# Studies on Some Green Supply Chain Problems: Model Development and Analysis

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by

**Chirantan Mondal**
Department of Mathematics
Jadavpur University
Kolkata - 700032, West Bengal, India

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যাদবপুর বিশ্ববিদ্যালয়

FACULTY OF SCIENCE
DEPARTMENT OF MATHEMATICS

JADAVPUR UNIVERSITY
Kolkata-700 032, India
Telephone : 91 (33) 2414 6717

## CERTIFICATE FROM THE SUPERVISOR

This is to certify that the thesis entitled "**Studies on Some Green Supply Chain Problems: Model Development and Analysis**" submitted by Sri **Chirantan Mondal** who got his name registered on 20th August, 2019 (INDEX NO : 29/19/Maths./26) for the award of Ph. D. (Science) Degree of Jadavpur University, is absolutely based upon his own work under the supervision of **Prof. Bibhas Chandra Giri** and that neither this thesis nor any part of it has been submitted for either any degree/diploma or any other academic award anywhere before.

14.09.2022

**Prof. Bibhas Chandra Giri**

**(Signature of the Supervisor, date with official seal)**

Professor
Department of Mathematics
Jadavpur University
Kolkata-700032

*Dedicated to*

*My beloved Family*

***"The universe doesn't allow perfection."***

– Stephen Hawking, 'A Brief History of Time'

# Acknowledgements

*"Acknowledgement is the only way to keep love alive"*

— Barry Long

As a kid, my school teachers used to say that they wouldn't be surprised if I wrote a book one day. I think they meant a book of fairy tales instead of a doctoral thesis at that time. Despite the numerous differences between the two, one thing they have in common is that they are both about to tell a story, which can be fictional or empirical. The key is to pick a topic that you are passionate about and try something new that will leave a mark on readers' mind or they will have something to contemplate after perusing the topic. I believe I have succeeded in that purpose to a lesser extent.

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Chirantan Mondal
(Chirantan Mondal)

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# Introduction

*"The environment and the economy are really both two sides of the same coin. If we cannot sustain the environment, we cannot sustain ourselves."*

– Wangari Maathai

In this 21st century, the rapid development of the world economy has brought relief to human life, but environmental degradation like earthquakes, heavy rains, floods, ozone layer depletion, etc. are causing great anxiety. These are a matter of grave importance to the manufacturing companies as they ended up becoming the major pollutants of the environment. These problems are even more acute in developing countries, which are in the throes of fast financial development. The production process consumes lots of natural resources and energy. Some of these resources are scarce and should be used wisely. These resources should only be used to the extent that they do not adversely affect the combination of natural resources, and therefore require conservation, protection, renewal, and management. It's time to ponder how to manage these catastrophes and present a cleaner world to future generations.

Now companies are realizing that financial progress and good environmental management are correlative to one another like two sides of the same coin. So, a manageable and fair utilization of resources must be guaranteed to meet the essential requirements of present and future generations without harming the environment. How much a country or government will be able to cope with environmental problems relies on its financial capacities. Without well-organized financial progress, environmental management will be flattened, at the same time, progress will be hampered in the absence of proper environmental management. Consequently, traditional business planning needs to incorporate environmental management. The goal of this thesis is to maximize the financial and environmental benefits of business organizations by incorporating environmental initiatives like green innovation and remanufacturing in their supply chains.

## 1.1 Green supply chain management

Managing supply chain practices appeared in the engineering and management literature in the early 1990s with a focus on cost reduction, improving operational performance, and waste minimization. The motivation behind waste reduction at that time was not actually for the environment, but rather for monetary motives as waste means significant financial losses. Also, in those days, environmental pollution was not a significant area of exploration. But now-a-days, the environmental impacts of industrial pollutions are key challenges faced by majority in a consistent way. It is expanding and spreading quicker than wildfires from region to country, country to global domain, which is a critical reason of global warming and climate change. Similarly, natural resources scarcity, pollution in air and water adversely affect human life as well as the flora and fauna. The present situation and the tendency of environmental deterioration underscore a need for an adjustment in the supply chain philosophy. Green supply chain management (GSCM) which is the management of green supply chain (GSC) or the green management of supply chain, has arisen as a paradigm for businesses to lessen the ecological effects and achieve monetary advantages.

Although there has been extensive research on supply chain management (SCM) over the past couple of decades, the thinking about GSCM escalated in the early 21st century. In general, GSCM is described as "*integrating environmental (green) 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*". Here the term '*green*' infers to whatever that is environmentally grasped and regarded as a way to incorporate ecological standards into the supply chain. Undoubtedly, the fundamental philosophy behind the concept of green is to improve environmental sustainability. However, due to the fact that GSC can create a competitive advantage in terms of customer satisfaction, positive brand image and reputation, financial development with lesser manufacturing costs and minimal natural contamination, companies undertake it as "*killing two enemies with a single bullet*".

GSCM first manifests itself as an essential contribution to create a win-win situation, accomplish benefits and market proportion goals with reduced environmental impacts and risks, then elevates their environmental efficiency. It's mile the technique of using eco-friendly measures and converting these measures into reusable outcomes at the end of their life cycles to create a sustainable supply chain. From the perspective of sustainability, it can preserve more natural resources for future generations while protecting natural environment, bringing about a superior and more secure world. The immensity of GSCM has been realized to be extended from green procurement to final delivery of the product to customers, and even to reverse logistics. In the packaging process, for example, plastic containers are usually used. Organizations ought to limit the utilization of plastic and move to packaging made from durable materials. This will help in reducing plastic as well as encouraging eco-friendly substances.

Companies around the globe including Xerox, Dell, HP, Canon, Kodak, Apple, Ford, BMW, Walmart, Target, etc. are demonstrating their responsibilities toward green issues. Xerox has designated to diminish its emission and energy utilization by approximately 25% in 2025 from the 2016 baseline. In March, 2022, the US Securities and Exchange Commission proposed a new environmental regulations for US organizations to list their emissions which may have adverse consequences for the so-called reputed organizations. Consequently, organizations cannot overlook ecological guidelines. As per the 2019 release of the European Commission's Consumer Conditions Scoreboard, 56.8% of European customers want to spend more for green products and less for contaminated products (Wang et al., 2022b).

## 1.2 Conventional vs green supply chain

Conventional supply chains (CSCs) begin with raw material suppliers and end with customers. The flow of products and services (in forward direction), information and finances (in backward direction) is unidirectional and irreversible. Each and every activities within CSC can be a source of waste, pollution, and other environmental hazards. In terms of raw materials, firms may use substances like 'lead' that are harmful to the environment. Here, cooperation, perceivability, and information sharing are limited. CSCs frequently focus on financial targets and values. They plan to reduce costs and work on the effectiveness of supply chain endeavor to leverage financial advantages. Sometimes the focus is on end-to-end supply chain costs, but costs are often not optimized due to limited information exchange. In addition, CSCs consumption patterns are voluntary initiatives driven by business activities and customer interests.

Green supply chains, on the other hand, provide important contemplations for environmental effectiveness in the internal and external management of firms in all processes, from raw material extraction to end product disposal. They integrate execution estimation and environmental goals with operational and financial goals. Through this initiative, they endeavor to accomplish that key issue which is difficult for an individual enterprise. This results in improved customer satisfaction and better benefits with reduced waste and environmental effects. Every member of GSCs persuade others to participate in ecological safety, share knowledge and information. They attempt to diminish energy, utilization of resources and to lessen pollutant emissions. Here, flow of products and services are bidirectional and circular. All products are regulated throughout the life cycle so that the 'waste' gets a subsequent life or turns into raw materials for brand new manufacturing or other agenda purposes. GSCs can be advanced through corporate social responsibility, green government acquirement, and sustainable practices.

## 1.3 GSCM practices

Environmentally cognizant organizations frequently ask an important question: What are GSCM practices, and what's the initial step to implement those practices? GSCM practices incorporate the concepts of environmental responsibility into conventional SCM. There is room for green improvement in every aspect of the supply chain, starting from raw material purchasing to reverse logistics for used products acquisition. So, there are a variety of practices and programs that can be implemented inside green supply chains. However, among those practices, have chosen the following few as most important.

- **Eco design:** It is the precise thought of health and environmental protection-related design issues throughout the product life cycle. It involves the use of green raw materials, equipments, technologies. It additionally supports reuse, recycling, and remanufacturing for reinforcing environmental performance as well as reducing various costs.

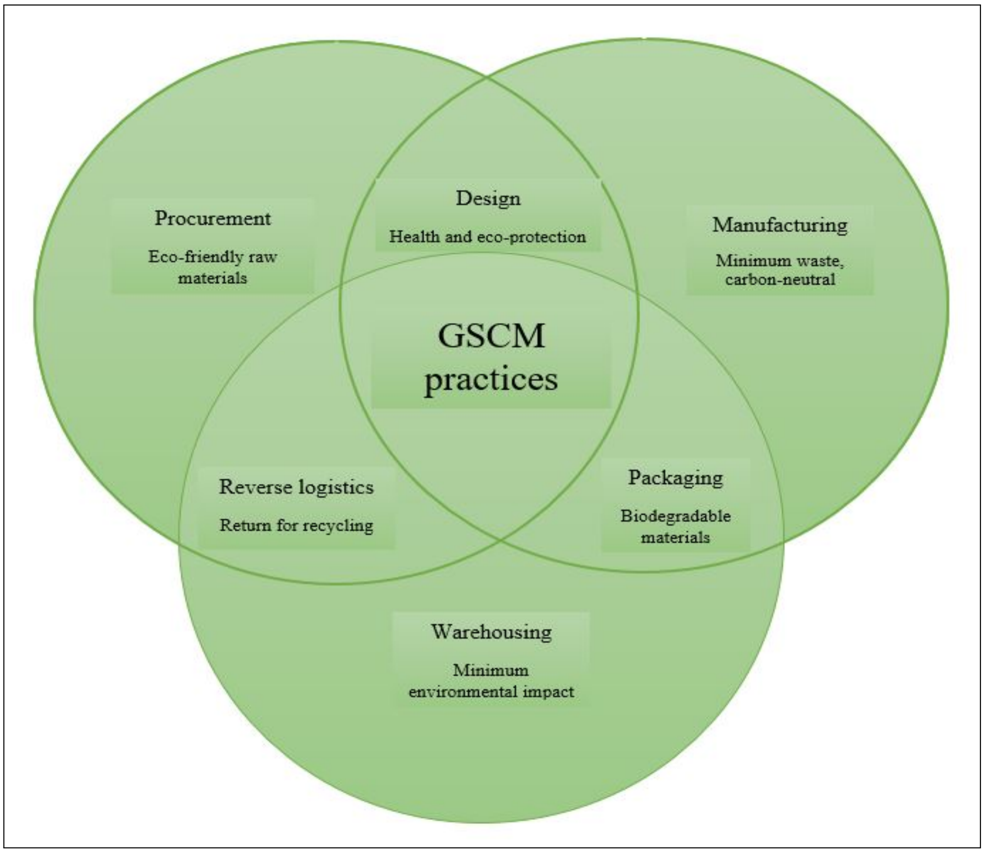


**Fig. 1.1:** Major GSCM practices.

- **Green procurement or purchasing:** Introducing green purchasing into supply chains and business activities is a reliable tool for reducing waste, air and water pollution. It implies purchasing materials, components, and services having eco-friendly qualities such as conservation of energy and water, use of unconventional energy sources like hydropower, solar energy, bio gas, and wind energy, nonuse of hazardous or toxic chemicals, ability of reuse, recycling. It further claims that companies need to place bulk orders to avoid superfluous use of energy, labor and packaging materials and those orders need to be emailed to make them paperless.

- **Green manufacturing:** Green manufacturing practices are the implementation of environmentally and socially responsive practices that lead to liquid and solid waste reduction, emissions reduction, product quality improvement, cost savings and increased profitability of companies. It focuses on using fewer nonrenewable natural resources, using biodegradable and recycled or reused materials, using alternative energy sources to reduce energy consumption. Product remanufacturing is also an important part of green manufacturing.

- **Green packaging:** Green packaging considers every step of a life cycle of a package, from packaging of a product to how customers disposes of the package. It focuses on limiting the production of packaging waste, downsizing overall packaging, utilization of renewable energy during package production, maximizing use of materials like biodegradable materials, recycled paper and plastics, post-consumer recycled materials, etc. instead of materials like plastic and Styrofoam. It is important to provide guidance on how consumers can recycle packaging or decompose packaging.

- **Green warehousing:** The goal of green warehousing is to make warehousing activities more efficient and reduce waste and energy usage. The challenge is that warehouses get old faster and older warehouses tend to be less energy efficient, resulting in higher emissions. Reforms can assist with making more environmentally friendly warehouses. The installation of equipment, the use of alternative energy sources, and the addition of windows to maximize natural light are just a few examples of strengthening convenience.

- **Reverse logistics:** It is the process of returning end-of-use or end-of-life products to manufacturers and suppliers for the objective of recovering their residual values or for proper disposal. It involves the process of refurbish, repair, recycle, remanufacture, and resale. These processes save raw materials, energy, water, resulting in cost savings and competitive business advantages for companies. Some companies set up collection points, while others hire individuals or third-parties to collect waste.

## 1.4 Driving factors for GSCM

There are many driving factors for implementing GSCM practices. These factors are mainly categorized into two types: External and Internal Drivers.

**External drivers:**

- **Regulatory pressures:** Regulatory pressures are contended to be one of the fundamental drivers of GSCM implementation. Growing environmental problems and scarcity of natural resources have led to regulation in various fields, with more stringent regulations at the domestic, governmental, and international level. These regulations increase the threat of penalties and fines for corporate non-compliance and non-implementation of green practices.

- **External stakeholders pressures:** External stakeholders influencing GSCM adoption include customers, suppliers, distributors, etc. Customers are turning out to be progressively mindful of the adverse environmental consequences resulting from specific organizations exercises. They pressurize companies to implement more eco-friendly initiatives, which ultimately reduces their environmental impact. The execution of GSCM initiatives by suppliers and distributors lessen the difficulties and risks of green adaptation for targeted companies, thereby increasing their excitement for GSCM.

- **Supply chain collaboration:** Supply chain collaboration affects a company's environmental impact. Quality certification, such as ISO 14000, encourages companies to maintain near-perfect improvement and thereby improving corporate culture.

**Internal drivers:**

- **Financial benefits:** Financial benefits address the potential of reducing the unit expenses of manufactured products or services provided without compromising the intended usage or degrading the quality of the product. In addition, financial benefits can be acquired by utilizing less raw materials, energy, and water in the manufacturing system, recycling and remanufacturing of used products, which won't just protect the surroundings yet additionally decreases manufacturing costs.

- **Competitive advantage and green image:** GSCM execution assists with acquiring competitive advantage through product and process innovation. It can improve both the image and reputation of the company simultaneously. Companies not only acquire competitive advantage by attracting customers with the right green image, but also benefit from easy access to credit, reduced taxes, and increased likelihood of winning government bids.

- **Environmental and social responsibility:** Some companies are pursuing environmental and social remedies because of their intrinsic interest in the environment and society. These companies operate on the basis of values, not on the rules of decision. They operate from a sense of responsibility, altruism or public interest, not from selfishness.

## 1.5 Benefits of GSCM

The implementation of GSCM practices has its own advantages across all types of industries, regardless of the nature and size. Implementing green practices across the supply chain can benefit companies in a variety of ways, as given below.

- **Competitive advantages and upward brand image –** Today's customers prefer to buy environmentally friendly products, even on paying more money. Manufacturers who apply GSCM practices attract these customers. It will help companies to gain competitive advantages and strengthen their reputation and brand image in the market.

- **Cost reduction and improved efficiency –** Recycling and remanufacturing help to reduce raw material purchasing costs. Reducing the production of waste and hazardous materials saves companies from being penalized for violating environmental guidelines, resulting in increased efficiency.

- **Financial benefits –** There is a typical misapprehension that green investment of a business is costly. In truth, it can result in large financial savings. By adopting several green practices, companies can see fast returns.

- **Reduced environmental impact –** Green design helps in reducing carbon emissions, air and water pollution; bulk order lessens the fuel consumption. Avoiding hazardous substances minimizes environmental risks. As a whole, environmental impact is reduced.

- **Sustainability of resources –** GSCM execution helps in appropriate and viable usage of natural resources. Consequently, the balance of natural resources is maintained.

## 1.6 Relevant topics

There are several issues affecting the performance of GSCM. In the following, we will shed light on a few of those major issues relevant to this thesis.

### 1.6.1 Warranty policy

Now-a-days, warranty policy is an integral part of any product due to customer requirements or business obligations. It is a service-related agreement made by a manufacturer at the time of sale of a product. According to this agreement, the manufacturer or their service center replaces or repairs the product free of charge or with little charge if the product fails or malfunctions within a specified period. While this may only seem convenient to the customer, warranty actually means protecting both customers and manufacturers. To customers, warranty is a compensatory insurance if the product does not meet its promised quality and functional features. On the other hand, to manufacturers, the length of time and the prerequisites prevent them from compensating its customer when he or she misuses or overuse the product. Since it is impossible to get an idea about the quality of the product before use, the warranty acts as an indicator of the quality of the product; a longer and wider warranty usually indicates better product quality. Thus, extending the warranty period can serve as an efficient technique for companies to promote product sales. In addition, warranty may be regarded as a competitive strategy similar to price and quality. Most customers prefer to buy products from manufacturers who offer warranties compared to those who sell the same quality products without warranties. Manufacturers may decide not to offer a warranty or offer a shorter warranty when customers are willing to pay less. In these situations, they provide an offer that allows customers to purchase some warranty at a relatively low price, known as an extended warranty policy. This is why we see a variety of warranty period for same product in different markets. At the time of seasonal sale, the manufacturer usually does not offer warranty. Sometimes the green manufacturers may offer superior warranty period for customer satisfaction. Evidently, a satisfactory warranty policy and easily accessible repair services will attract customers and enhance the company's image.

