the number of hits when a molecule attains the Maximum Structure $(MaxStruct)$.

Each iteration of CRO algorithm performs one of the four elementary collisions types as shown in Table 1. These collision are employed to manipulate solutions (i.e. explore the solution space) and to re-distribute the energy among the molecules and the buffer. Next subsection describes the energy transformations for each kind of elementary reaction.

4.1.1 On-Wall Ineffective Collision

During an on-wall ineffective collision, a molecule collides with the wall of the container and bounces back retaining its singularity. Therefore, for this type of collision, the molecular structure is only slightly perturbed from existing ω to ω' i.e. the values of price and emissions corresponding to the colliding molecule are slightly altered to search for the local optima. ω' is selected in the neighbourhood of ω which is randomly selected from a population. During a collision, a certain portion of KE_{ω} of the initial molecule is withdrawn by the central buffer. A $KELossRate \in [0,1]$ parameter defines the rate of loss of KE in a particular reaction. A random

number $a \in [KELossRate,\ 1]$ is generated. The $KE_{\omega'}$ of the molecule generated as mentioned in equation (14).

$$KE_{\omega'} = (PE_{\omega} - PE_{\omega'} + KE_{\omega})a \quad (14)$$

The remaining energy is transferred to the central buffer as mentioned in equation (15).

$$BE = (PE_{\omega} - PE_{\omega'} + KE_{\omega})(1-a) \quad (15)$$

This reaction takes place when the total energy of the existing molecule is greater than the potential energy of the newly created molecule i.e. $PE_{\omega} + KE_{\omega} \geq PE_{\omega'}$.

4.1.2 Decomposition

The second type of elementary reaction which a randomly selected molecule can undergo is decomposition which splits it into two parts.

$$\omega \rightarrow \omega_1' + \omega_2'$$

That means two different matrices corresponding to price and emissions values are randomly generated. This reaction explores the solution space globally, after enough local exploration has been done. Since a bigger number of molecules are created, energy conservation may not be satisfied. As a result, decomposition will not take place. Energy from the central buffer is then utilised to support the decomposition reaction. Two random numbers $\phi_1, \phi_2 \in [0,1]$ are generated, which decide sthe amount of energy to be withdrawn from the central buffer. The energy involved in decomposition reaction E_{dec} is given by equation (16).

$$E_{dec} = (PE_{\omega} + KE_{\omega} + \phi_1 \times \phi_2 \times buffer) - (PE_{\omega_1'} + PE_{\omega_2'}) \quad (16)$$

The remaining energy is transformed into the kinetic energies of the newly generated molecules, given by equations (17) and (18).

$$KE_{\omega_1'} = E_{dec} \times \phi_3 \quad (17)$$

$$KE_{\omega_2'} = E_{dec} \times (1-\phi_3) \quad (18)$$

Where ϕ_3 is a random number generated in $[0,1]$. The buffer energy is updated to:

$$buffer' = (1-\phi_1\phi_2)buffer \quad (19)$$

Now, if $PE_{\omega_2'} \leq PE_{\omega_1'}$ that means the objective function $NetProfit$ value corresponding to the first part ω_1' (with one set of price and emissions values) is superior to that of ω_2' (with another set of price and emissions values).Thus, solution corresponding to ω_1' is chosen.

4.1.3 Inter-molecular Ineffective collision

The third type of reaction that a molecule can undergo is Inter-molecular Ineffective collision. In this, two randomly selected molecules ω_1 and ω_2 collide with each other to produce two new molecules ω_1' and ω_2'.

$$\omega_1 + \omega_2 \rightarrow \omega_1' + \omega_2'$$

Energy distribution is similar to that of decomposition. However, the buffer energy is not required for this reaction. The newly created molecules help to exploit the solution in the immediate surroundings of the existing molecule. For an Inter-molecular Ineffective collision to take place, the energy condition, given by equation (20) should be satisfied.

$$PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2} \geq PE_{\omega_1'} + PE_{\omega_2'} \qquad (20)$$

The energy released in Inter-molecular Ineffective collision is given by equation (21).

$$E_{inter} = (PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2}) - (PE_{\omega_1'} + PE_{\omega_2'}) \qquad (21)$$

The remaining energy is distributed between the two molecules ω_1' and ω_2'. The distribution of kinetic energy between the two molecules is decided by a random number $\phi_4 \in [0,1]$.