### 1.6.2 Fairness concerns

Fairness in supply chains is a vital and exciting research topic due to the fact that supply chain members frequently have diverse power positions, which makes the weaker member to vulnerabilities. Three major dimensions of fairness concerns are often studied in supply chain literature – distributive, procedural, and interactional fairness. Distributive fairness raises important questions about whether responsibilities and benefits are pretty-shared among supply chain members. Procedural fairness arises during decision-making process in the supply chain and it concerns whether all supply chain members share their opinions while decision-making, do major buyers genuinely tell their suppliers about expenses, quality and purchase decisions or do suppliers speak truth in the negotiation process? Stronger supply chain members may not always be aware of the situations under which weaker supply chain members are operating and it shows how important it is to be involved in decision making. Interactional fairness is about mutual respect, consistent and bilateral communication. The fairness of the supply chain implies that individuals have open communication for conflict management.

In the context of GSCM, fairness behavior become even more important. If a member thinks not only of maximizing his own profits but also of allocating profits, then the fairness issue comes into play. At GSCM, manufacturers are focal members and mainly involved in product greening and remanufacturing. Sometimes their strong position can push them to make a favorable decision. For instance, they may intentionally increase the wholesale price of a product, forcing retailers to feel unfair in the business. Since retailers have strong relationships with customers, their concerns about unfairness affect market demand and used product collection strategies. Again, if a common retailer sells the products of competing manufacturers and the retailer enters into separate agreements with different manufacturers, then one of the manufacturers may think about the unfairness. On the other hand, some retailers are so greedy that they demand more profits than manufacturers. If the focal member or business manager does not address this concern, this notion of injustice will affect sustainable development. For instance, P&G terminated its partnership with Xuzhou Wanji Trading of China in 2010 because of unfair profit distribution (Nie and Du, 2017).

### 1.6.3 Dual-channel supply chain

With the spread of the internet and the advancement of information technology, the usage of e-commerce in consumer and commercial activities has increased significantly during the past two decades. It has created extraordinary opportunities for manufacturers to have easy and vast access to customers. Additionally, the revolution in the supply of goods through third-party shipping is helping to increase online sales. Customers today are increasingly embracing and becoming accustomed to buying products online, prompting large numbers of manufacturers such as IBM, Microsoft, Apple, HP, Dell, Lenovo, Panasonic, Sony, Mattel, Cisco System, Pioneer Electronics, Estee Lauder, Nike to redesign their strategies for selling their products via a brick-and-mortar retailer (called a conventional retail channel), as well as an online channel (called a direct channel), *i.e.*, utilizing dual-channels consisting of an indirect retail channel and a direct online channel. Obviously, execution of online channel assists a manufacturer with making its own market and acquire benefits from the growing market. It additionally allows to have interaction with customers, grasp their necessities, and provide products that meet their needs. A side effect of this trend is that the retailers may feel frustrated. This can lead to channel conflict that diminishes channel members' endeavors to construct collaborative connections.

However, sometimes direct channel and retail channel may complement each other. Online channels support conventional retail channels by providing product information. Again, some customers often visit conventional retail stores, enjoy retail services, learn about the effectiveness of a product or even try it (specifically, apparel) but end up buying the same product at a lower price from an online channel. Most importantly, customers opt for dual channels, which benefit them via offering more affordable options at lower expenses, so manufacturers are compelled to or willfully launch direct channels as an essential requirement. Retailers have also realized that it is not wise to blacklist the direct channel and drive customers away to purchase somewhere else. Similar to the forward dual-channel, manufacturers can use reverse dual-channels to collect used products. In the context of GSCM, it is important to investigate how each channel member adopts strategies when adding a direct channel into the customary retail channel.

### 1.6.4 Closed-loop supply chain

It's easy to waste when resources are unlimited. But the unavailability of adequate natural resources has forced business organizations to consider recycling used products that are flooding landfills by toxic materials. This is why instead of focusing solely on the smooth delivery process of the product to customers, many companies create a 'closed-loop' by acquiring used products from the consumer and recovering their residual value which lessens the usage of resources and creates less wastage and this gives rise to closed-loop supply chain (CLSC).

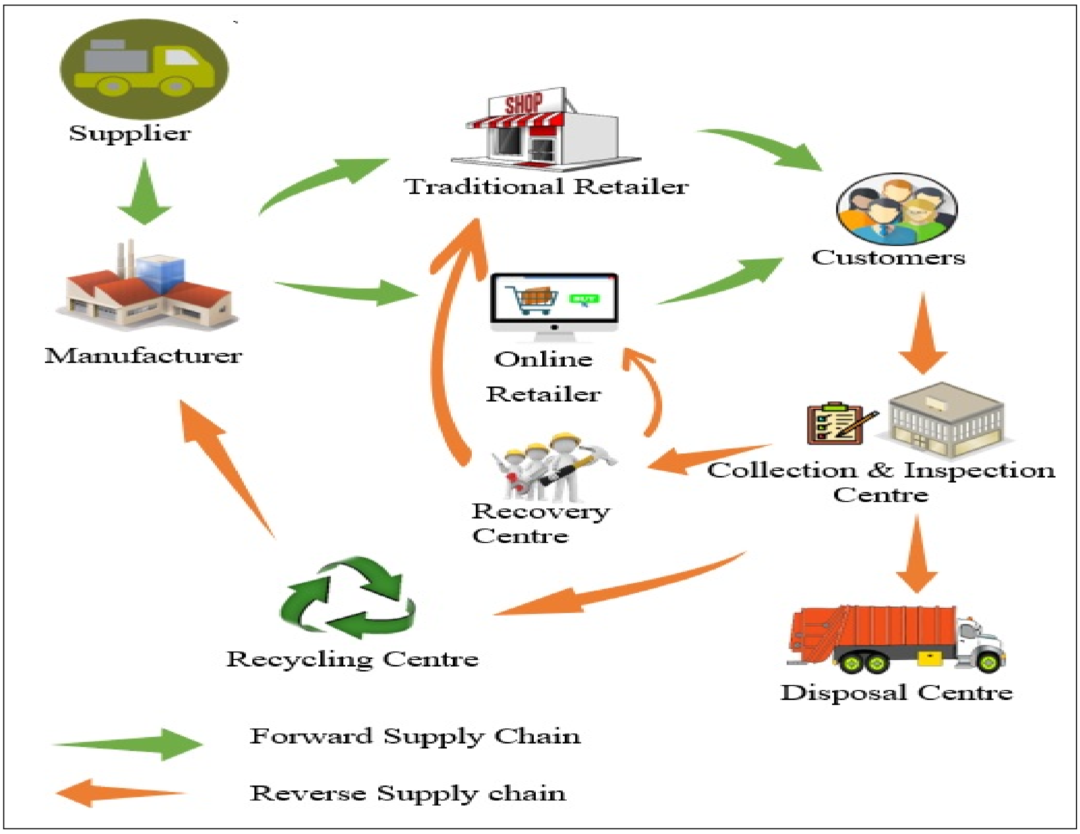


**Fig. 1.2:** Closed-loop dual channel supply chain.

A CLSC is comprised of two separate supply chains – forward supply chain and reverse supply chain. The conventional supply chain is called the forward supply chain. It only works in one direction, from manufacturers to customers. After the production of a product, it is shipped and delivered to customers through a forward supply chain. Then manufacturers encourage customers to return their products once they are no longer needed or no longer in functional state. The reverse supply chain then kick in, and the products can either be repaired and resold, or they can be disassembled for reuse in future production. The term 'closed-loop' refers to the fact that the chain is created for the purpose of retaining and retrieving value from unused products while minimizing waste generation. According to Guide et al. (2003), CLSC is a supply chain network that "*include the returns processes and the manufacturer has the intent of capturing additional value and further integrating all supply chain activities.*"

CLSC an important part of the circular economy, aimed at eliminating waste. It also helps in lessening resource acquisition and processing costs. When a business organization reuses and recycles more, it preserves raw materials further, becomes more affordable. Moreover, it generates more customer loyalty, providing ongoing success. A recent survey revealed that 34% customers have chosen brands with eco-friendly practices. So, companies need to incorporate eco-friendly practices to gain competitive advantages and achieve sustainable development, and CLSCs provide a way to that end. Xerox, HP, Canon, etc. are some companies that are implementing reverse channel activities to reduce ecological impacts of their products.

### 1.6.5 Governmental intervention

The government performs a key role in GSCM by encouraging manufacturers in green assembling and buyers in buying eco-friendly products. Governments of different countries have enacted a number of rules and regulations for the reutilization of used products. For example, the U.S. government has enacted a law regarding the usage of remanufactured products in government transports (Jensen et al., 2019). Green innovation requires superior technologies, which leads to an increase in manufacturing costs, consequently, resulting in increased product prices. Government endowment to green manufacturers assists to diminish manufacturing expenses and serve as an effective remedy to encourage consumers to purchase products. For instance, the UK-based development organization Innovate the UK gave £20 million in R&D investment to further develop low-carbon footprint in the automobile sector (Li et al., 2020), the US government offers a subsidy up to $7500 to encourage purchasing electric vehicles. India has voluntarily committed to lessen emissions by 20-25% by 2025 in the Copenhagen Accord.

Besides these subsidy policies, governments in developed countries utilize various guidelines to reduce carbon emissions. Out of many environmental policies for lowering emission, the cap-and-trade policy (CTP) is the most efficient policy (Li et al., 2019a). Under this policy, the government allocates a certain amount of emissions (called *cap*) to manufacturers toward the start of their businesses. They can sell or buy (called *trade*) excess emissions in the emissions trading market contingent upon whether their actual emissions are more or less than the cap (Xu et al., 2016a). The use of CTP can be noticed significantly in lots of advanced countries like China, EU, Germany, USA etc. The emissions trading system of European Union (EU ETS) lowered its cap by 15% in 2015 compared with the program began in 2005. The Indian government is emphasizing on sustainable energy, especially solar energy; making plans to remodel traditional fuel vehicles and electrify as many new automobiles as possible by 2030 (Zhang et al., 2020b).

### 1.6.6 Substitutable products

The two products will be called substitutable products if they can partially or completely meet the same needs or requirements of customers. Customers can easily move from one product to another as the products are comparable or similar-enough to each other from the customer's point of view. If the price of one product increases (decreases), then the interest of customers towards its substitute product may increase (decrease) *i.e.* there is a positive cross-price sensitivity on the demand of the product. Again sometimes two products will be said to be substitutable if they are sold within the same geographical region or require the same event to use them. Some common examples of substitutable products are tea and coffee, desktops and laptops, ink pens and ball pens, Coke and Pepsi, Domino's and Pizza Hut, Burger King and McDonald's, toothpaste of Colgate and Sensodyne, smartphone of two different brand, etc. For example, tea and coffee are substitutable because both products quench thirst (the same needs of customers), both can be used in the morning (the same event to be used), customers can buy both products from the same local markets (the same geographical region for trading). Similar features can be observed in other substitute products. The demand for substitute products can be affected by various factors like quality, price, etc. Substitute products will be effective when any one of these factors changes. These products can be non-green or green. We are mainly interested in the substitutable green product for non-green products. For example, electric or solar-powered automobile can be an alternative to diesel-powered automobile, LED bulbs can replace normal bulbs, jute bags are alternatives to conventional nylon bags, etc. When a green alternative to a conventional product comes on the market, customers choose between conventional non-green and newly emerged green products based on their preferences and environmental awareness which affects the demand for both products. It is noted that the demand for electric automobiles in the United States has exceeded their actual market supply.

### 1.6.7 Corporate social responsibility

Corporate social responsibility (CSR) alludes to the techniques that organizations use as a component of their corporate governance and aims to promote their activities from an ethical and social perspective. It can be considered as a kind of corporate self-guideline, which has no remarkable unique definition. It's a business plan for business people while an administration official might consider it as voluntary guideline. In short, CSR is a plan of action that moves policy makers out of the narrow mindset of expanding their own advantages toward improving the triple bottom line *i.e.* economic, environmental and social aspects for a global perspective. Charitable activities have a positive impact on companies, so they need to think about participating in CSR endeavors while setting their business goals. In the present worldwide business surroundings, CSR acts as a decisive factor for customers and clients selection that companies cannot ignore. Companies that fail to do their utmost to adopt the CSR strategy will lag behind (Panda et al., 2015). Channel individuals can perform various CSR acts to strengthen social responsibility. Investing in CSR can be considered as one of the CSR initiatives through which organizations can enhance their popularity and corporate image. It's far a powerful strategy for improving the marketing power of the company.

### 1.6.8 Game-theoretic approach

Game theory is an effective decision-making approach on supply chain optimization problem. It is a theoretical framework for decision-making among rival members, called players, in a strategic setting. It provides a simplified version of the problem to investigate how two or more members interact to make decisions. Over the years, many economists and mathematicians have come up with different definitions in different assumptions. The basic idea of all definitions is that one member's payoff depends on the strategy applied by the others *i.e.* each member has to consider other member's strategies or decisions while making its strategy or decision. In the early 1940s, mathematician John von Neumann and his fellow Princeton University economist Oscar Morgenster revolutionized game theory, and for that contribution they were officially recognized as the fathers of modern game theory (Cachon and Netessine, 2006). Then different mathematicians and economists have extended game theory in different ways. For instance, Mathematician John Nash Jr (1950) extended the work of von Neumann and Morgenstern by incorporating the concept of Nash equilibrium, Kuhn and Tucker (1953) extended it to incorporate imperfect information, Aumarm (1959) extended it to include cooperative game and so on. Despite having different extensions, in terms of SCM, these extensions can be seen as cooperative and non-cooperative games. Over the past two decades, academics and practitioners have shown renewed interest in dealing game theory to analyze supply chain-related problems and new emphasis has been placed on collaboration among decision makers forming a supply chain.

#### *1.6.8.1 Non-cooperative game*

Non-cooperative game comes into play when the players of a game prefer to choose their strategies independently by focusing on their own goals. In this case, players cannot form alliances. It can be divided into two sub-games depending on whether the players will make their decisions simultaneously or sequentially.
**Nash game –** In this case, the players make their decisions simultaneously and the next players have no idea about the earlier players' strategies. It basically depends on Nash equilibrium, which is a state of outcome from which no members desire to deviate from when they reach it unless other members do not change their strategies, because by doing so the member cannot improve its profitability. The solution concept of this game was introduced by John Nash Jr (1950).
**Stackelberg game –** It is a sequential-based simplest game pioneered by the German economist Heinrich Freiherr von Stackelberg in 1934. It is a leader-follower game and the leader first makes its decisions then the follower makes its decisions. So, in this case, the followers have some idea about the leader's strategies. The followers may not know all the information of the leader perfectly, rather they may know that the leader did not perform a particular action. In this case, the leader gets some advantages because being the first mover. There are various types of Stackelberg game depending on the leadership of the players. In most of the SCM literature, the manufacturer is considered as a leader and the game they play is called manufacturer-led Stackelberg game. If the retailer or the third-party has more power than any other members then that game will be called retailer-led Stackelberg game or third-party-led Stackelberg game, respectively. The Stackelberg game is more realistic than the Nash game in competitive business scenario because in this case one of the channel members plays the leading role.

In case of multi-members situation in horizontal level, the Stackelberg game can be further classified into two sub-games depending on whether the horizontal players will work simultaneously or jointly. If they want to make their decisions simultaneously like Nash game, then that game will be termed as Cournot game. Again, if they make their decisions jointly as a single player, then that game will be termed as Collusion game.

#### 1.6.8.2 Cooperative game

In a cooperative game, players are allowed to form alliances so that overall better results are possible than in the Nash and Stackelberg games. It is a game of alliance and the focus is on the outcome of the game in terms of the value created by the alliance of players without emphasizing the actions that each player will take. Although outside of a common goal, their objectives may be contradictory, the channel members share a common goal to retain market share.

### 1.6.9 Channel coordination

In SCM, the goal of any supply chain is to improve overall performance. Tragically, channel members focus only on improving their individual benefits by forgetting this global perspective. This self-contemplation leads to poor execution in terms environmental performance, service level, etc. This type of decision-making strategy is known as decentralized policy. There is also another decision-making strategy, called centralized policy where a central entity takes all the decisions aimed at improving global performance by negotiating internal transfer prices.

In spite of the fact that the centralized policy can improve overall performance, in reality, such strategies are difficult to implement by channel members, especially by small enterprises who do not have sufficient financial or administrative support to manage the supply chain, or in a supply chain with enormous members. Again, centralized policy can adversely affect the personal gain of channel members. In this situation, channel members need to some mutual agreement which will be convenient for themselves as well as the whole supply chain. This type of mutually advantageous decision-making strategy is known as coordination mechanism. This allows channel members to align their individual goals with the overall supply chain goals. According to Malone and Crowston (1994), the most recognized definition of coordination is "*the act of managing dependencies between entities and the joint effort of entities working together towards mutually defined goals*".

Relying on diverse characteristics of parameters involved in the supply chain, researchers and practitioners have proposed a variety of coordination mechanisms. One of the most important mechanism is coordination by contract. Generally, a contract is designed in the sort of manner that all optimal results become consistent with the centralized policy. At the same time, it can enhance the performance of every channel members. A supply chain is considered as *coordinated* if it provides identical performance with the centralized scenario. Improving the performance of all channel members in terms of profitability is termed as *win-win situation*.

There is ample reason to emphasize channel coordination in GSC. First, without coordination with different individuals, it is very difficult to improve environmental performance by reducing environmental hazards. Second, coordination can help customers by providing better service. Thus, coordination is beneficial from the view point of consumers. Third, if channel members individually make their decisions, the double-marginalization impact will reduce the benefits of each individual and the whole supply chain. However, channel individuals can enhance their benefits through collaboration. Overall, the fruitful execution of a coordination process can help all individuals in the supply chain to significantly increase their main concerns – financial, ecological, and social exhibitions (Paulraj and Blome, 2017). Due to these importance of channel coordination, channel members should implement this mechanism while making their decisions.

There is a variety of contracts for improving the performance of channel individuals. Some well-known contracts are revenue sharing, profit sharing, cost sharing, two-part tariff (TPT), quantity discount, buy back, etc. In addition to these simple contracts, channel members may implement some composite contracts by combining two or more of these simple contracts. In short, their focus should be always on overall performance rather than individual performance.

## 1.7 Significance of the study

As a thriving branch of SCM, GSCM is one of the most discussed topics in today's competitive and challenging business world. Extensive government pressure and consumer environmental consciousness have forced business organizations to adopt advanced technologies. Again, unavailability of adequate natural resources and financial outlook lead companies to incorporate acquisition and reutilisation of end-of-use products/wastages. In spite of rapid advances in GSCM literature over the past couple of decades, this doctoral study is capable of finding some research gaps and develops various GSCM models by addressing the issues such as warranty policy, individual used product collection, fairness concern, multi-member situation, CSR investment, recycling competition, channel coordination, etc. It is intended to provide business managers with some recommendations regarding these issues. The contributions and scope of the thesis are described as follows:

❖ This study analyses the impact of warranty policy under the manufacturer's green innovation as well as non-green environment. From these investigations, business managers can get an idea about warranty policy related investments and consumers' sensitivity towards warranty policy under both green and non-green environment.

❖ Different collection strategies are considered under the two-period scenario as well as the retailer's fairness concerns which will assist production managers to decide which member should be employed in the collection of used products. The retailing managers can also gather ideas about when to focus more on the fairness of the business.

❖ The inclusion of both dual forward and dual backward channel helps to estimate reasonable pricing for retail and e-tail channels under diverse channel powers of the entities.

❖ In the case of multi-member situations, it determines optimal decision under different behaviors of competing members. This exploration will help them decide whether their decisions should be made collectively or simultaneously or sequentially. An investigation into the impact of government sponsorship in this situation is also noteworthy.

❖ Finally, the consideration of social sustainability through the CSR investment in CLSC lay the groundwork for exploration. Moreover, the implementation of simple and composite contracts enriches about channel coordination issues.

## 1.8 Organization of the thesis

Recalling the importance of incorporating environmental performance into the traditional supply chain, this doctoral study plans to develop and investigate various models in view of a few significant issues associated with GSCM. This thesis comprises **eight chapters**. The first two chapters are related to the introductory discussions and the literature review, respectively. From the third chapter onwards, we develop various mathematical models depending on GSCM related issues and investigate its effect of channel performance. Some techniques, explanations, mathematical expressions, and numerical articulations can be seen as repetitive or similar in a few chapters. This is done to maintain the integrity of the model and the uniqueness of each chapter. The content of each chapter is summed up beneath to provide the reader a brief idea of the study.

**Chapter 1: Introduction**

It focuses on the basic concepts of GSCM, its features, benefits obtained from GSCM adaptation, etc. There is also a concise portrayal on the relevant topics like warranty policy, dual-channel, fairness concerns, governmental intervention, return policy, game-theoretic approach, etc. It ends with the scope and organization of the thesis.

**Chapter 2: Literature review**

This chapter has been enriched by a brief literary review on relevant topics to explore research gaps.

**Chapter 3: Green closed-loop supply chain with warranty period under revenue sharing contract**

This chapter considers the manufacturer's green innovation under the warranty period as a preliminary step to investigate how the implementation of GSCM practices specifically affects channel benefits. It presents two game-theoretic models considering the demand dependency on selling price, warranty period and greening level. Customers can return their defective products to the manufacturer within the warranty period. The manufacturer is able to refurbish a certain portion of the returned products and returns them to customers, while the rest portion is sold in the secondary market after remanufacturing and the same portion is supplanted by the new product. Both models are solved in centralized, decentralized, and revenue sharing contract scenarios. Through analytic and numerical comparison, it is observed that although green innovation requires additional investments, it leads the supply chain to improved environmental progress and economic prosperity. It is also observed that the proposed revenue sharing contract is unable to coordinate the supply chain, rather it may provide win-win situation to channel members.

**Chapter 4: Used product collection strategies in a green closed-loop supply chain**

In addition to green innovation, since the collection of used products can also improve the environmental performance, we discuss the various strategies utilized in used products collection in this chapter, which consists of two parts. The market demand for both parts is thought to be reliant upon the selling price, greening level and marketing effort. It is also assumed that not all remanufactured products are like-new. Only a small part of the remanufactured products passes for being sold with the new one in the primary market while the rest of the remanufactured products is sold at a lower price in a secondary market. The following two sections examine how different used product collection strategies influence GSCM decisions.

*4.1: Used product collection strategies in a two-period green closed-loop supply chain*
This section represents a green CLSC model with one manufacturer and one retailer under a two-period setting to examine the effect of marketing effort, green innovation, and used products collection rate on the supply chain decisions. In the first period, the manufacturer manufactures new product from fresh raw materials while in the second period, in addition to manufacturing new products, he collects and remanufactures used products. A centralized model and three decentralized models (depending on whether the manufacturer or the retailer or both collect used products) are considered. A cost sharing contract is employed to address the coordination issue. Three special cases are developed to investigate the effect of green innovation and marketing effort. It is seen that the supply chain responds better when both the manufacturer and the retailer acquire used products simultaneously, and the efficiency of the supply chain can be improved by integrating either marketing effort or green innovation or both. The proposed contract is capable of improving channel performance.

*4.2: Strategies in a green closed-loop supply chain under retailer's fairness behavior*
Besides engaging in product recycling, now-a-days, the retailing firms are also taking care of the fairness of the business. With that in mind, this section explores the impact of recycling activities and fairness behavior of the retailer on pricing, green improvement, and marketing effort in a green CLSC. Here, the forward channel activity is the same as the previous study. But in the reverse channel, either the manufacturer or the retailer or an independent third-party acquires used products. A centralized model and six decentralized models are developed relying upon the retailer's fairness behavior and/or product recycling. A restitution-based wholesale price contract is designed for channel conflict resolution and supply chain coordination. It is seen that the manufacturer never chooses a third-party as the collector of used products under the fair-neutral retailer; the fairness behavior of the

retailer improves her profit, but lessens the profit of the manufacturer. The transfer price plays important role in deciding appropriate reverse channel for collecting used products. Transformation of all the remanufactured products to like-new products is profitable for all channel members including consumers. The proposed contract is capable of elevating all three dimensions of sustainability – economic, environmental, and social; above all, it can coordinate the supply chain.

**Chapter 5: Strategies for a dual-channel green closed-loop supply chain**

Product sale through the retailer can be affected by double-marginalization effect which can increase the product price, leading to loss of channel members. Because of rapid boom of online business, both selling products and collecting used products through e-tail channel is an excellent choice for adapting channel members' concerns about the loss of profits from green innovation. This chapter deals with a green CLSC with both forward and reverse dual-channels for selling new product and collecting used products. The greening and pricing decisions are derived both analytically and numerically under a centralized and three decentralized scenarios namely, manufacturer-led and retailer-led decentralized scenarios and Nash game. From numerical analysis, it is observed that the selling price in the centralized scenario is higher than that in the decentralized scenario, which contradicts the result due to double-marginalization, and the retailer-led decentralized policy provides higher profit than other decentralized policies. The inclusion of e-tail channel together with the retail channel improves channel performance; selling prices in the retail and e-tail channel depend on customers' loyalty to those channels.

**Chapter 6: Cooperative and non-cooperative behavior of same level players under governmental intervention**

When a manufacturer starts manufacturing green product, its competition with traditional non-green product is unavoidable. Again, when more than one retailer sells those products, there is likewise a competition between them. Therefore, an urgent inquiry might emerge – how do contending manufacturers and contending retailers act while settling on their decisions? The following two sections find the answer to this question.

*6.1: A green closed-loop supply chain with manufacturing competition for substitutable products*

Here we describe a green CLSC including two competing manufacturers and a common retailer for marketing substitutable products under consideration of government sponsorship. It considers several scenarios viz. centralized, Nash game, and manufacturer-led Stackelberg game. In case of the Stackelberg game, the competing manufacturers may work jointly or simultaneously or sequentially. Depending on that the Stackelberg game is divided into three sub-policies. Cost sharing (CS) and revenue sharing under cost sharing (RCS) contracts are designed to improve the greening level and the supply chain performance. Results demonstrate that Nash game is beneficial for the retailer and the whole supply chain; CS contract fails to provide a win-win outcome but RCS contract assists with providing it; the government subsidy can effectively expand sales volume by enhancing product's greening level. In case of the Stackelberg game, the competing manufacturers' cooperative decision-making strategy is beneficial to the green manufacturer, simultaneous decision-making strategy is preferable to the retailer and sequential decision-making strategy is favorable for the non-green manufacturer.

*6.2: Retailers' competition in a green closed-loop supply chain under CTP*
Here we analyse retailers' cooperation and competition in a green CLSC consisting of one common manufacturer and two competing retailers under governmental intervention and CTP. Under consideration of a consistent pricing strategy of the manufacturer, it develops a centralized and three decentralized policies namely, Cournot, Collusion, and Stackelberg depending on various competing behaviors of the retailers. Optimal decisions are compared analytically through a special case where the retailers face the same basic market, and numerically where basic markets are the same as well as different. A transfer payment mechanism is designed to achieve Pareto improvement of all channel members. Results indicate that among three decentralized policies, Cournot behavior is beneficial for the manufacturer, customers, and the entire supply chain, but Collusion behavior is profitable to the retailers only when the difference between their basic markets is small; when the retailers face the same basic market and play Stackelberg game, it is beneficial for the retailers to be a follower rather than a leader; occurrence of both the government subsidy and CTP is profitable to all channel members.

**Chapter 7: Integrating CSR in a sustainable closed-loop supply chain**
So far we have studied economic performance and environmental sustainability, but the global covid epidemic and lockdown have shown us how important it is

to emphasize social performance. In this regard, this chapter extends the boundaries of GSCM to a sustainable supply chain management by integrating CSR in two parts.

*7.1: Retailer's CSR investment under government subsidy*
Here we introduce CSR effort of the retailer, and develop an integrated model and three manufacturer-led decentralized models (Model M, R, and C) depending on various collection options of used products under price and CSR effort dependent demand. To facilitate CSR efforts, the government provides CSR dependent subsidy to retailer. In addition to deriving closed-form optimal solutions, it also determines optimal environmental damage, consumer surplus, and social welfare for the proposed models. Results demonstrate that among three decentralized models, Model M offers the best performance but cannot compete with the integrated model, and government subsidy plays an important role in improving channel performance. A TPT contract is proposed to cope with the channel coordination problem, and the asymmetric Nash bargaining method is used to divide the surplus profit between the manufacturer and the retailer.

*7.2: Both manufacturer's and retailer's CSR investment under recycling competition*
Here we examine pricing, product quality, CSR investment, and collection strategies of used products in a CLSC where both the manufacturer and the retailer contribute to CSR. We develop a centralized model and three decentralized models namely, MR-Model, MT-Model, and RT-Model depending on the competition between any two of the manufacturer, the retailer, and the third-party for collecting used products. A joint revenue-and-cost sharing contract is proposed to address the coordination issue. Optimal decisions are derived and analytically compared to decide the most productive decentralized model, and verified with the assistance of a real case study. Results illustrate that MT-Model is disadvantageous to all channel individuals while MR-Model gives the best performance under nearly less rivalry. The proposed contract can coordinate the supply chain and provide more profit to both the manufacturer and the retailer than their decentralized profits. It's far additionally observed that higher CSR investment, cost savings, and collection rate lead to sustainable development.

**Chapter 8: Conclusions and future research avenues**
This chapter provides an overall conclusion of the study, recommends some insights for business managers and outlines scopes for further research.

# 2

# Literature Review

This chapter presents a brief literature review on green supply chain management related issues and explores a few research gaps of the prior investigations.

## 2.1 Green supply chain

In recent years, due to rapid environmental changes, a massive variety of customers want to purchase eco-friendly products even paying greater penny. This makes GSC a fascinating field of research. Zhu et al. (2005) and Wu and Pagell (2011) recommended various aspects of green practices which includes the excessive inventory sales, scrap and used material sales, environmental audit programs, commitment from senior managers and overall environmental quality management, cleaner production, internal service quality, green design, green procurement and green innovation. Srivastava (2007) provided a comprehensive review of GSC literature. Ghosh and Shah (2012) reviewed the greening strategies across various GSC structures and indicated the importance of manufacturer-retailer integration for improving green innovation. Considering coordination issue in a manufacturer-retailer vertical supply chain, Swami and Shah (2013) addressed a few significant inquiries concerning greening efforts, channel coordination, etc. Introducing e-market to GSCM, Li et al. (2016) analyzed the pricing and greening policies of the supply chain individuals under consistent pricing policies. Under the guise of fuzzy uncertainties, Yang and Xiao (2017) studied how pricing, greening level and profits are affected by different channel powers. In a smartphone supply chain, Patra

(2018) explored greening investments and profit distribution under various channel leadership. A comprehensive assessment of GSC literature is supplied with the aid of Tseng et al. (2019) who has seen a consistent expansion in publications on this topic over the last decade. Hong and Guo (2019) examined the pricing and green product design strategies taking into account customer reference pricing behavior. Pourjavad and Shahin (2020) analyzed the risks of GSC and explored appropriate responses for prioritizing those risks. Shen et al. (2020) developed quality and price sensitive model at GSC with the aim of identifying perfect product line design for different product quality. Roh et al. (2022) explored various green activities of companies to advance environmental goals. Das et al. (2022) performed a comparative analysis of optimal decisions in a three-echelon GSC under two-period setting. They suggested that channel members should stop thinking about their financial goals for reaching sustainable development.

## 2.2 CLSC with different collection options

Due to natural resources scarcity, used products collection, more explicitly product recycling has turned into an intriguing issue for both policymakers and researchers. There exists a enormous literature on various collection options for used products in CLSC. In a manufacturer-led Stackelberg game, Savaskan et al. (2004) highlighted a brief discussion about which channel member among the manufacturer, the retailer and the third-party should be employed to collect used products from customers. Savaskan and Van Wassenhove (2006) considered two types of collection: direct collection, where the manufacturer himself collects used products, and indirect collection, where retailers are responsible for this purpose. Maiti and Giri (2015) addressed the same issue by incorporating a third-party collector under various channel leaderships to find the best outcomes. Miao et al. (2017) developed three types of collection options including the centralized collection, the manufacturer-led collection and the retailer-led collection with trade-ins and considered three types of collection strategies, namely no collection, partial collection, and full collection. Giri and Dey (2019) investigated two recycling strategies, namely recycling through the collector and the recycler in a CLSC with backup supplier. Wang et al. (2022a) addressed information value and power structures in CLSC under consideration of third-party collection.

There are plenty of literatures which extended the model of Savaskan et al. (2004)

under various perspective. For instance, Hong et al. (2015) investigated the influence of advertising investment, Xu and Liu (2017) examined the effect of reference price, Modak et al. (2018) analyzed pricing, product quality, and recycling management, Chen et al. (2018) explored the impacts of marketing activities and product quality improvement, Modak et al. (2019) focused on social work donation as corporate social responsibility (CSR) practice, Chen and Akmalul'Ulya (2019) studied the effect of reward-penalty mechanism, etc. All of these literatures suggested that third-party-led collection is always disadvantageous. Between the manufacturer-led collection and the retailer-led collection which will provide better outcomes depends on various internal parameters.

Besides single collection modes, there is competition in the reverse channel as well. Wu (2015) considered a CLSC comprising an original equipment manufacturer (OEM) and a remanufacturer, who compete in both forward and reverse channels for selling new product and collecting used products, respectively. Targeting on the optimal collection decisions of a construction machinery industry, Yi et al. (2016) focused on competing dual recycling channels (through retailer and TPC) under a retailer-led model while Ranjbar et al. (2020) considered the same issue under different channel leadership, viz. manufacturer-led, retailer-led and TPC-led Stackelberg game. Zhao et al. (2017) established two models such as manufacturer and retailer dual collection, and manufacturer and TPC dual collection to analyze the optimal collecting channel. Wang et al. (2019a) studied a hybrid CLSC with two recycling competition, namely manufacturer-remanufacturer collection and retailer-remanufacturer collection. With the aim of choosing a suitable reverse channel, Liu et al. (2017a) and Wei et al. (2019) examined three competing collection options such as manufacturer and retailer dual collection, manufacturer and TPC dual collection, and retailer and TPC dual collection. These studies demonstrated that recycling competition is able to improve channel performance.

Wei et al. (2018) was the first to incorporate product greening with product remanufacturing. They studied it in a two-period CLSC consisting of a manufacturer and a retailer where either the manufacturer or the retailer or both competitively collect used products, and observed that the recycling competition not only raises the profits of channel individuals, but also enhances the eco-friendliness of the product. Walking in the same line with Savaskan et al. (2004), Wu et al. (2020) proposed three different single collection modes to investigate the pricing, recycling and green investments decisions. Similar to Liu et al. (2017a) and Wei et al. (2019), Shekarian et al. (2021) explored three different competing collection options under carbon footprints and customers' different willingness to pay for new and remanufactured products.