$$KE_{\omega_1'} = \phi_4 \times E_{inter} \qquad (22)$$

$$KE_{\omega_2'} = (1-\phi_4) \times E_{inter} \qquad (23)$$

4.1.4 Synthesis

In this process, two molecules collide and combine together to form a new molecule.

$$\omega_1 + \omega_2 \rightarrow \omega'$$

This reaction takes place when the energy conservation criterion given by equation (24) below is satisfied.

$$PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2} - PE_{\omega'} > 0 \qquad (24)$$

The kinetic energy of the newly created molecule is equal to the remaining energy given by equation (25)

$$KE_{\omega'} = PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2} - PE_{\omega'} \qquad (25)$$

The newly created molecule is supposed to have a better ability to explore the solution space because of its higher value of kinetic energy. In this manner, this process helps us to diversify the solution space.

The basic assumption of conservation of energy remains valid throughout the evolution of the algorithm. Similar to other evolutionary algorithms, CRO algorithm too consist of three stages: initialization, iteration, and the termination. The steps of the algorithm have been summarized in a flowchart as shown in Figure 1. The parameters of the algorithm are tuned during the initialization stage and then the algorithm explores the solution space in iterations until the termination criterion is attained. In the final stage, the algorithm terminates and the best found solution is accepted as the output.