## 2.3 Dual-channel supply chain

In this section, we review the literature related to strategies in dual-channel supply chain. Moriarty and Moran (1990) showed that the advent of dual channel definitely leads to channel conflict. Balasubramanian (1998) analyzed the competition between direct marketers and the traditional retailers to identify the strategy for controlling competition, and obtained that the proper utilization of market coverage may able to control competition. Huang and Swaminathan (2009) and Cai (2010) explored the optimal pricing strategy of a manufacturer who distributes its products by using traditional retail and online channels. Chen et al. (2013) examined pricing policies for substitutable products in a dual-channel supply chain and demonstrated that improving brand loyalty would benefit both members. Huang et al. (2013) developed centralized and decentralized policies for a CLSC under consideration of dual recycling to investigate the optimal pricing policies and recycling options. Giri and Sharma (2014) developed a two-tier dual-channel supply chain model to determine the impact of pricing policies, sales efforts and market proportion. Saha et al. (2016) discussed a dual-channel CLSC coordination by using reward-driven remanufacturing policy where the manufacturer makes use of two channels in the forward chain, and three channels in the reverse chain. Taleizadeh et al. (2016) explored the effect of marketing effort on a dual-channel CLSC under consideration of various marketing effort supported models. Zheng et al. (2017) composed a dual-channel CLSC for determining impacts of channel competition and power structure. In a dual-channel supply chain, Chen et al. (2017) analyzed price and quality decisions while Zhao et al. (2017) studied pricing policies for complementary products. Assuming e-tailer and third party as collector of used products, Giri et al. (2017) introduced dual-channel in both forward and reverse channels. Pathak et al. (2022) modelled a dual-channel CLSC to analyze the pricing and effort decisions.

Now, researchers are showing their interest on both the green issue and dual-channel. Ghosh et al. (2020) analyzed a stochastic dual-channel GSC considering customers' low carbon preference. Gao et al. (2020, 2021) focused on eco-level policy in dual-channel GSC. Meng et al. (2021) considered both channel preference and green preference of customers and examined collaborative pricing policies in a dual-channel GSC. Pal and Sana (2022) explored a dual-channel green CLSC under consideration of product recycling.

## 2.4 Warranty policy in SCM

Warranty has become progressively more significant in customer and commercial transactions. Naini and Shafiee (2011) calculated the ideal pricing and upgrade decisions for warranted second-hand products in order to improve the anticipated earnings of the vendor. Under consideration of warranty period-dependent demand, Chen et al. (2012) examined the pricing decisions of the manufacturer in a two-tier supply chain under various pricing options. Taking two-stage game-theoretic approach into account, Wei et al. (2015) developed various models under the cooperative/non-cooperative strategies of horizontal firms to explore the ideal pricing and warranty period decisions. Modak et al. (2015) studied price, quality, and warranty period decisions in a two-echelon supply chain where demand is dependent on these decisions. Cole et al. (2016) explored an issue confronted by manufacturer of durable consumer goods during the warranty period under two trade-in policies. Taleizadeh et al. (2017) proposed price and warranty optimization in a competing duopoly supply chain considering parallel importation. Under consideration of duopoly market, Fang (2020) studied both price and warranty competitions between two manufacturers. In an e-tail-retail supply chain, Panda et al. (2020) considered extended warranty policy of the retailer for gaining competitive advantage and discovered that the retailer can achieve higher benefit margin than the manufacturer by means of designing this policy. Considering both exogenous and endogenous wholesale prices, Hosseini-Motlagh et al. (2022) analyzed e-tailer's warranty replacement service and the retailer's sales service under various decision-making scenarios including centralized, semi-centralized, decentralized, semi-coordinated, and coordinated scenarios.

## 2.5 Fairness concern

The development of the fairness model within the operation management framework is a new area of exploration. Haitao Cui et al. (2007) initiated this revolutionary work considering linear demand function in a two-tier supply chain comprising of a fair-minded manufacturer and a retailer. Caliskan-Demirag et al. (2010) introducd non-linear demand function to extend the work of Haitao Cui et al. (2007). Again, Yang et al. (2013) extended the work of Haitao Cui et al. (2007) to study the issue of collaborative advertising. Liu et al. (2017b) developed a supply chain where both the manufacturer and the retailer are concerned about fairness. Their outcomes illustrated that fairness issue undermines the profitability of the manufacturer and the entire supply chain. In a dual-channel supply chain, Song et al. (2018) focused on the fairness behavior of the retailer and the mental accounting strategy of the supplier. Wang et al. (2019b) concentrated on the coordination issue of an e-commerce supply chain with a fair-minded manufacturer. The impact of the retailer's fairness behavior and customers' ecological mindfulness on the pricing policy are investigated by Zhang et al. (2019). Their study demonstrated that the profitability of the retailer is dependent on its power and level of fairness issue. With the aim of providing a couple of insights on pricing policies, Zhen et al. (2019) used a Stackelberg gaming approach under the fairness concern of both the manufacturer and the multi-channel retailer. Wang et al. (2020b) studied the decision and coordination strategy in an e-commerce supply chain under a fair-minded manufacturer. Du and Zhao (2021) explored a dual-channel supply chain under retailer's fairness behavior.

Now-a-days, some researchers have started focusing on the fairness concern while utilizing green practices. Introducing the fairness issue of the retailer in CLSC, Ma et al. (2017) analyzed the pricing and marketing effort decisions. They observed that the fairness issue enhances the profit of the retailer only. Using both cooperative and non-cooperative gaming approaches, Zheng et al. (2019) selected a three-echelon CLSC including a manufacturer, a distributor, and a retailer to explore the impact of the retailer's fairness concern. Taking products' greening level and e-tailer's service into account, Wang et al. (2020a) studied decisions and coordination issues under manufacturer's fairness concern. Jian et al. (2021) focused on the manufacturer's fairness concern and the retailer's sales effort in a CLSC. Zhang et al. (2021) introduced the retailer's horizontal and vertical fairness behavior in a dual-channel CLSC and investigated the ideal situation for opening a direct channel. Song et al. (2022b) examined pricing strategy in a low carbon e-commerce supply chain under online retailer's asymmetric fairness issue.

## 2.6 Operational decisions under CTP

There are several studies considering the impact of CTP on the optimal decision-making. Chen and Hao (2015) studied the optimal pricing and production decisions of two contending firms under CTP. Xu et al. (2016b) examined the joint production and pricing decisions of a manufacturing company under two low-carbon policies, namely CTP and carbon tax, and compared the impacts of these two policies on total emissions, profit, and social welfare. Aiming to maximize profit and social welfare, He et al. (2017) explored a regulator's optimal cap-setting decisions and a manufacturer's optimal production decisions under CTP. Xu et al. (2017) discussed about the production and pricing policies under CTP in a make-to-order (MTO) supply chain which deals with two complementary or substitutable products, and demonstrated that CTP may not induce manufacturing low-carbon products. Under consideration of Stackelberg game-theoretic approach, Ji et al. (2020) analyzed the production decision under CTP, and obtained that utilizing green technology may enhance the total emission.

Xu et al. (2016a) analyzed the sustainability strategy in a two-stage MTO supply chain under CTP. Qi et al. (2017) analyzed pricing policies in a two-tier MTO supply chain under the carbon cap guideline and provided policymakers with an appropriate range of a carbon cap to efficiently diminish carbon emissions. Bai et al. (2018) also incorporated emissions reduction strategy in a MTO supply chain to curb emissions under CTP and derived several conditions for attaining lower emissions. Keeping customers' environmental awareness in mind, Pang et al. (2018) investigated the impacts of CTP on emissions reduction, while Tong et al. (2019) further explored the impacts of CTP on retailer's promotion of low-carbon products in retailer-led supply chains. Employing technology investments and CTP in a CLSC, Taleizadeh et al. (2019) examined their impacts on three stimulating factors – return policy, quality improvement effort, and emission reduction under two hybrid remanufacturing scenarios depending on collection through the distributor and the collector. Qian et al. (2020) considered a two-tier sustainable supply chain consisting of a socially responsible manufacturer and a fair-minded retailer, and investigated the coordination issue under CTP. In a CLSC, Wang and Wu (2021) focused on emissions reduction and used product recycling on the basis of CTP. Utilizing game-theoretic modelling, Ebrahimi et al. (2022) proposed double-level sustainability effort in a sustainable supply chain under CTP, and introduced a compensation-based wholesale price contract to coordinate it.

## 2.7 Government sponsorship

Government sponsorship can inspire channel members to deal with eco-friendly products and improve the environment. Constructing a three-level game, Luo and Fan (2015) investigated the impact of several subsidy policies on optimal decisions and emissions reduction under consideration of exogenous carbon tax. Guo et al. (2016) discussed a supply chain under two subsidy policies, and demonstrated that a government selects subsidy depending on the price sensitive of customers. In a government-led supply chain, Madani and Rasti-Barzoki (2017) analyzed pricing, greening, and government tariffs determining strategies. In a dual-channel supply chain, Li et al. (2018) considered two types of subsidy, namely, consumption subsidy and replacement subsidy for producing eco-friendly products. In a dual-channel CLSC comprising a manufacturer, a retailer to sell new product, and a third-party to sell remanufactured product, He et al. (2019) derived optimal pricing, channel structures, and government subsidy under three possible channel structure, namely, no direct sale, sale of new product via direct channel, and sale of remanufactured product via direct channel. Zhang et al. (2020a) used a Stackelberg dynamic game theory to investigate various government policies in a dual-channel CLSC and found that despite reducing emissions and enhancing social welfare, various government policies lessen the benefits of retailers and consumers. Nielsen et al. (2020b) developed various models under manufacturer-led and retailer-led Stackelberg game-theoretic approaches to determine suitable subsidy policy, and suggested that government should inspect different attributes before implementing any subsidy policy. In multiple competing photovoltaic supply chains, Chen et al. (2021) investigated the effect of government subsidy on operational strategies for promoting healthy competition within the supply chain. Long et al. (2022) explored joint impacts of firms' green sensitivity, customers' green preference and power structures in a green CLSC under government subsidy.

## 2.8 Pricing policies of substitutable products

Estimating a reasonable pricing for substitutable products is becoming a popular research stream in SCM. Zhang et al. (2015) considered a supply chain of two substitutable products and examined the impact of customers' ecology awareness on order volumes and coordination mechanism. Basiri and Heydari (2017) developed a mathematical model to explore the problem of coordination in a two-tier supply chain that plans to launch a substitutable green product for a non-green product. Jamali and Rasti-Barzoki (2018) considered two dual-channel supply chains to investigate pricing policies for two substitutable products through game-theoretic approach. In a two-tier supply chain including a monopolistic manufacturer and two competing retailers, Hosseini-Motlagh et al. (2018) evaluated pricing, greening, and warranty decisions for substitutable products under competing retailers' various decision-making behaviors. Chakraborty et al. (2019) looked at how collaborative quality improvement techniques and different cost sharing contract benefit channel individuals who produce and sell substitutable products. Hadi et al. (2020) formulated twelve scenarios in a government-led supply chain on the basis of government policies and various production modes of substitutable products and discussed the effect of government intervention in encouraging customers. Nielsen et al. (2020a) focused on evaluating the decisions of various integration strategies between channel individuals at the horizontal and vertical level of GSCs while dealing with substitutable products. Saha et al. (2021) explored the pricing and greening competition for substitutable green products under various market power structures between the manufacturer and the retailer. Song et al. (2022a) investigated the pricing and coordination problems for the substitutable product in a GSC under consideration of centralized, decentralized, and coordinated scenarios.

## 2.9 Supply chain model considering CSR

The idea of CSR was first proposed with the aid of Bowen who mentioned that besides focusing on monetary desires, commercial agencies need to pay attention on society. Over the current decades, the concept of CSR has been integrated into the supply chain. In an exploratory study, Murphy and Poist (2002) recommended that the logistic managers ought to incorporate the social issues alongside the economy to reach its complete potential and growth. In a dyadic supply chain, Ni and Li (2012) examined the cooperation between channel individuals regarding their CSR endeavors by utilizing sequential and simultaneous move games. Taking into account the retailer's charitable donations as a CSR measure, Arya and Mittendorf (2015) explored the impact of government sponsorship and found that government sponsorship helps in reducing double marginalization effect. Adopting consumer surplus to address companies' CSR initiative, Bian et al. (2016) conducted a strategic analysis in a duopoly supply chain under Cournot and Bertrand competition modes. Wang and Sarkis (2017) examined the connection between the monetary execution and CSR administration, and suggested that the effective management of an organization's CSR administration assumes a huge part in impacting the monetary exhibition of that organization. Consolidating consumer surplus as a CSR initiaitve, Panda et al. (2017) discussed its effect in a socially responsible CLSC and discovered that the intention of the channel's nonprofit growth through CSR practice generated more net income than the goal of profit expansion. Liu et al. (2019) developed a three-echelon retailer-led supply chain comprising the government, $n$ suppliers, and a retailer to explore optimal government subsidy, CSR effort and social welfare, and determined the relationship between these factors. In a reverse supply chain, Hosseini-Motlagh et al. (2019) assessed the impact of CSR investment and e-tail channel demand disruptions. In another study, Hosseini-Motlagh et al. (2020) coordinated CSR investment as a social responsibility and dual-function acquisition value as an environmental responsibility by thinking about a sustainable CLSC with two competing manufacturers and a retailer. Dey and Giri (2021) considered a CLSC comprising two suppliers, a manufacturer, and two competing retailers, one of whom was CSR-concerned, and analyzed various competitive behavior of the retailers by utilizing manufacturer-led Stackelberg game-theoretic approach. They revealed that social responsibility of the retailer allows it to earn more benefit than other retailer. Vosooghidizaji et al. (2022) analyzed channel coordination issue in a dyadic supply chain considering CSR and bilateral information asymmetry and showed that information asymmetry is disadvantageous for channel individuals.

## 2.10 Channel coordination

Since the effective performance of SCM significantly relies upon laying out an efficient coordination process, numerous researchers have begun to work on this issue. Among various sorts of coordination mechanism, coordination by contract is quite possibly of the most widely utilized mechanism. The principle objective of any contract is to share business-related risks among channel individuals as well as boost the benefit or limit the expense. An excellent review on contracts and coordination issues was portrayed by Cachon (2003). As we are interested in GSCM, here we mainly focus on those literatures which consider eco-friendly issues like green innovation and remanufacturing. In a GSC, Ghosh and Shah (2015) incorporated bargaining cost sharing contract to explore channel coordination issues and its impacts on key decisions of channel individuals. In a low-carbon supply chain, Wang et al. (2016) concentrated on the emissions reduction issue and illustrated that retailer can reach the goal of reducing emissions under the wholesale price premium and cost-sharing contract and enable the manufacturer to further improve its emission reduction rate and the benefit of the supply chain. Bai et al. (2017) proposed two contracts, namely revenue and promotional cost-sharing and TPT contract to coordinate a two-tier supply chain that deals with perishable products under CTP, and demonstrated that the TPT contract is stronger than other contract. In a sustainable supply chain, Raj et al. (2018) investigated five various contracts such as wholesale price, TPT, revenue sharing, cost sharing, and revenue and cost sharing contract under simultaneous consideration of greening and CSR initiatives. Song and Gao (2018) established two types of revenue sharing contract depending on bargaining strategy of channel individuals in a two-echelon GSC. Keeping customers' environmental awareness and channel members' environmental responsibility in mind, Hong and Guo (2019) modelled three contracts such as price only, TPT, and cost sharing contract, and showed that cost sharing contract is not favorable for the retailer. Ranjan and Jha (2019) addressed the pricing and coordination issues in terms of profit sharing between channel individuals under price, sales effort, and greening level dependent market demand. In a MTO supply chain, Wang and Choi (2020) incorporated Pareto-efficient coordination under consideration of three contracts, namely cost sharing, revenue sharing, and TPT contracts and a flexible CTP. Liu et al. (2020) explored the ability of cost sharing and revenue sharing contract in improving greening level of product under various channel powers. Li et al. (2021) examined the effect of various contracts including price only, revenue sharing, and cost sharing contract in a GSC where the manufacturer is green-conscious and the retailer exerts marketing effort. Heydari et al. (2021) proposed a hybrid greening cost and revenue sharing contract to analyze the coordination issue in a two-tier GSC. Considering behavioral pricing strategy, Liu et al. (2022) examined the problems of pricing and coordination mechanisms through a revenue sharing contract in a GSC.

When it comes to CLSC, we observe that it is difficult to set up a coordination mechanism in CLSC because the main focus of a CLSC is to integrate forward and reverse supply chains for the convenience of manufacturing firms and ecological issues. Zhang et al. (2016) analyzed the impact of revenue-and-expense sharing and TPT contracts on the performance of channel individuals in a three-level CLSC. Feng et al. (2017) discussed problems of designing and coordinating a dual-recycling reverse supply chain through a TPT and a profit sharing contract. Aiming to elevate profitability of channel individuals through improving recycling and service effort of the retailer, Xie et al. (2018) combined revenue sharing and cost sharing contract in a dual-channel CLSC. Wu et al. (2020) focused on an environmentally responsible CLSC for exploring pricing, recycling, and environmental investment under consideration of a bargaining revenue sharing contract. Taleizadeh et al. (2021) applied two gaming approach, namely Stackelberg and Nash to investigate the impact of cost sharing contract on optimal decisions and profitabilities under green investment and CTP. Their analysis demonstrated that the CS contract has a positive effect under Stackelberg game while it has no interaction under Nash game. Based on the supplier's involvement, Dey and Giri (2022) implemented a revenue sharing contract in two separate settings in a three-echelon CLSC with waste recycling. Asghari et al. (2022) utilized several cooperative games and contracts like revenue sharing, cost sharing, and TPT contract to coordinate a green CLSC.

The aforementioned literature review reveals that supply chain issues have been extensively investigated over the past couple of decades. Due to the importance of green innovation and product remanufacturing, many researchers have recently begun to concentrate on these challenges. There is a very little literature that discusses green manufacturing and remanufacturing together. As far as we know, green supply chain models considering various realistic issues including warranty policy, fairness concerns, multi-period situation, channel competition, CSR investment, etc. have not yet been studied. Thus, there is a large scope to explore these issues in a green environment. This doctoral thesis aims to address these issues.

# 3

# Green closed-loop supply chain with warranty period under revenue sharing contract

## 3.0 Introduction

In this chapter, a two-echelon CLSC model with a single manufacturer and a single retailer is considered. The manufacturer manufactures new products from fresh raw materials and at the same time, s/he also refurbishes and remanufactures the returned products. The manufacturer provides an opportunity to the customers to return defective items, if any, during the warranty period. Depending on market demand dependency on the selling price, warranty period, and greening level, two models are proposed under game-theoretic approach. Both models are developed under the centralized policy, decentralized policy and revenue sharing contract. The main objective of this chapter is to find the answers of the following questions:

- Which one of the two models gives the best optimal decisions of the CLSC?
- What is the impact of warranty period investment cost on optimal decisions?
- How does greening cost impact on the optimal decisions of the supply chain members and whole supply chain?

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## 3.1 Notations and assumptions

The following notations are used for developing the proposed model:

| | |
|---|---|
| $p$ | unit selling price of the new item at the retailer. |
| $w$ | unit wholesale price of new item at the manufacturer. |
| $w'$ | unit wholesale price of the remanufactured product at the manufacturer. |
| $\omega$ | warranty period provided by the manufacturer. |
| $\theta$ | level of green innovation. |
| $c_m$ | production cost per unit of newly produced item. |
| $c_{r_1}(< c_m)$ | production cost per unit of remanufactured item. |
| $c_{r_2}(< c_{r_1})$ | production cost per unit of refurbished item. |
| $D$ | demand at the retailer place. |
| $D_0$ | basic demand at the retailer place. |
| $D'$ | return quantity of the product. |
| $\eta, \delta$ | fractions. |
| $\lambda$ | warranty period investment cost coefficient. |
| $\mu$ | green innovation investment cost coefficient. |
| $\Pi_m$ | profit of the manufacturer. |
| $\Pi_r$ | profit of the retailer. |
| $\Pi$ | profit of the whole system. |
| $(.)^j$ | optimal results under $j$-th scenario, where $j = c, d, cg, dg, RSI, RSII$. |

The following assumptions are made to develop the proposed model:

**(1)** The demand at the retailer depends on the selling price and the warranty period. So, demand function can be taken as $D = D_0 - \alpha p + \beta\omega$, where $\alpha$ and $\beta$ are positive constants so that the demand is always positive. For a green sensitive customer, the demand increases linearly with greening level. So, in that case, the demand function would be $D = D_0 - \alpha p + \beta\omega + \gamma\theta$, where $\gamma$ is a positive constant (Ghosh and Shah, 2012, 2015).

**(2)** The return of the product during warranty period is taken as a fraction of the demand *i.e* $D' = \delta D$, where $\delta$ depends on $\omega$, which is given by $\delta = \delta_0 + \delta_1\omega$, where $\delta_0$ and $\delta_1$ are positive constants such that $\delta$ is a non-negative fraction.

**(3)** The manufacturer may remanufacture or refurbish the returned products during the warranty period. It is assumed that the manufacturer remanufactures a fraction ($\eta$) of the returned products and then sells in the other market. The same quantity of new product along with the refurbished quantity is given to the customers who had returned.

## 3.2 Model development and analysis

It is assumed that, in the forward channel of the CLSC, the manufacturer produces the product at a unit production cost $c_m$ and sells to the retailer at a unit wholesale price $w$ and a warranty period $\omega$. The retailer then sells it to the potential customers

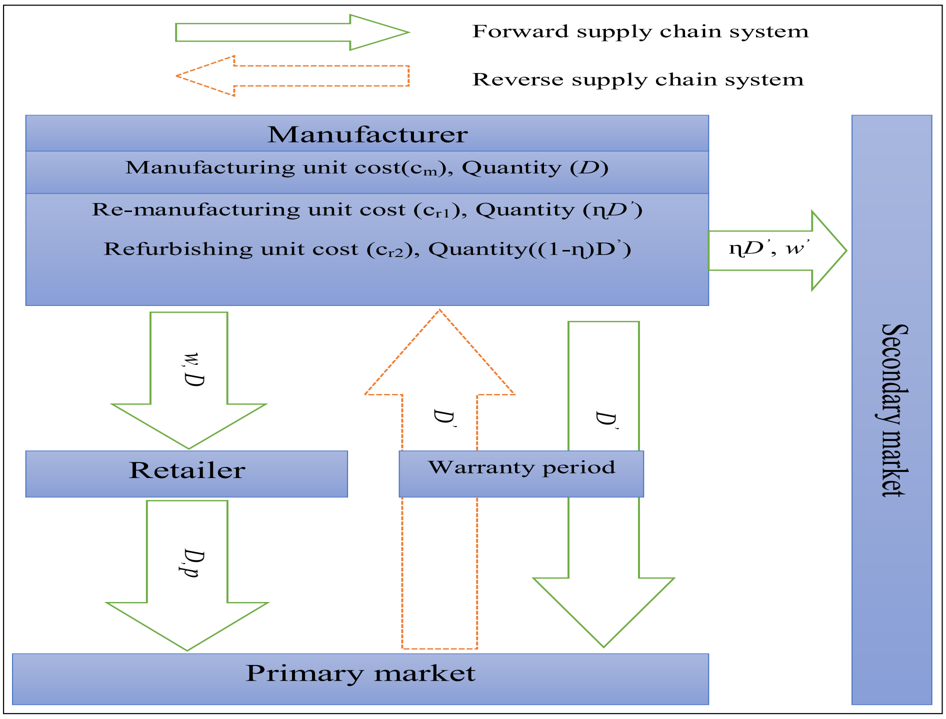



**Fig. 3.1:** Graphical representation of the closed-loop supply chain.

at the selling price $p$ $(> w)$. In the reverse channel, s/he accept the defective items during warranty period (see Fig. 3.1). After collection, the returned products are inspected carefully. A fraction of returned items is refurbished at a cost of $c_{r_2}$ and sent to the customer while the other fraction is remanufactured at a cost of $c_{r_1}$ $(> c_{r_2})$. The remanufactured quantity is sold in the other market at a wholesale price $w'$ $(< w)$ but the same amount of new item is given to the customers who had returned.

### 3.2.1 Model I

In this subsection, the case of regular traditional customers is considered. We introduce an increasing and convex cost component $\lambda\omega^2$, where the scalar $\lambda$ $(> 0)$ represents the warranty period investment cost coefficient, as warranty cost for the manufacturer for offering warranty period $\omega$. The profits of the manufacturer, the retailer and the whole system are, respectively, given by

$$\Pi_m(w,\omega) = (w-c_m)D + (w'-c_{r_1})\eta D' - c_m\eta D' - (1-\eta)D'c_{r_2} - \lambda\omega^2 \quad (3.1)$$

$$\Pi_r(p) = (p-w)D \quad (3.2)$$

$$\text{and } \Pi(p,\omega) = \Pi_m(w,\omega) + \Pi_r(p) \quad (3.3)$$

The expression in the right hand side of Eq. (3.1) includes sales profit obtained from the manufactured and remanufactured products, cost of manufacturing, refurbishment cost, and warranty period investment cost. The right hand side of Eq. (3.2) is the profit obtained from selling new products to the potential customers.

#### 3.2.1.1 *Centralized policy*

In the centralized decision scenario, the manufacturer and the retailer are considered as an integrated business unit. They make a joint decision on retail price as well as warranty period in order to promote sales and optimize the total profit of the supply chain. As usual, the internal credit transfer parameter (wholesale price $w$) does not play any role. For convenience, the following notations are used:
$X = (w'-c_{r_1})\eta - c_m\eta - (1-\eta)c_{r_2}$, $Y = \beta + \alpha\delta_1 X$, and $Z = D_0 - \alpha(c_m - \delta_0 X)$.

**Proposition 3.1.** *The profit function $\Pi(p,\omega)$ is jointly concave in $p$ and $\omega$ if $\lambda > \frac{Y^2}{4\alpha}$. At the equilibrium, optimal selling price, warranty period and profit of the whole system are as follows:*

$$p^c = \frac{D_0(4\alpha\lambda - Y^2) + Z(\beta Y - 2\alpha\lambda)}{\alpha(4\alpha\lambda - Y^2)},\ \omega^c = \frac{YZ}{4\alpha\lambda - Y^2},\ \Pi^c = \frac{\lambda Z^2}{4\alpha\lambda - Y^2}.$$

**Proof.** From Eq. (3.3), we have
$\frac{\partial\Pi}{\partial p} = D_0 - \alpha p + \beta\omega - \alpha(p-c_m) - \alpha(\delta_0 + \omega\delta_1)X$, $\frac{\partial^2\Pi}{\partial p^2} = -2\alpha$, $\frac{\partial^2\Pi}{\partial\omega\partial p} = \beta - \alpha\delta_1 X$,
$\frac{\partial\Pi}{\partial\omega} = \beta(p-c_m) + \beta(\delta_0 + \omega\delta_1)X + \delta_1(D_0 - \alpha p + \beta\omega)X - 2\lambda\omega$, $\frac{\partial^2\Pi}{\partial\omega^2} = -(2\lambda - \beta\delta_1 X)$
The Hessian matrix associated with $\Pi$ is given by

$$H_1 = \begin{pmatrix} \frac{\partial^2\Pi}{\partial p^2} & \frac{\partial^2\Pi}{\partial p\partial\omega} \\ \frac{\partial^2\Pi}{\partial\omega\partial p} & \frac{\partial^2\Pi}{\partial\omega^2} \end{pmatrix} = \begin{pmatrix} -2\alpha & \beta - \alpha\delta_1 X \\ \beta - \alpha\delta_1 X & -(2\lambda - \beta\delta_1 X) \end{pmatrix}$$

Clearly, $\frac{\partial^2\Pi}{\partial p^2} = -2\alpha < 0$ and $|H_1| > 0$ if $\lambda > \frac{Y^2}{4\alpha}$, which ensures the existence of unique solution. Using the first order conditions for optimality of $\Pi(p,\omega)$, *i.e.* $\frac{\partial\Pi}{\partial p} = 0$, $\frac{\partial\Pi}{\partial\omega} = 0$, the equilibrium solution can be obtained. ■

The optimal demand is then $D^c = \frac{2\alpha\lambda Z}{4\alpha\lambda - Y^2}$. In order that the demand and the warranty period are positive, it is necessary that $Z > 0$ and $Y > 0$. The following are some properties of the optimal selling price, warranty period and total profit of the supply chain, which can easily be established:

P.1 $\frac{\partial p^c}{\partial c_m} > 0,\ \frac{\partial \omega^c}{\partial c_m} < 0,\ \frac{\partial \Pi^c}{\partial c_m} < 0.$

P.2 $\frac{\partial p^c}{\partial \beta} > 0,\ \frac{\partial \omega^c}{\partial \beta} > 0,\ \frac{\partial \Pi^c}{\partial \beta} > 0.$

P.3 $\frac{\partial \omega^c}{\partial \lambda} < 0,\ \frac{\partial \Pi^c}{\partial \lambda} < 0.$

P.4 $\frac{\partial p^c}{\partial \eta} > 0,\ \frac{\partial \omega^c}{\partial \eta} < 0.$

P.1 shows that selling price increases with the unit production cost of new products, which is quite obvious. In order to maintain the profit of the whole system the central decision maker has to increase the selling price with the increment of production cost. At the same time, s/he decreases the warranty period. As the production cost increases, the profit of the whole system decreases. P.2 implies that, as the warranty period sensitivity coefficient increases, the selling price, the warranty period and the profit of the whole system increase because in this case demand increases. P.3 shows that when warranty period investment efficiency cost increases, the warranty period as well as the profit of the whole system decreases. P.4 shows that when the manufacturer has to remanufacture more returned items, s/he has to increase the selling price and decrease the warranty period.

**Proposition 3.2.** *If $w' - c_{r_1} - c_m + c_{r_2} \geqslant 0$, then $\frac{\partial \Pi^c}{\partial \eta} \geqslant 0$; otherwise, $\frac{\partial \Pi^c}{\partial \eta} < 0$.*

**Proof.** Differentiating $\Pi^c$ with respect to $\eta$, it is obtained that

$$\frac{\partial \Pi^c}{\partial \eta} = \frac{2\alpha\lambda Z(w' - c_{r1} - c_m + c_{r2})[\delta_0(4\alpha\lambda - Y^2) + YZ\delta_1]}{(4\alpha\lambda - Y^2)^2}$$

Since $Y > 0$, $Z > 0$ and $(4\alpha\lambda - Y^2) > 0$, therefore, $[\delta_0(4\alpha\lambda - Y^2) + YZ\delta_1] > 0$. So if $(w' - c_{r1} - c_m + c_{r2}) \geqslant 0$, then $\frac{\partial \Pi^c}{\partial \eta} \geqslant 0$. Otherwise, $\frac{\partial \Pi^c}{\partial \eta} < 0$. This completes the proof. ■

Proposition 3.2 shows that the profit of the whole system increases with $\eta$ when $(w' - c_{r_1} - c_m + c_{r_2}) > 0$ and decreases with $\eta$ when $(w' - c_{r_1} - c_m + c_{r_2}) < 0$. A higher value of $\eta$ means more remanufacturing which implies more profit. However, when the manufacturer remanufactures more returned items, he has to deliver more new product to customers. In practice, manufacturers gain more from refurbishing than remanufacturing. In order that $(w' - c_{r_1} - c_m + c_{r_2})$ be positive, the manufacturer has to set higher wholesale price for the remanufactured item and lower production cost and remanufacturing cost. The manufacturer cannot set higher wholesale price for remanufactured product because, in this case, demand will be lower.

#### 3.2.1.2 Decentralized policy

In the decentralized policy, the manufacturer and the retailer are independent self-interested parties who aim to maximize their own profits. The manufacturer acts as the Stackelberg leader and the retailer as the follower. The manufacturer sets the wholesale price and the warranty period and then the retailer sets his selling price. This game is studied in the reverse way *i.e.* the retailer gives the best reaction to the manufacturer and then the manufacturer decides optimal decisions.

From Eq. (3.2), we have $\frac{\partial \Pi_r}{\partial p} = D_0 - \alpha p + \beta\omega - \alpha(p-w)$. Also, $\frac{\partial^2 \Pi_r}{\partial p^2} = -2\alpha < 0$. Therefore, unique reaction exists. From the first order necessary condition for optimality, we get $p = \frac{D_0+\alpha w+\beta\omega}{2\alpha}$. After getting this reaction, the manufacturer optimizes his own profit and determines the optimal decisions which leads to the following proposition:

**Proposition 3.3.** *The manufacturer's profit function $\Pi_m(w,\omega)$ is jointly concave in $w$ and $\omega$ if $\lambda > \frac{Y^2}{8\alpha}$. At the equilibrium, the optimal values of wholesale price, selling price, warranty period, and profits of the manufacturer, the retailer and the whole supply chain are as follows:*

$$\begin{aligned} w^d &= \frac{D_0(8\alpha\lambda - Y^2) + Z(\beta Y - 4\alpha\lambda)}{\alpha(8\alpha\lambda - Y^2)}, & p^d &= \frac{D_0(8\alpha\lambda - Y^2) + Z(\beta Y - 2\alpha\lambda)}{\alpha(8\alpha\lambda - Y^2)}, \\ \omega^d &= \frac{YZ}{8\alpha\lambda - Y^2}, & \Pi_m^d &= \frac{\lambda Z^2}{8\alpha\lambda - Y^2}, \\ \Pi_r^d &= \frac{4\alpha\lambda^2 Z^2}{(8\alpha\lambda - Y^2)^2}, & \Pi^d &= \frac{\lambda Z^2(12\alpha\lambda - Y^2)}{(8\alpha\lambda - Y^2)^2}. \end{aligned}$$

**Proof.** From Eq. (3.1), we have

$\frac{\partial \Pi_m}{\partial w} = \frac{D_0 - 2\alpha w + \beta\omega + \alpha c_m - \alpha(\delta_0 + \delta_1\omega)X}{2}$, $\frac{\partial^2 \Pi_m}{\partial w^2} = -\alpha$, $\frac{\partial^2 \Pi_m}{\partial \omega \partial w} = \frac{\beta - \alpha\delta_1 X}{2}$

$\frac{\partial \Pi_m}{\partial \omega} = \frac{\beta(w-c_m) + \beta(\delta_0+\delta_1\omega)X + \delta_1(D_0 - 2\alpha w + \beta\omega)X}{2} - 2\lambda\omega$, $\frac{\partial^2 \Pi_m}{\partial \omega^2} = -(2\lambda - \beta\delta_1 X)$

The Hessian matrix associated with $\Pi_m$ is given by

$$H_2 = \begin{pmatrix} \frac{\partial^2 \Pi_m}{\partial w^2} & \frac{\partial^2 \Pi_m}{\partial w \partial \omega} \\ \frac{\partial^2 \Pi_m}{\partial \omega \partial w} & \frac{\partial^2 \Pi_m}{\partial \omega^2} \end{pmatrix} = \begin{pmatrix} -\alpha & \frac{\beta - \alpha\delta_1 X}{2} \\ \frac{\beta - \alpha\delta_1 X}{2} & -(2\lambda - \beta\delta_1 X) \end{pmatrix}$$

Clearly, $\frac{\partial^2 \Pi_m}{\partial w^2} = -\alpha < 0$ and $|H_2| > 0$ if $\lambda > \frac{Y^2}{8\alpha}$. Using the first order conditions for optimality, we can obtain the optimal results. ∎

In addition to the properties outlined in the case of centralized policy, the following property on the optimal wholesale price also holds in this model:

P.5 $\frac{\partial w^d}{\partial c_m} > 0,\ \frac{\partial w^d}{\partial \beta} > 0,\ \frac{\partial w^d}{\partial \eta} > 0.$

P.5 shows that when the unit production cost of the new product increases, the manufacturer sets higher wholesale price. Again, when the manufacturer has to remanufacture most of the returned items, s/he increases the wholesale price.