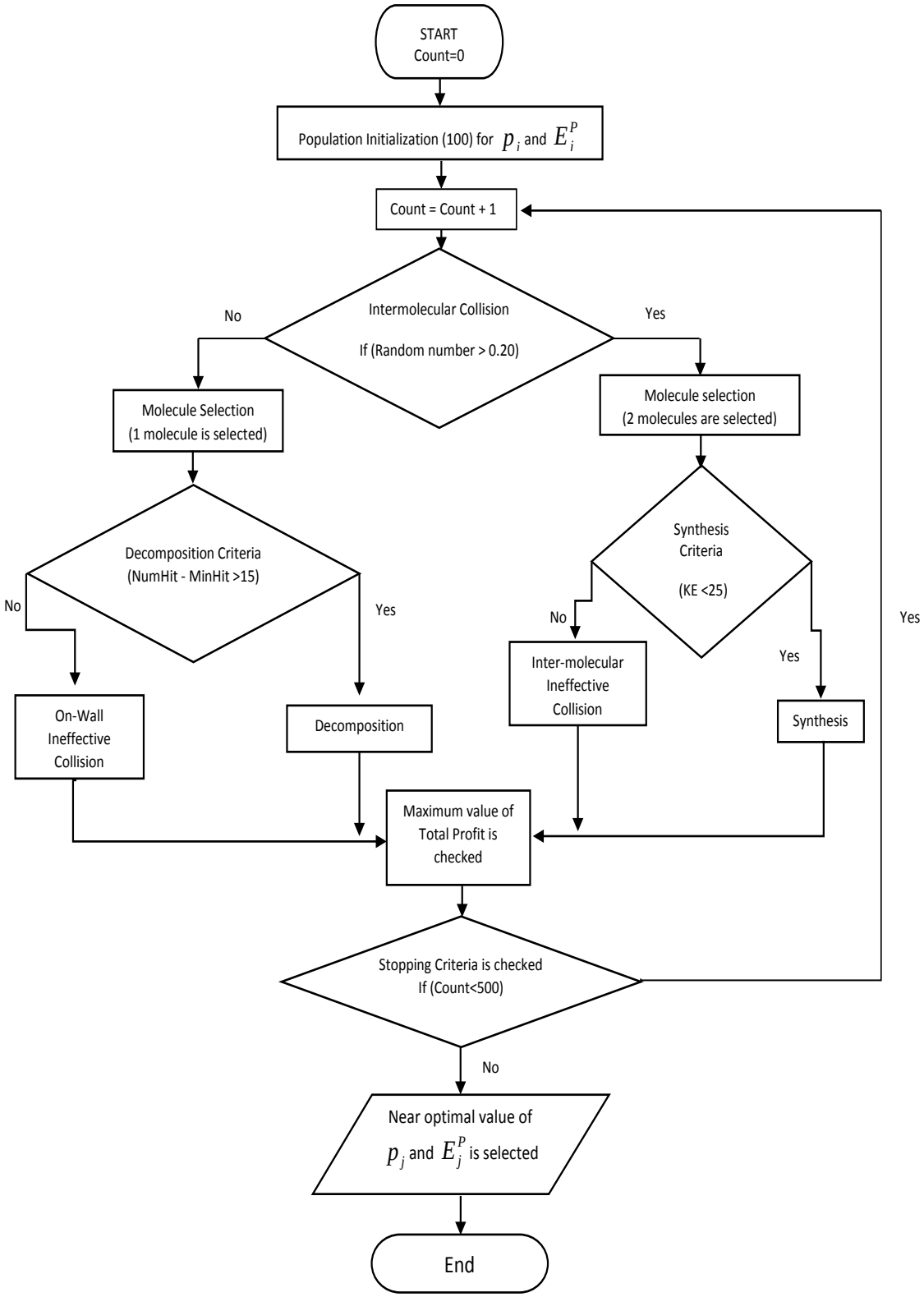


Figure 1: Schematic Diagram of CRO

5. An Illustrative Example

This section illustrates our problem formulation and implementation of CRO algorithm through a numerical example. For the scenario, we consider two products $J = \{A, B\}$ and four different modes of transportation $I = \{1, 2, 3, 4\}$. Furthermore, the following parameters from Table 2 are assumed.

Table 2: Parameter values for numerical example.

Market size of products A and B	$D_j = \{125, 120\}$
Price elasticity of demand of products A and B	$b_j = \{1.28, 1.25\}$
Emission elasticity of demand of products A and B	$c_j = \{0.02, 0.02\}$
Cost of production per unit of products A and B	$k_j = \{35, 30\}$
Penalty charged by regulators per unit of production	$m = 0.09$
Investment computation coefficients for products A and B	$t_j = \{0.025, 0.025\}$
Initial emission due to production of per unit of products A and B	$E_j^{P^0} = \{180, 185\}$

Transportation of products is assumed to be outsourced to a third party logistics provider which operates on four different modes. It charges on per unit basis and calculates the resulting transportation emissions following NTM methodology. Table 3 provides per unit transportation cost u_{ij} and per unit emissions e_{ij} due to the transportation of product type $j \in J$ (A and B) using mode $i \in I$ .We have assumed that both products have same weight. The self-imposed limit on transportation emission λ is set to 750.

Table 3: Per unit transportation cost and per unit emission.

Mode $i \in I$	1	2	3	4
Product $j \in J$	A and B			
$u_{i,j}$	2	4	7	10
e_{ij}	22	13	10	14

CRO algorithm is applied to solve the NLP. Initial population size is 100 molecules and the termination criterion is set to 10000 i.e. number of iterations being performed without any improvement in the optimal value of emission and the selling price of the products. After parameter tuning exercise, following values are initialized: $MoleColl = 0.2$, $InitialKE = 800$, $\alpha = 25$, $\beta = 15$ and $buffer = 0$.

The overall objective is to maximize the net profit. The output of CRO algorithm provides near optimal selling price p_j ,demand fulfilled Q_j , revised production emissions E_j^P , investment I_j for emissions reductions and mode of transportation choice for each type of product A and B. Table 4 shows the near optimal output.

Table 4: Near optimal results of CRO implementation

	Product A	Product B
NetProfit	\$1143.83	
Selling price p_j	\$74.46	\$69.34
Demand fulfilled Q_j	27	30.65
Profit by each product type PR_j	\$496.94	\$646.89
Revised production emissions E_j^P	122.86	120.30
Preferred transportation mode i	Mode 3	Mode 2
Total Investment for reduction of emissions due to production I_j	\$81.63	\$104.65

The profit values for both products corresponding to different values of percentage reduction of production emissions (when the selling prices are set to near optimal value) are plotted in Figures 2.1 and 2.2. The parabolic curve opening downwards shows that increase in net profit is possible till a certain value of the percentage reduction in emissions $(E_j^{P^0} - E_j^P) * 100 / E_j^{P^0}$: 31.74% for product A and 34.97 % for product B. After this value, significant increase in investments is required (see Figure 3) as explained in Section 2.2. It far exceeds the marginal benefit achieved by capturing a larger market share of environmentally conscious customers. The net result is the reduction in the net profit value.