#### 3.2.1.3 Revenue sharing (RS) contract

In this case, the manufacturer and retailer sign a contract with the agrement that the retailer keeps a fraction $\phi$ $(0 < \phi < 1)$ of the total revenue for himself and offers the remaining fraction $(1-\phi)$ to the manufacturer, and in turn the manufacturer guarantees to sell the product in lower wholesale price (Giri and Bardhan, 2012). Under revenue sharing contract, the profit of the manufacturer and the retailer are given by

$$\Pi_m^{RS}(w,\omega) = (w-c_m)D + (w'-c_{r_1})\eta D' - c_m\eta D' - (1-\eta)D'c_{r_2} - \lambda\omega^2 + (1-\phi)pD \quad (3.4)$$

$$\Pi_r^{RS}(p) = (\phi p - w)D \quad (3.5)$$

From Eq. (3.5), $\frac{\partial \Pi_r^{RS}}{\partial p} = \phi(D_0 - \alpha p + \beta\omega) - \alpha(\phi p - w)$ and $\frac{\partial^2 \Pi_r^{RS}}{\partial p^2} = -2\alpha\phi < 0$. This shows that there exists a unique optimal value of $p$. From the first order condition for optimality, we get $p^{RS} = \frac{\phi(D_0+\beta\omega)+\alpha w}{2\alpha\phi}$. Comparing this price with $p^c$, it is seen that $p^{RS} = p^c$ if and only if $w = \frac{2\phi[D_0(4\alpha\lambda-\Upsilon^2)+Z(\beta\Upsilon-2\alpha\lambda)]}{\alpha(4\alpha\lambda-\Upsilon^2)} - \frac{\phi(D_0+\beta\omega)}{\alpha}$. Putting this value of $w$ in Eq. (3.4), and using the first order condition for optimality of $\Pi_m^{RS}$ with respect to $\omega$, we get $\omega^{RS} = \frac{Z[\Upsilon\{\beta(\beta-\Upsilon)+\alpha\lambda+\beta^2\phi\}-2\alpha\beta\lambda\phi]}{(4\alpha\lambda-\Upsilon^2)[\beta(\beta-\Upsilon)+\alpha\lambda+\beta^2\phi]}$. Comparing this result with $\omega^c$, we get $\phi = 0$, which contradicts our assumption $0 < \phi < 1$ and leads to the following proposition:

**Proposition 3.4.** *Channel coordination is not possible through revenue sharing contract.*

Although coordination is not possible through revenue sharing contract, a "win-win" situation may be established. With the values of $p^{RS}, w^{RS}$ and $\omega^{RS}$, we have from Eqs. (3.4) and (3.5),

$$\Pi_m^{RS} = \frac{\lambda Z^2[\{\beta(\beta-\Upsilon)+\alpha\lambda\}(4\alpha\lambda-\Upsilon^2) - \phi(\Upsilon\beta-2\alpha\lambda)^2]}{(4\alpha\lambda-\Upsilon^2)^2[\beta(\beta-\Upsilon)+\alpha\lambda+\beta^2\phi]}$$

$$\Pi_r^{RS} = \frac{4\alpha\lambda^2 Z^2[\beta(\beta-\Upsilon)+\alpha\lambda]^2\phi}{(4\alpha\lambda-\Upsilon^2)^2[\beta(\beta-\Upsilon)+\alpha\lambda+\beta^2\phi]^2}$$

Now, both the players will be interested in contract if and only if $\Pi_m^{RS} \geq \Pi_m^d$ and $\Pi_r^{RS} \geq \Pi_r^d$. From $\Pi_m^{RS} \geq \Pi_m^d$, we get $\phi \leq \frac{4\alpha\lambda(4\alpha\lambda-\Upsilon^2)[\beta(\beta-\Upsilon)+\alpha\lambda]}{(8\alpha\lambda-\Upsilon^2)(\Upsilon\beta-2\alpha\lambda)^2+\beta^2(4\alpha\lambda-\Upsilon^2)^2}$ $(=\phi_1$, say$)$.

So, region of acceptance is $\phi \in (0, \phi_1]$. From $\Pi_r^{RS} \geq \Pi_r^d$, we get $M\phi^2 - N\phi + P \leq 0$, where $M = \beta^4(4\alpha\lambda - Y^2)^2$, $N = (8\alpha\lambda - Y^2)^2[\beta(\beta - Y) + \alpha\lambda]^2 - 2\beta^2[\beta(\beta - Y) + \alpha\lambda](4\alpha\lambda - Y^2)^2$, $P = (4\alpha\lambda - Y^2)^2[\beta(\beta - Y) + \alpha\lambda]^2$.
Let us consider the equation $f(x) = Mx^2 - Nx + P = 0$. Then $f(0) = P > 0$. It can be shown that $f(1) = M - N + P < 0$. So, by Descartes' rule of signs, $f(x) = 0$ has at least one zero in (0,1). It can also be shown that $N^2 - 4MP > 0$. So all the roots are real. Let the root which lies between (0,1) be $\phi_2$, which implies that region of acceptance is $\phi \in [\phi_2, 1)$. We then have the following proposition:

**Proposition 3.5.** *A "win-win" situation under revenue sharing contract is permissible for both the players if* $\phi \in [\phi_2, \phi_1]$.

As per construction of the revenue sharing contract, the selling price will be the same as that of the centralized policy. A higher value of the contract parameter implies more profit share to the retailer but less profit to the manufacturer.

### 3.2.2 Model II

In this subsection, the model for green sensitive customer is developed. In addition to the cost components of the manufacturer in Model I, another increasing and convex cost component $\mu\theta^2$ as the green investment cost is assumed (Ghosh and Shah, 2012, 2015), where $\mu$ $(> 0)$, represents green investment cost coefficient. Then the profits of the manufacturer and the retailer are given respectively by

$$\Pi_m(w, \omega, \theta) = (w - c_m)D + (w' - c_{r_1})\eta D' - c_m\eta D' - (1 - \eta)D'c_{r_2} - \lambda\omega^2 - \mu\theta^2 \quad (3.6)$$
$$\text{and } \Pi_r(p) = (p - w)D \quad (3.7)$$

#### 3.2.2.1 Centralized policy

In this policy, the profit of the whole supply chain is

$$\Pi(p, \omega, \theta) = \Pi_m(w, \omega, \theta) + \Pi_r(p) \quad (3.8)$$

**Proposition 3.6.** *At the equilibrium, optimal selling price, warranty period, greening level, and profit of the whole system are achieved as follows:*

$$p^{cg} = \frac{D_0[\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda] + Z[\mu(\beta Y - 2\alpha\lambda) + \gamma^2\lambda]}{\alpha[\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda]}, \quad \omega^{cg} = \frac{\mu Y Z}{\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda},$$
$$\theta^{cg} = \frac{\gamma\lambda Z}{\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda}, \quad \Pi^{cg} = \frac{\lambda\mu Z^2}{\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda}.$$

**Proof.** From Eq. (3.8), we have
$\frac{\partial \Pi}{\partial p} = D_0 - \alpha p + \beta\omega + \gamma\theta - \alpha(p - c_m) - \alpha(\delta_0 + \omega\delta_1)X$, $\frac{\partial^2 \Pi}{\partial p^2} = -2\alpha$,
$\frac{\partial \Pi}{\partial \omega} = \beta(p - c_m) + \beta(\delta_0 + \omega\delta_1)X + \delta_1(D_0 - \alpha p + \beta\omega + \gamma\theta)X - 2\lambda\omega$, $\frac{\partial^2 \Pi}{\partial \omega^2} = -(2\lambda - \beta\delta_1 X)$,
$\frac{\partial \Pi}{\partial \theta} = \gamma(p - c_m) + \gamma(\delta_0 + \omega\delta_1)X - 2\mu\theta$, $\frac{\partial^2 \Pi}{\partial \theta^2} = -2\mu$,
$\frac{\partial^2 \Pi}{\partial \omega \partial p} = \beta - \alpha\delta_1 X$, $\frac{\partial^2 \Pi}{\partial \theta \partial p} = \gamma$, $\frac{\partial^2 \Pi}{\partial \omega \partial \theta} = \gamma\delta_1 X$.
The Hessian matrix associated with $\Pi(p, \omega, \theta)$ is given by

$$H_3 = \begin{pmatrix} \frac{\partial^2 \Pi}{\partial p^2} & \frac{\partial^2 \Pi}{\partial p \partial \omega} & \frac{\partial^2 \Pi}{\partial p \partial \theta} \\ \frac{\partial^2 \Pi}{\partial \omega \partial p} & \frac{\partial^2 \Pi}{\partial \omega^2} & \frac{\partial^2 \Pi}{\partial \omega \partial \theta} \\ \frac{\partial^2 \Pi}{\partial \theta \partial p} & \frac{\partial^2 \Pi}{\partial \theta \partial \omega} & \frac{\partial^2 \Pi}{\partial \theta^2} \end{pmatrix} = \begin{pmatrix} -2\alpha & \beta - \alpha\delta_1 X & \gamma \\ \beta - \alpha\delta_1 X & -(2\lambda - \beta\delta_1 X) & \gamma\delta_1 X \\ \gamma & \gamma\delta_1 X & -2\mu \end{pmatrix}$$

Here $\frac{\partial^2 \Pi}{\partial p^2} = -2\alpha < 0$ and the second order minor will be positive if $\lambda > \frac{Y^2}{4\alpha}$ and $|H_3| = -2\mu(4\alpha\lambda - Y^2) + 2\gamma^2\lambda < 0$ if $\mu(4\alpha\lambda - Y^2) > \gamma^2\lambda$. Therefore, $H_3$ is negative definite if $\lambda > \frac{Y^2}{4\alpha}$ and $\mu(4\alpha\lambda - Y^2) > \gamma^2\lambda$, which ensures the existence of unique solution. Using the first order conditions for optimality of $\Pi(p, \omega, \theta)$, the equilibrium solution can be obtained as given in the Proposition 3.6. ■

We now state the following properties of the optimal selling price, warranty period, level of green innovation and total profit of the supply chain without proof:

P.6 $\frac{\partial p^{cg}}{\partial \gamma} > 0$, $\frac{\partial \omega^{cg}}{\partial \gamma} > 0$, $\frac{\partial \theta^{cg}}{\partial \gamma} > 0$, $\frac{\partial \Pi^{cg}}{\partial \gamma} > 0$.

P.7 $\frac{\partial \omega^{cg}}{\partial \mu} < 0$, $\frac{\partial \theta^{cg}}{\partial \mu} < 0$, $\frac{\partial \Pi^{cg}}{\partial \mu} < 0$.

#### 3.2.2.2 Decentralized policy

From Eq. (3.7), we have $\frac{\partial \Pi_r}{\partial p} = D_0 - \alpha p + \beta\omega + \gamma\theta - \alpha(p - w)$. Also, $\frac{\partial^2 \Pi_r}{\partial p^2} = -2\alpha < 0$. Therefore, a unique value of the reaction exists. From the first order condition, we get $p = \frac{D_0 + \alpha w + \beta\omega + \gamma\theta}{2\alpha}$. After getting this reaction, the manufacturer optimizes his own profit and determines the optimal decisions which give the following results:

**Proposition 3.7.** *At the equilibrium, the optimal values of wholesale price, selling price, warranty period, green innovation level, profits of the manufacturer, the retailer and the whole system are as follows:*

$$w^{dg} = \frac{D_0[\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda] + Z[\mu(\beta Y - 4\alpha\lambda) + \gamma^2\lambda]}{\alpha[\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda]},$$
$$p^{dg} = \frac{D_0[\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda] + Z[\mu(\beta Y - 2\alpha\lambda) + \gamma^2\lambda]}{\alpha[\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda]},$$
$$\omega^{dg} = \frac{\mu Y Z}{\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda}, \quad \theta^{dg} = \frac{\gamma\lambda Z}{\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda},$$

$$\Pi_m^{dg} = \frac{\lambda\mu Z^2}{\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda}, \quad \Pi_r^{dg} = \frac{4\alpha\lambda^2\mu^2 Z^2}{[\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda]^2},$$
$$\Pi^{dg} = \frac{\lambda\mu Z^2[\mu(12\alpha\lambda - Y^2)]}{[\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda]^2}$$

**Proof.** From Eq. (3.6), we have
$\frac{\partial\Pi_m}{\partial w} = \frac{D_0 - 2\alpha w + \beta\omega + \gamma\theta + \alpha c_m - \alpha(\delta_0 + \delta_1\omega)X}{2}$, $\frac{\partial^2\Pi_m}{\partial w^2} = -\alpha$,
$\frac{\partial\Pi_m}{\partial\omega} = \frac{\beta(w - c_m) + \beta(\delta_0 + \delta_1\omega)X + \delta_1(D_0 - 2\alpha w + \beta\omega + \gamma\theta)X}{2} - 2\lambda\omega$, $\frac{\partial^2\Pi_m}{\partial\omega^2} = -(2\lambda - \beta\delta_1 X)$,
$\frac{\partial\Pi_m}{\partial\theta} = \frac{\gamma(w - c_m) + \gamma(\delta_0 + \omega\delta_1)X}{2} - 2\mu\theta$, $\frac{\partial^2\Pi_m}{\partial\theta^2} = -2\mu$,
$\frac{\partial^2\Pi_m}{\partial\omega\partial w} = \frac{\beta - \alpha\delta_1 X}{2}$, $\frac{\partial^2\Pi_m}{\partial\theta\partial w} = \frac{\gamma}{2}$, $\frac{\partial^2\Pi_m}{\partial\omega\partial\theta} = \frac{\gamma\delta_1 X}{2}$.

The corresponding Hessian matrix associated with $\Pi_m$ is given by

$$H_4 = \begin{pmatrix} \frac{\partial^2\Pi_m}{\partial w^2} & \frac{\partial^2\Pi_m}{\partial w\partial\omega} & \frac{\partial^2\Pi_m}{\partial w\partial\theta} \\ \frac{\partial^2\Pi_m}{\partial\omega\partial w} & \frac{\partial^2\Pi_m}{\partial\omega^2} & \frac{\partial^2\Pi_m}{\partial\omega\partial\theta} \\ \frac{\partial^2\Pi_m}{\partial\theta\partial w} & \frac{\partial^2\Pi_m}{\partial\theta\partial\omega} & \frac{\partial^2\Pi_m}{\partial\theta^2} \end{pmatrix} = \begin{pmatrix} -\alpha & \frac{\beta - \alpha\delta_1 X}{2} & \frac{\gamma}{2} \\ \frac{\beta - \alpha\delta_1 X}{2} & -(2\lambda - \beta\delta_1 X) & \frac{\gamma\delta_1 X}{2} \\ \frac{\gamma}{2} & \frac{\gamma\delta_1 X}{2} & -2\mu \end{pmatrix}$$

Here $\frac{\partial^2\Pi_m}{\partial w^2} = -\alpha < 0$ and the second order minor will be positive if $\lambda > \frac{Y^2}{8\alpha}$ and $|H_4| = -\frac{\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda}{2} < 0$ if and only if $\mu(8\alpha\lambda - Y^2) > \gamma^2\lambda$. This shows that $H_4$ is negative definite if $\lambda > \frac{Y^2}{8\alpha}$ and $\mu(8\alpha\lambda - Y^2) > \gamma^2\lambda$. Under these conditions, we obtain the results of Proposition 3.7. ■

#### 3.2.2.3 Revenue sharing (RS) contract

Similar to Model I of subsection 3.2.1.3, we obtain $\Pi_m^{RS}$ and $\Pi_r^{RS}$ as follows:

$$\Pi_m^{RS} = \frac{\lambda\mu Z^2}{[\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda]^2[-X^2\alpha\gamma^2\delta_1^2 - 4X\alpha\beta\delta_1\mu + 4\alpha\lambda\mu + 4\phi(\gamma^2\lambda + \beta^2\mu)]} \times \Big[[\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda][-X^2\alpha\gamma^2\delta_1^2 - 4X\alpha\beta\delta_1\mu + 4\alpha\lambda\mu] - 4\phi[\gamma^2\lambda + \beta^2\mu + \alpha\mu(X\beta\delta_1 - 2\lambda)]^2\Big],$$

$$\Pi_r^{RS} = \frac{4\alpha^3\lambda^2\mu^2 Z^2[-X^2\gamma^2\delta_1^2 - 4X\beta\delta_1\mu + 4\lambda\mu]^2\phi}{[\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda]^2[-X^2\alpha\gamma^2\delta_1^2 - 4X\alpha\beta\delta_1\mu + 4\alpha\lambda\mu + 4\phi(\gamma^2\lambda + \beta^2\mu)]^2}$$

In this case also, channel coordination is not possible but a "win-win" situation may be obtained from the conditions $\Pi_m^{RS} \geq \Pi_m^{dg}$ and $\Pi_r^{RS} \geq \Pi_r^{dg}$. The condition $\Pi_m^{RS} \geq \Pi_m^{dg}$ gives,

$$\phi \leq \frac{\alpha\lambda\mu[\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda][-X^2\alpha\gamma^2\delta_1^2 - 4X\alpha\beta\delta_1\mu + 4\alpha\lambda\mu]}{\Big[[\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda]^2(\gamma^2\lambda + \beta^2\mu) + [\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda][\gamma^2\lambda + \beta^2\mu + \alpha\mu(X\beta\delta_1 - 2\lambda)]^2\Big]} \; (= \phi_3, \text{ say}).$$

So, region of acceptance is $\phi \in (0, \phi_3]$. Similarly, the condition $\Pi_r^{RS} \geq \Pi_r^{dg}$ gives the region of acceptance as $\phi \in [\phi_4, 1)$, where $\phi_4$ is a root of the equation $Ax^2 - Bx +$

$C = 0$ and it lies between (0,1); $A, B$ and $C$ are given as follows:

$$\begin{aligned}
A &= 16(\gamma^2\lambda + \beta^2\mu)^2[\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda]^2, \\
B &= 8[\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda]^2[X^2\alpha\gamma^2\delta_1^2 + 4X\alpha\beta\delta_1\mu - 4\alpha\lambda\mu] + [X^2\alpha\gamma^2\delta_1^2 + 4X\alpha\beta\delta_1\mu - 4\alpha\lambda\mu]^2 \\
&\quad [\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda]^2, \\
C &= [\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda]^2[X^2\alpha\gamma^2\delta_1^2 + 4X\alpha\beta\delta_1\mu - 4\alpha\lambda\mu]^2,
\end{aligned}$$

**Proposition 3.8.** *A "win-win" situation in Model II under revenue sharing contract is permissible for both the players if* $\phi \in [\phi_4, \phi_3]$.