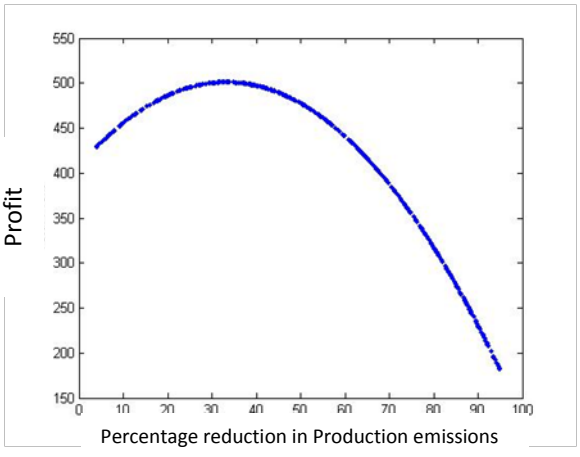


Figure 2.1: Profit of Product A versus percentage reduction in production emissions

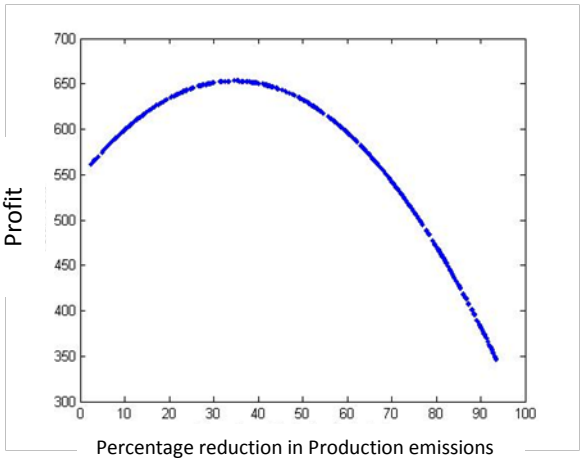


Figure 2.2: Profit of Product B versus percentage reduction in production emissions

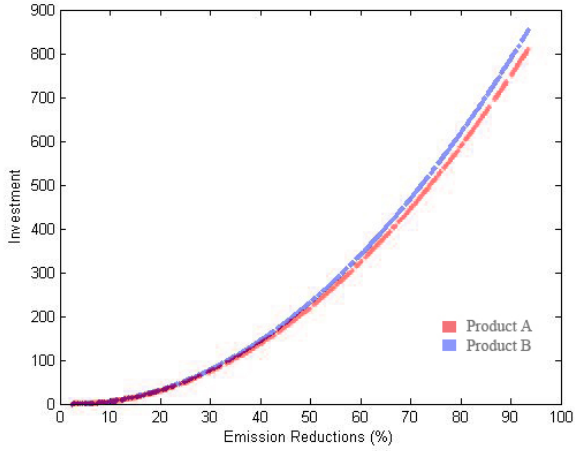


Figure 3: Per unit investment required to decrease emission for product A and B.

5.1. Sensitivity analysis of emission elasticity of demand

In this sub-section, we examine the impact of varying the degree of customers' emission elasticity on revised production emissions, investment on cleaner technologies, selling price of the products and net profit. The values of emission elasticity in the range $c_j \in [0.02, 0.12]$ have been considered and it covers a broad range of realistic values for the data set. CRO is implemented to solve different instances of the problems with varying c_j values. Refer to Figures 4.1, 4.2, 4.3 and 4.4 for results. All other parameters are constant as in table 2 and table 3.

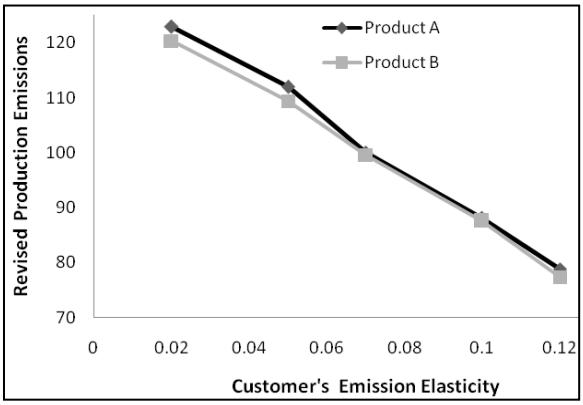


Figure 4.1: Revised production emissions versus Customers' emission elasticity

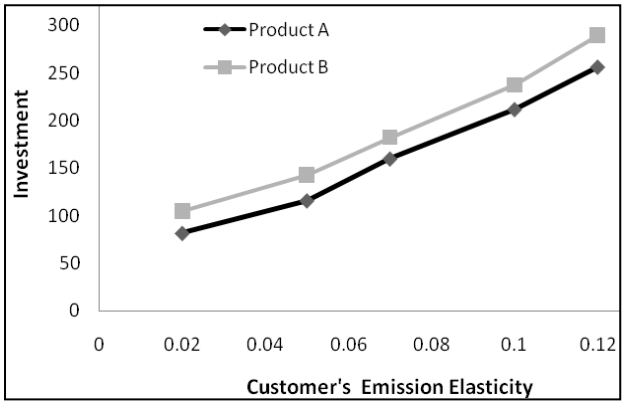


Figure 4.2: Investment versus Customers' emission elasticity

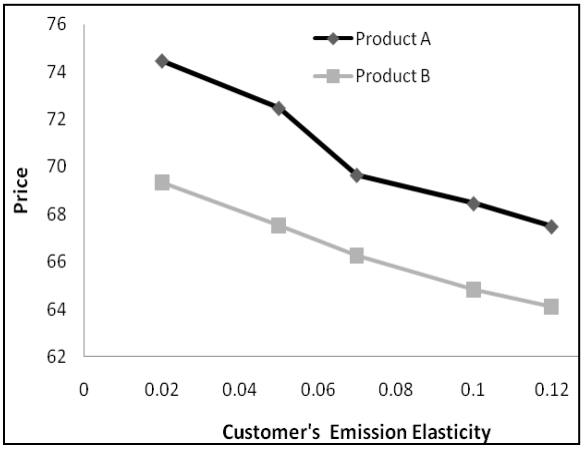


Figure 4.3: Price versus Customers' emission elasticity

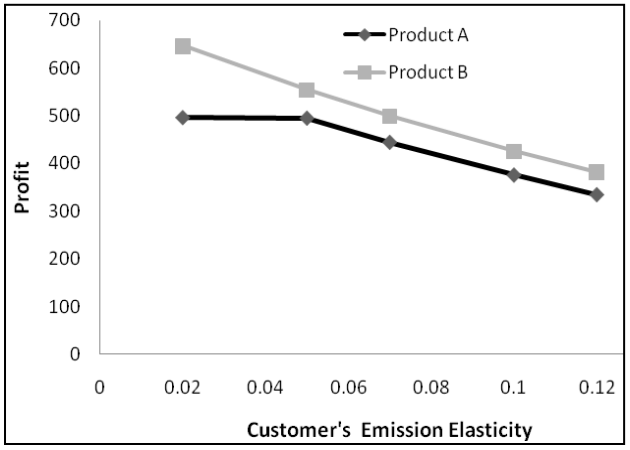


Figure 4.4: Profit versus Customers' emission elasticity

Higher values of emission elasticity c_j reflect that the customers are highly conscious about the emissions. As the value of c_j rises, the pressure on the manufacturer to reduce the overall emission increases. These forces manufacturer to invest more on environmentally friendly technologies to reduce production emissions E_A^P and E_B^P (refer to Figure 4.1 and 4.2). Furthermore, to maintain its demand the firm reduces the selling price of its products p_A and p_B (refer to Figure 4.3). The net effect of falling selling price and rising investment is the decrease in net profit (refer to Figure 4.4). Note that the above results support the following proposition given by Yalabik and Fairchild (2013). "In clean industries, the amount of environmental innovation is positively related to customer and regulatory environmental pressure". Furthermore, based on the trend observed in Figures 4.1, 4.2, 4.3 and 4.4, we summarize the results in the form of following corollary.

Corollary: $\frac{dp_j}{dc_j} < 0, \frac{dE_j^P}{dc_j} < 0$ and $\frac{d(NetProfit)}{dc_j} < 0$

5.2. Sensitivity analysis of penalty charged per unit of emission

In this sub-section, we examine the impact of varying degree of penalty charged per unit of emission on revised production emissions, investment on cleaner technologies, selling price of the products and net profit. We consider different values of penalty charged in the range $m \in [0.05, 0.15]$ which covers a broad range of realistic values of the data set. CRO algorithm is implemented to solve different instances of problem with varying values of m. Figures 5.1, 5.2, 5.3 and 5.4 illustrate the results of these instances. All other parameters remain constant as mentioned in table 2 and table 3.