## 3.2.3 Comparison between Model I and Model II

Here, we compare the optimal decisions viz., wholesale price, selling price and warranty period and profit of the manufacturer, the retailer and the whole system.

**Proposition 3.9.** *The wholesale prices follow the order:* $w^{dg} > w^d$ *and the selling prices are in the orders:* $p^{cg} > p^c$; $p^{dg} > p^d$.

**Proof.** We have

$$w^{dg} - w^d = \frac{Z\gamma^2\lambda[4\alpha\lambda - Y^2 + \beta Y]}{[\alpha(8\alpha\lambda - Y^2)\{\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda\}]} > 0.$$
$$p^{cg} - p^c = \frac{Z\gamma^2\lambda[2\alpha\lambda - Y^2 + \beta Y]}{[\alpha(4\alpha\lambda - Y^2)\{\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda\}]} > 0.$$
$$p^{dg} - p^d = \frac{Z\gamma^2\lambda[6\alpha\lambda - Y^2 + \beta Y]}{[\alpha(8\alpha\lambda - Y^2)\{\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda\}]} > 0. \qquad \blacksquare$$

Due to green improvement, the manufacturer has to bear an extra cost and therefore, s/he sets higher wholesale price to maintain profit. The retailer is then forced to set higher selling price. So, green products become more expensive for the customers.

**Proposition 3.10.** *The warranty periods follow the orders:* $\omega^{cg} > \omega^c$; $\omega^{dg} > \omega^d$.

**Proof.** We have

$$\omega^{cg} - \omega^c = \frac{\gamma^2\lambda YZ}{[(4\alpha\lambda - Y^2)\{\mu(4\alpha\lambda - Y^2) - \gamma^2\lambda\}]} > 0.$$
$$\omega^{dg} - \omega^d = \frac{\gamma^2\lambda YZ}{[(8\alpha\lambda - Y^2)\{\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda\}]} > 0. \qquad \blacksquare$$

As the wholesale price and the selling price are higher in green sensitive market, the manufacturer's aim is to serve better quality product to customers. If there is any defect in the product, customers can send the product back to the manufacturer for improvement. So, the manufacturer sets higher warranty period.

**Proposition 3.11.** *The profits of the manufacturer, the retailer and the whole system follow the orders:* $\Pi_M^{dg} > \Pi_M^d$, $\Pi_R^{dg} > \Pi_R^d$, $\Pi^{cg} > \Pi^c$, $\Pi^{dg} > \Pi^d$, *respectively.*

**Proof.** We have

$$\Pi_M^{dg} - \Pi_M^d = \frac{\gamma^2\lambda^2 Z^2}{[(8\alpha\lambda - Y^2)^2\{\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda\}^2]} > 0.$$

$$\Pi_R^{dg} - \Pi_R^d = \frac{4\alpha\gamma^2\lambda^3 Z^2}{[(8\alpha\lambda - Y^2)^2\{\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda\}^2]} > 0.$$

$$\Pi^{cg} - \Pi^c = \frac{\gamma^2\lambda^2 Z^2}{[(4\alpha\lambda - Y^2)\{\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda\}]} > 0.$$

$$\Pi^{dg} - \Pi^d = \frac{\gamma^2\lambda^2 Z^2[\mu(8\alpha\lambda - Y^2)(16\alpha\lambda - Y^2) - \gamma^2\lambda(12\alpha\lambda - Y^2)]}{[(4\alpha\lambda - Y^2)\{\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda\}]}.$$

Recalling that $\mu(8\alpha\lambda - Y^2) - \gamma^2\lambda > 0$ and $(16\alpha\lambda - Y^2) > (12\alpha\lambda - Y^2)$, we find $\Pi^{dg} - \Pi^d > 0$. ∎

From above, it is seen that, in Model II, the manufacturer produces environment-friendly products with a higher wholesale price and a higher warranty period (Propositions 3.9 and 3.10) and the retailer then sets a higher selling price (Proposition 3.9). Further, the profits of the manufacturer, the retailer and the whole supply chain system increase (Proposition 3.11).

## 3.3 Numerical analysis

In this section, a numerical example is developed to analyze the equilibrium results in different strategies proposed. We consider the data set: $D_0 = 65$, $\alpha = 0.11$, $\beta = 0.94$, $\gamma = 0.32$. $\delta_0 = 0.43$, $\delta_1 = 0.007$, $c_m = 60$, $c_{r_1} = 45$, $c_{r_2} = 25$, $w' = 70$, $\eta = 0.45$, $\lambda = 10$, $\mu = 20$, in appropriate units. With these values, we get $\phi \in [0.301, 0.685]$ from Proposition 3.5, and $\phi \in [0.313, 0.704]$ from Proposition 3.8. So, we set $\phi = 0.35$ for revenue sharing contract.

**Table 3.1:** Optimal results.

| Optimal decisions | Model I | | | Model II | | |
|---|---|---|---|---|---|---|
| | Centralized | Decentralized | RS ($\phi$=0.35) | Centralized | Decentralized | RS ($\phi$=0.35) |
| $p$ | 396.097 | 503.801 | 396.097 | 400.818 | 506.593 | 400.818 |
| $w$ | - | 360.548 | 50.7417 | - | 362.412 | 52.2144 |
| $\omega$ | 14.6939 | 6.5702 | 6.58934 | 14.9084 | 6.61.274 | 6.79179 |
| $\theta$ | - | - | - | 2.60044 | 1.15345 | 1.20469 |
| $\Pi_r$ | - | 2257.36 | 2427.87 | - | 2286.69 | 2437.81 |
| $\Pi_m$ | - | 4083.05 | 6034.05 | - | 4109.49 | 6115.71 |
| $\Pi$ | 9131.51 | 6340.41 | 8461.93 | 9264.81 | 6396.18 | 8553.52 |

Table 3.1 shows optimal results for Model I and Model II. It can be seen that,

Model II provides the better results for all the decision variables and the profit of the whole system than Model I. Although green products have a higher price but its environment-friendly behavior affects more on the customers satisfaction. Again, the manufacturer provides higher warranty period for green product. So, the demand of the green product is higher. The more the demand, the more the profit shares to the manufacturer, the retailer and the whole supply chain will be.

**Table 3.2:** Optimal results when $\eta = 0$.

| Optimal decisions | Model I | | | Model II | | |
|---|---|---|---|---|---|---|
| | Centralized | Decentralized | RS ($\phi$=0.35) | Centralized | Decentralized | RS ($\phi$=0.35) |
| $p$ | 395.496 | 503.619 | 395.496 | 400.245 | 506.424 | 400.245 |
| $w$ | - | 359.716 | 50.1006 | - | 361.588 | 51.5824 |
| $\omega$ | 14.831 | 6.62494 | 6.66301 | 15.0479 | 6.66788 | 6.86709 |
| $\theta$ | - | - | - | 2.60129 | 1.15869 | 1.21029 |
| $\Pi_r$ | - | 2277.9 | 2451.73 | - | 2307.51 | 2461.76 |
| $\Pi_m$ | - | 4116.89 | 6086.46 | - | 4143.57 | 6168.99 |
| $\Pi$ | 9216.33 | 6394.79 | 8478.65 | 9351.11 | 6451.08 | 8630.74 |

Table 3.2 represents the optimal results when $\eta = 0$ *i.e.* when the manufacturer refurbishes all the returned products. It means the manufacturer does not need to remanufacture any products. The manufacturer provides higher green product with lower wholesale price and offers higher warranty period (comparing with results on Table 3.1). The retailer also sets lower selling price so that market demand increases. For higher warranty period, return rate also increases. Profits of the manufacturer, the retailer and the whole supply chain system increase. Although $\eta = 0$ gives better result, in reality all returned items may not be refurbishable.

**Table 3.3:** Optimal results when $\eta = 1$.

| Optimal decisions | Model I | | | Model II | | |
|---|---|---|---|---|---|---|
| | Centralized | Decentralized | RS ($\phi$=0.35) | Centralized | Decentralized | RS ($\phi$=0.35) |
| $p$ | 396.832 | 504.025 | 396.832 | 401.519 | 506.8 | 401.519 |
| $w$ | - | 361.565 | 51.5234 | - | 363.418 | 52.9849 |
| $\omega$ | 14.5277 | 6.50369 | 6.49996 | 14.7393 | 6.54576 | 6.70044 |
| $\theta$ | - | - | - | 2.56959 | 1.14706 | 1.19787 |
| $\Pi_r$ | - | 2232.45 | 2398.99 | - | 2261.43 | 2408.82 |
| $\Pi_m$ | - | 4041.93 | 5970.43 | - | 4067.08 | 6051.04 |
| $\Pi$ | 9028.69 | 6274.38 | 8499.98 | 9160.2 | 6329.5 | 8459.85 |

Table 3.3 represents the optimal results when $\eta = 1$ *i.e.* when the manufacturer

has to remanufacture all the returned products, sell them in the other market and give new product to the customers who had returned. In this case, the manufacturer has to provide new product against all the returned products. For this additional expense, the manufacturer sets higher wholesale price and lower warranty period. The retailer also sets higher selling price. This affects the demand of the retailers. As a result, profits of the manufacturer, the retailer and whole supply chain system decreases.

From Tables 3.1-3.3, it can be noted that profits of the manufacturer, the retailer and the whole system are higher in the centralized policy followed by the revenue sharing contract policy and the decentralized policy. A "win-win" situation exists under the revenue sharing contract. Warranty period and greening level are higher in the centralized policy followed by the revenue sharing policy and the decentralized policy. It is also noted that, as $\eta$ increases, profits of the manufacturer, the retailer and the whole supply chain system decrease.

**Corollary 3.1.** *In Model II, the warranty period and the greening level of the product in the centralized scenario are more than double compared to those in the decentralized scenario.*

## 3.4 Sensitivity analysis

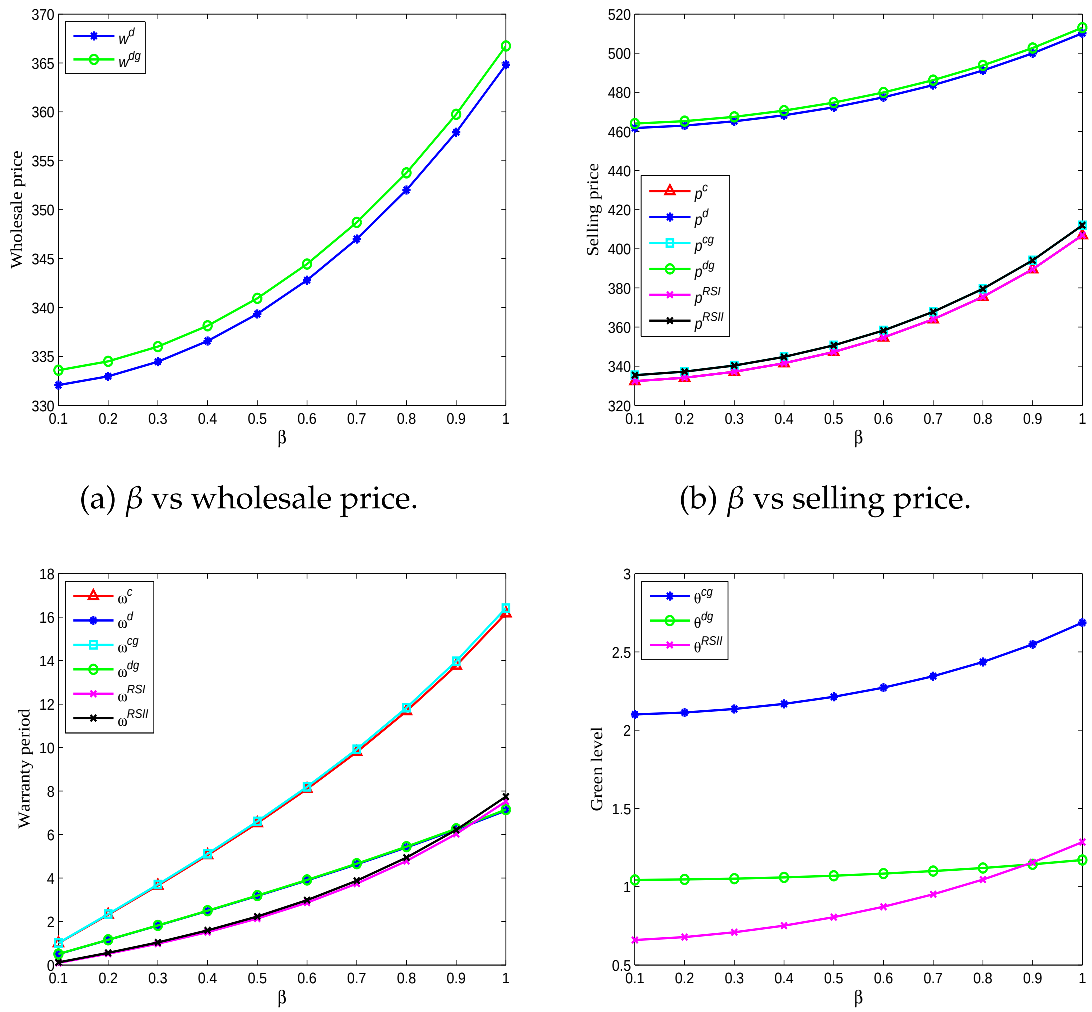
In this section, the sensitivity of some key parameters of the model is discussed by keeping all parameters fixed and changing the value of one parameter at a time to investigate its impact on the optimal solution.

The following conclusions can be drawn from **Fig. 3.2**

(i) As the warranty period sensitivity coefficient ($\beta$) increases, the manufacturer has to invest more. So, the wholesale price increases in both the models.

(ii) The selling price being closely related to the wholesale price, with the increment of wholesale price, the retailer also increases the selling price. The rate of increase is higher in the centralized case and lower in the decentralized case.

(iii) The manufacturer must have a principle to increase the warranty period when s/he increases wholesale price. The warranty period is more sensitive to $\beta$ compare to other optimal decision variables. From Fig. 3.2(c), it can be noticed that when $\beta$ crosses the value 0.93, the warranty period under revenue sharing contract becomes higher than that of the decentralized policy.




(a) $\beta$ vs wholesale price.

(b) $\beta$ vs selling price.

(c) $\beta$ vs warranty period.

(d) $\beta$ vs greening level.

**Fig. 3.2:** Change (%) in optimal results w.r.t. $\beta$.

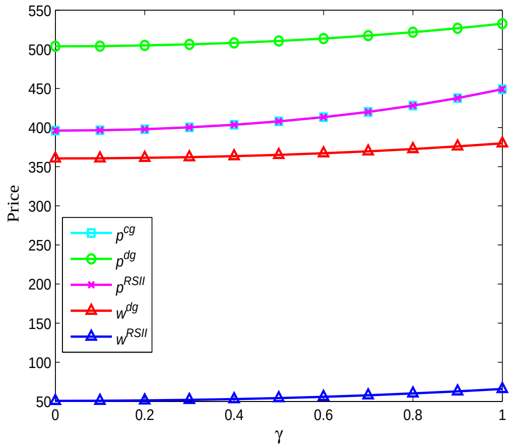
(iv) An increased value of warranty period sensitivity parameter $\beta$ has similar impact on greening level as that of the warranty period. When $\beta$ crosses the value 0.9, the greening level under revenue sharing contract becomes higher than that of the decentralized policy.

From **Fig.** 3.3, we have the following observations:

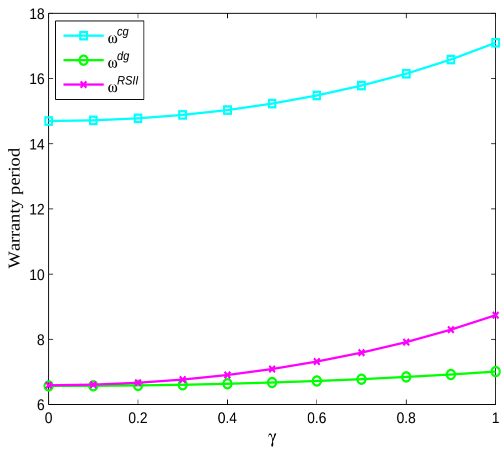
As Model I is independent of $\gamma$, here only Model II is considered.

(i) Similar to the warranty period sensitivity parameter $\beta$, the greening level sensitivity parameter $\gamma$ has a positive impact on the wholesale price. The wholesale price increases with $\gamma$. As a result, the selling price also increases.

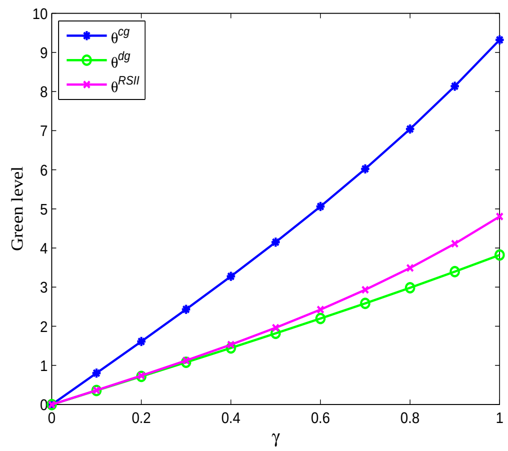
(ii) The warranty period and greening level both increase with $\gamma$. It can be noted




(a) $\gamma$ vs price.




(b) $\gamma$ vs warranty period.