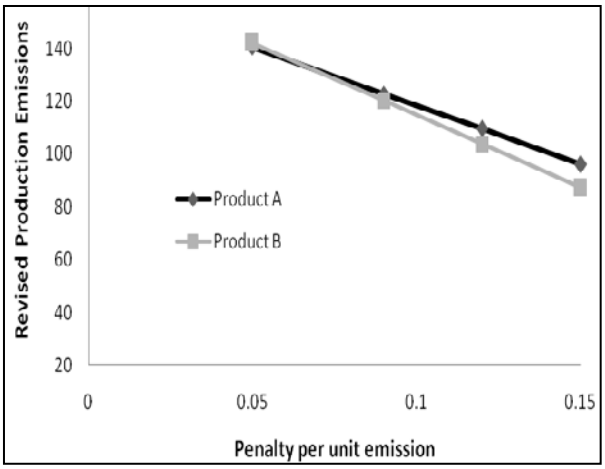


Figure 5.1: Revised Production Emissions versus penalty per unit emission

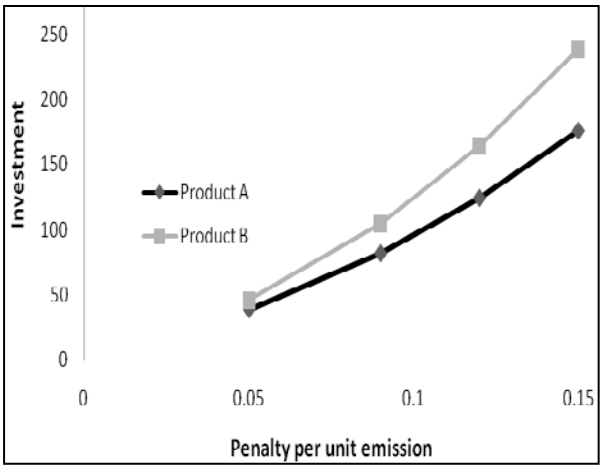


Figure 5.2: Investment versus penalty per unit emission

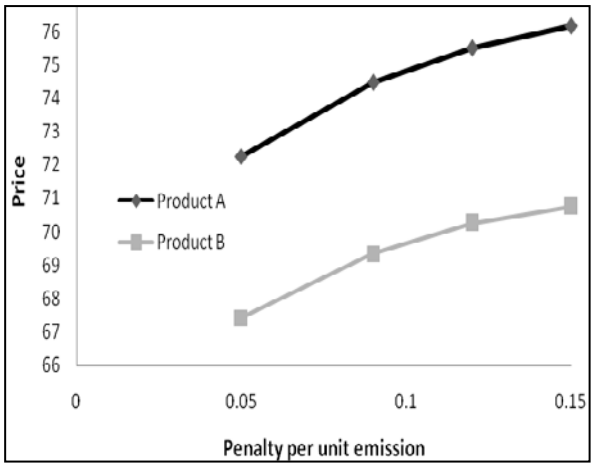


Figure 5.3: Price versus penalty per unit emission

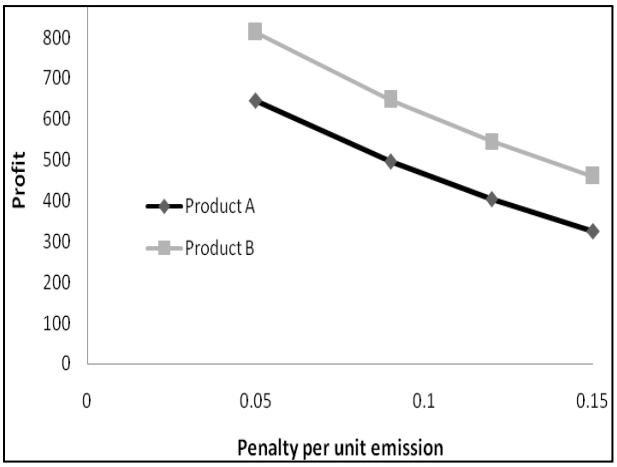


Figure 5.4: Profit versus penalty per unit emission

It can be observed from figure 5.1 that the imposition of higher penalty by the regulators forces the manufacturer to reduce its production emissions. The investment on cleaner technologies rises and the amount invested depends on the marginal benefit derived through it. The emission level is determined by equating the marginal benefit of clean-up with its cost as shown in figure 5.2. Due to its cleaner image, the firm is able to attract the environmentally conscious customers and therefore raises the selling price of its products as shown in figure 5.3. However, increased penalty and investments lower the net profit of the firm. Thus, increasing marginal clean-up costs in the form of penalty reduces the net emission level in equilibrium as shown in figure 5.4. The overall impact identifies the need of financial aids in the form of subsidies to increase the marginal benefit to the manufacturers and encourage them for a higher level of clean-up.

5.3. Sensitivity analysis of Investment coefficient

In this sub-section, we examine the impact of variation of investment coefficient on selling price of the products; net profit and the revised production emissions. We consider different values of investment coefficient in the range $t_j \in [0.02, 0.12]$. Varying Investment coefficient t_j in this range would help us analyse its effect

on the Net Profit. CRO is implemented to solve different instances of problem with varying values of t_j (Refer to Figures 6.1, 6.2, 6.3, 6.4 and 6.5). All other parameters remain constant as shown in Tables 2 and 3.

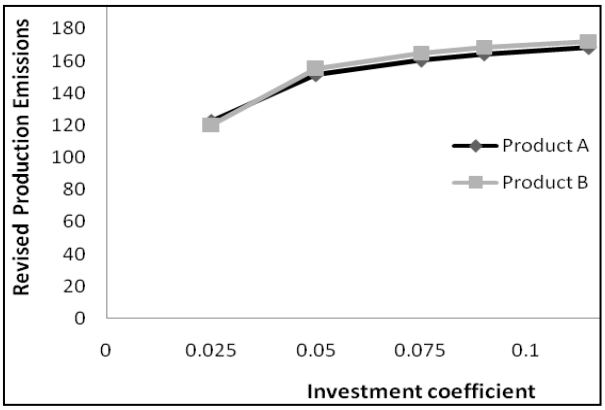


Figure 6.1: Revised Production Emissions versus Investment coefficient

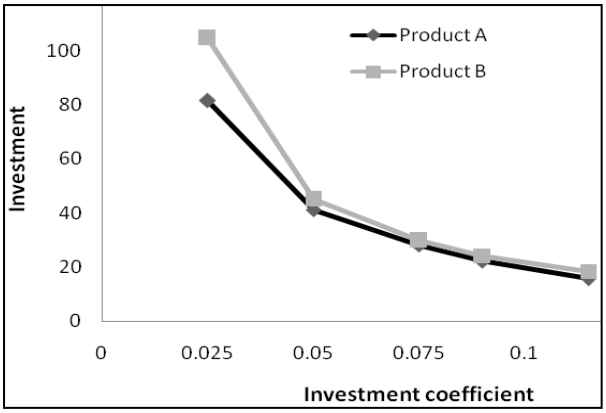


Figure 6.2: Investment versus Investment coefficient

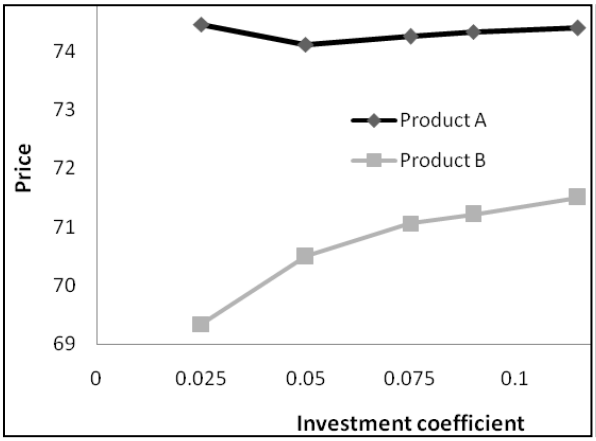


Figure 6.3: Price versus Investment coefficient

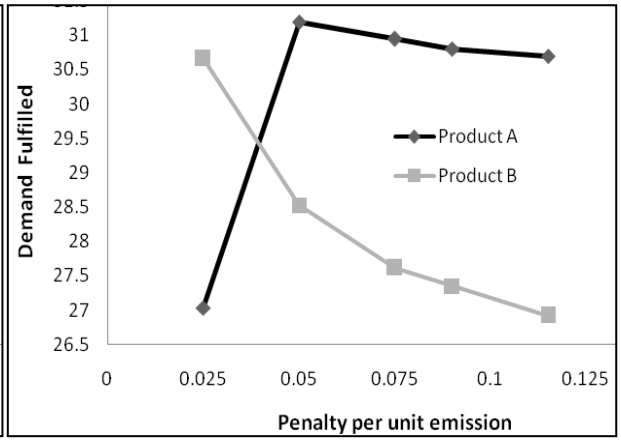


Figure 6.4: Demand fulfilled versus Investment coefficient

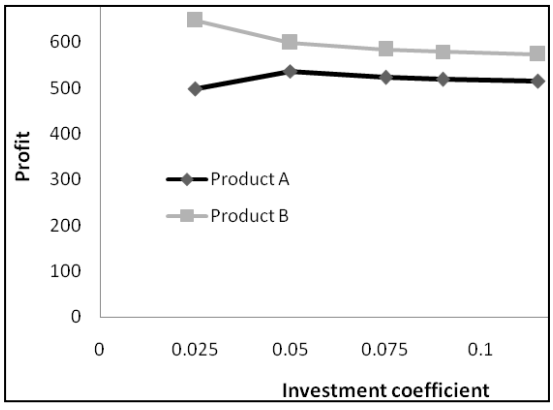


Figure 6.5: Profit versus Investment coefficient

As the investment coefficient increases, the manufacturer adopts a conservative approach of reducing production emissions. Therefore, the revised emissions increase and the investments on cleaner technology decrease as shown in figures 6.1 and 6.2. Due to emission elasticity of the demand, the rise in emissions soon leads to the drop in demand of the products as shown in figure 6.4. To compensate the loss due to lower

demand, the manufacturer strives to increase its net profit by increasing the prices of its products as shown in figure 6.3. However, the net results of falling demand and rising price is the decrease in the net profit of the firm (refer to Figure 6.5). No matter how, such overall effect is not acceptable for a profit maximizing firm. The results suggest that, investments in cleaner technologies can be promoted if they are compensated in the form of subsidy, other financial aids or royalty. Brunnermeier and Cohen (2003) pointed out that environmental innovations in the form of successful patents application granted to industry responded to increase in pollution abatement expenditures. They also provided empirical evidence that most of the environmental innovations occur in internationally competitive industries. This fact has to be exploited by the policy makers to ensure industries that their investment activities are not going in vain.

Downing and White (1986) demonstrated that, investments in cleaner technologies depend on the structure of the regulation schemes, such as competitive permit market price, abatement cost, initially allocated permit to the firms by the regulators. They opine that a firm should invest in a new technology if and only if the associated expected cost savings outweigh the investment costs. For a given pollution permit and permit price, the expected cost savings associated with the technology adoption only depend on the optimal pollution level, and the latter is independent of the monitoring strategy. The investment decision is thus, independent of the monitoring strategy.

6. Conclusion

This research considers a monopolist firm which faces the following twin challenges of serving an environmentally sensitive market. The first challenge is the demand's elasticity to emissions and price. To entice its emission conscious customers and generate higher demand, the firm incrementally invests in cleaner production technologies and pays regulatory penalties. It also adopts a voluntary limit on its emissions from transportation. However, such investments and penalty lead to the second challenge of reduced net profit. To address above trade-off a Non-Linear Programming model with a maximization quadratic profit function has been formulated. A novel CRO algorithm has been used to solve this computationally complex NP hard problem. This research contributes to the body of knowledge by incorporating various dimensions of sustainability suggested in the extant literature including emission sensitive customers, green supply chain, and cleaner manufacturing technologies, in a single holistic and integrated model.

The output of the model provides near optimal monopolistic price, best attainable reduction in manufacturing emissions through proportional investment and makes a choice of suitable mode of transport for each type of product. We provided an illustrative numerical example depicting our model. There was 31.74% reduction in emission for product A and 34.97 % for product B. Three types of sensitivity analyses were performed. First type of sensitivity analysis observes the effect of varying degree of customers' emission elasticity. Its results, underpin the investments in cleaner technologies for generating higher profits in cleaner markets. The second analyses the effect of varying degree of penalty charged per unit emission. It reflects that as the penalty increases the production emission level drops but the net profit generated suffers. The third type of analysis varies the investment coefficient and indicates that cheaper technologies or financial aids are needed to make the cleaner production sustainable for profit maximizing firms. Overall, the model, the suggested solution

methodology CRO and sensitivity analyses provide a decision making tool to determine the near optimal degree of each of the above dimension in multiple business fronts.

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