(c) $\gamma$ vs greening level.

**Fig. 3.3:** Change (%) in optimal results w.r.t. $\gamma$.

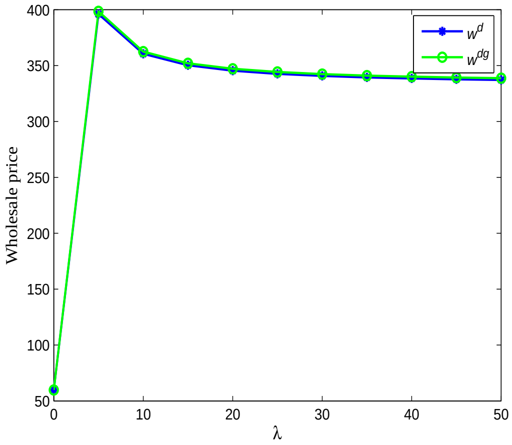
that, for a lower value of $\gamma$, the warranty period and greening level in the revenue sharing contract become lower than those in the decentralized policy.

**Fig.** 3.4 reveals the following insights:

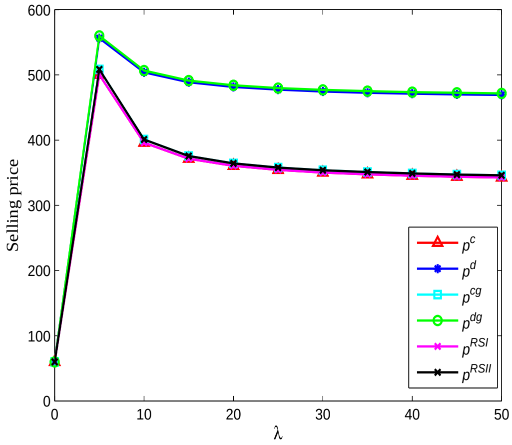
(i) Initially the warranty period investment cost parameter $\lambda$ has a positive impact on the wholesale price and it increases rapidly. As $\lambda$ crosses the value 5.0, the wholesale price decreases in both the models. As a result, the selling price also follows the similar pattern.

(ii) The warranty period investment cost increases means the manufacturer has to invest more to keep the product quality intact. So, the warranty period decreases significantly for higher investment.

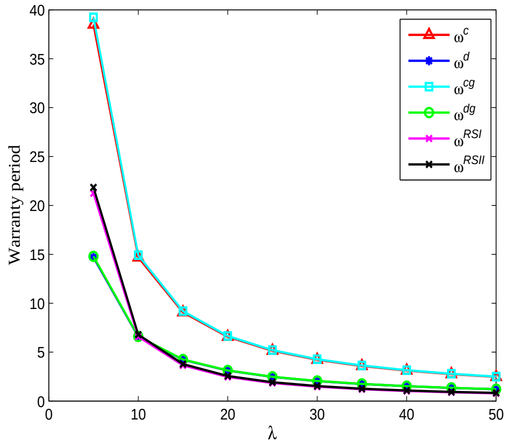
(iii) If the manufacturer and the retailer charge higher price, they have to sell the



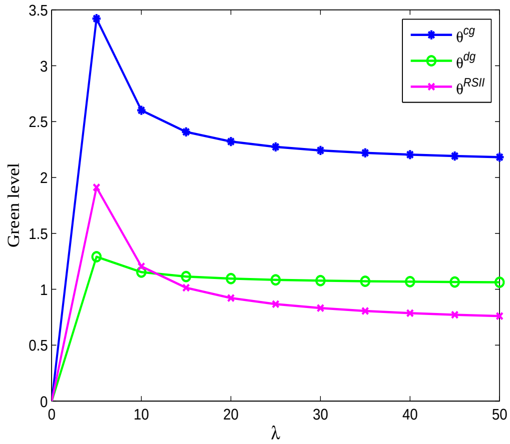

(a) $\lambda$ vs wholesale price.




(b) $\lambda$ vs selling price.




(c) $\lambda$ vs warranty period.

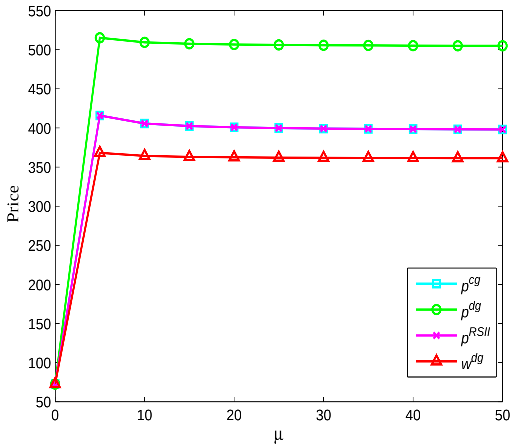



(d) $\lambda$ vs greening level.

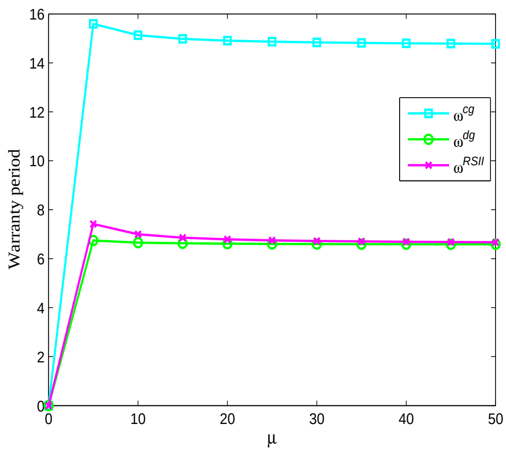
**Fig. 3.4:** Change (%) in optimal results w.r.t. $\lambda$.

product with higher greening level. Until $\lambda$ crosses the value 5.0, the greening level increases. After that, it starts to decrease. For smaller value of $\lambda$, the greening level follows the sequence $\theta^c > \theta^{RS} > \theta^d$ but when $\lambda$ crosses the value 12.0, it follows the sequence $\theta^c > \theta^d > \theta^{RS}$. In order to obtain a 'win-win' situation under revenue sharing contract, the greening level should follow the sequence $\theta^c > \theta^{RS} > \theta^d$.

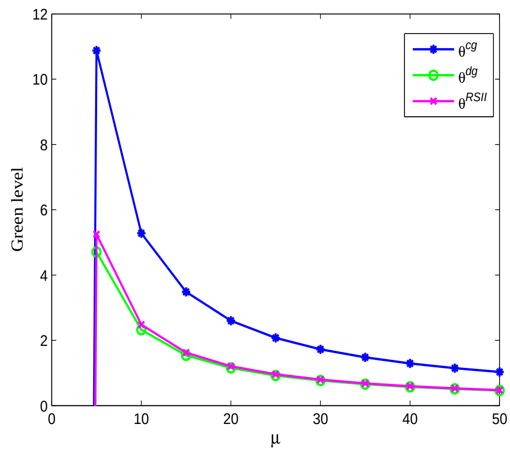
The green investment cost parameter $\mu$ has the same effect on the optimal decisions as those of the warranty period investment cost parameter $\lambda$ but the greening level decreases significantly. Until $\mu$ crosses the value 5.0, all the decision variables increase and after that start decreasing (see Fig. 3.5).




(a) $\mu$ vs price.




(b) $\mu$ vs warranty period.

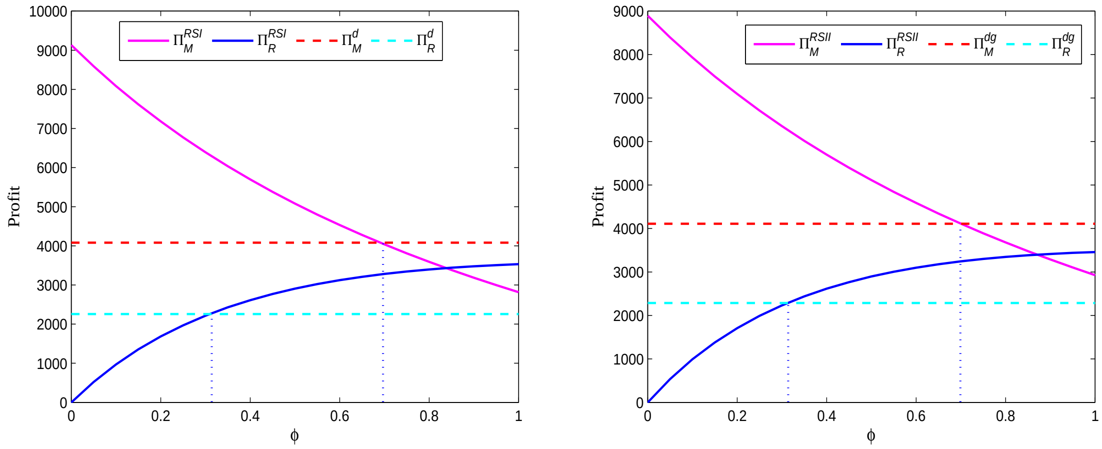



(c) $\mu$ vs greening level.

**Fig. 3.5:** Change (%) in optimal results w.r.t. $\mu$.

# 3.5 Managerial implications and conclusions

In a CLSC, the upstream and downstream members not only implement the coordination for their economic development, but also need to produce greener product for environmental development. In this chapter, a two-echelon CLSC model with one manufacturer and one retailer is considered. Two game theoretic models are presented depending on whether the manufacturer produces green product or not. From the numerical study, it is seen that introduction of green innovation gives better result in terms of profits of the manufacturer, the retailer and the whole system. Although the wholesale price and selling price are higher under green production, due to higher warranty period and green sensitive product, consumers are keen to buy more products. It is also noted that when it is possible to refurbish all the return items, the wholesale price and the selling price decrease but the warranty period and the greening level increase. As a result, the market demand increases, which leads to higher profits of the players and the whole system. However, when all the returned items need to be remanufactured, the wholesale price and the selling price increase but the warranty period and the greening level decrease. The revenue sharing contract not only helps the channel members to achieve the 'win-win' situation but also leads to higher supply chain profit than the decentralized policy when revenue sharing ratio lies in a certain interval (see Fig. 3.6).




(a) Win-win region of $\phi$ for Model I. (b) Win-win region of $\phi$ for Model II.

**Fig. 3.6:** Win-win situation for the manufacturer and the retailer in both models.

There are several insights of our developed model. Firstly, business managers should strengthen the awareness of coordination contract regardless of improving their own profit levels. They should implement policies for long term interests of business and go for all-out to promote the overall performance of the supply chain. Secondly, manufacturers should develop green products and extend the awareness of environment issues. New companies which do not have brand name can develop green products to promote their marketing sense in the competitive market. Thirdly, being attracted by the warranty period and eco-friendly behavior, the consumers are keen to buy green products, which makes more demand as well as more profit for managers with more environmental awareness. Lastly, the effective coordination contract mechanism (here revenue sharing contract) gives a higher level profit of each supply member than the decentralized scenario.

# 4

# Used product collection strategies in a green closed-loop supply chain

## 4.0 Introduction

In CLSC, it is necessary for the manufacturer and the retailer to find a suitable reverse channel for the collection of used products from end users. Manufacturers have employed various effective approaches such as product design and reconstruction of the process of recycling, advertising services, and employees training courses, etc. for collecting used products. Xerox produces waste-free products with advanced technologies in order to minimize the wastes. Their customer-friendly recycling programs help them to collect millions of cartridges for remanufacturing in each year. Hewlett-Packard (HP) has created an innovative partnership with the people of Haiti, who collect the used plastic bottles, to produce new HP ink cartridges (http://www8.hp.com/h20195/v2/GetPDF.aspx/c05507473.pdf). Canon India has tied up with Producer Responsibility Organization to collect the used e-waste such as end-of-life copiers, scanners, printers, ink cartridges, toner cartridges, camera batteries for recycling in an environment-friendly way (https://in.canon/en/consumer/web/company-qehs-recycling). Kodak is making contracts with a large number of retailers (Savaskan et al., 2004), while Dell is making agreement with third parties to collect used products. Therefore, how to design a suitable reverse channel for collecting used products and mutual agreement or contract between channel individuals are crucial decisions in CLSC.

The common assumptions of this chapter are as follows:

**(1)** The market demand at the retailer's end is deterministic and negatively related to the selling price while positively related to the greening level of the product and the marketing effort of the retailer.

**(2)** Although the quality of all the returned products may not be the same, to focus on the pricing, marketing effort and greening level of the product, we assume that all the return products are of the same quality (Savaskan et al., 2004; Choi et al., 2013) having the same remanufacturing cost $c_r (< c_m)$, where $c_m$ is unit manufacturing cost of the finished product from the fresh raw material. Not all the remanufactured products become like-new. Only a fraction ($\rho$) of the remanufactured products passes for being sold with the new one in the primary market while the rest of the remanufactured products is sold at a lower price $w_R$ in a secondary market (Maiti and Giri, 2017). This situation is more clearly depicted in Fig. 4.2.2. Therefore, the unit cost saving from product remanufacturing is $X = \rho c_m + (1 - \rho) w_R - c_r$. For instance, Dell has a separate website (`www.delloutlet.com`) for selling low-quality refurbished computers and accessories. Toyota sells and leases its under-standard used/remanufactured automobiles to an international secondary market. BMW, Ford, and Mercedes-Benz use trade-in programs to collect used automobiles and sell them in a secondary market after refurbishing and/or remanufacturing (Li et al., 2019b).

**(3)** The manufacturer engages in the product remanufacturing only when unit cost savings from product remanufacturing is higher than the unit price paid to customers for the used products *i.e.* $X > A$. It is also assumed that the manufacturer outsources the collection activity to the retailer and/or the third-party only when the unit cost savings from the product remanufacturing exceeds the transfer price *i.e.* $X > B$ (Savaskan et al., 2004).

Based on the above assumptions, the present chapter considers various used product collection strategies under different scenarios. More specifically, used products collection through the manufacturer and the retailer are considered in Section 4.1 while used products collection through the manufacturer and the retailer as well as the third-party collector is considered in Section 4.2.

# 4.1

# *Used product collection strategies in a two-period green closed-loop supply chain*

This study takes into account a two-period marketing scenario under various collection strategies of used products through a manufacturer-retailer Stackelberg game. The manufacturer as a Stackelberg leader divides his selling season in two periods and, at the beginning of the first period, announces the respective decisions for both the periods. Three models based on the manufacturer's collection options of used products, namely, manufacturer collects used products, retailer collects used products, and both manufacturer and retailer collect used products are considered. A cost sharing contract between the manufacturer and the retailer is proposed to improve the overall performance. During calculation, we use backward induction. So, after knowing the decisions of the manufacturer, the retailer first optimizes her decisions for both periods and then the manufacturer optimizes his decisions. To investigate the effect of green innovation effort and marketing effort, we consider three special cases. The main purpose of this study is to find out the answers to the following questions:

- Which one of the three models gives the best possible outcomes of the CLSC?
- What are the effects of green-innovation investment cost and marketing cost on the optimal decisions?
- How do the green innovation effort and marketing effort affect the optimal decisions and profitability of the supply chain members?
- What are the impacts of the cost sharing contract on the key decisions and profitability of the supply chain players and the whole system?
- How do different collection options of used products affect consumer surplus?

This study is based on the paper published in *Journal of Cleaner Production*, 2020, 265, 121335.

### 4.1.1 Notations and assumptions

The following notations are used to develop the proposed models:

| | |
|---|---|
| $w_i$ | unit wholesale price of the manufacturer for $i$th period ($i = 1, 2$). |
| $p_i$ | unit selling price of the retailer for $i$th period ($i = 1, 2$). |
| $e_i$ | unit marketing effort level of the retailer for $i$th period ($i = 1, 2$). |
| $\theta_i$ | level of green innovation for $i$th period ($i = 1, 2$). |
| $D_i$ | demand function of the retailer for $i$th period ($i = 1, 2$). |
| $D_r$ | return quantity. |
| $d_i$ | basic market demand for $i$th period ($i = 1, 2$). |
| $\delta$ | common discount factor in the second period. |
| $\tau_1$ | collection rate of used products to the manufacturer ($0 \leq \tau_1 \leq 1$). |
| $\tau_2$ | collection rate of used products to the retailer ($0 \leq \tau_2 \leq 1$). |
| $\lambda_i$ | green investment coefficient for $i$th period ($i = 1, 2$). |
| $\epsilon$ | competition factor of the two members' collection activities ($0 \leq \epsilon \leq 1$). |
| $G_i$ | marketing cost coefficient for $i$th period ($i = 1, 2$). |
| $H$ | collection cost coefficient to the manufacturer and/or retailer. |
| $\Pi_{m_i}$ | profit of the manufacturer for $i$th period ($i = 1, 2$). |
| $\Pi_{r_i}$ | profit of the retailer for $i$th period ($i = 1, 2$). |
| $\Pi$ | profit of the whole system. |

In addition to the common assumptions, the following assumptions are also made to establish the proposed model:

**(1)** Following the common assumption, we assume that the demand functions for the two periods are positively dependent on the greening level and marketing effort, and negatively dependent on the selling price of the respective period *i.e.* $D_i = d_i - \alpha_i p_i + \beta_i \theta_i + \gamma_i e_i$, $i = 1, 2$, where $\alpha_i$, $\beta_i$ and $\gamma_i$ are positive constants.

**(2)** We consider the return quantities to the manufacturer and the retailer as $\tau_1 D_1$ and $\tau_2 D_1$, respectively so that $D_r = (\tau_1 + \tau_2) D_1$, where $0 \leq \tau_1 + \tau_2 \leq 1$. Note that $\tau_1 + \tau_2 = 0$ means that no used products are returned, and $\tau_1 + \tau_2 = 1$ indicates that all used products are returned. When the manufacturer only collects used products, we have $\tau_2 = 0$ and when the retailer only collects used products, we have $\tau_1 = 0$. When both the manufacturer and the retailer collect used products simultaneously, each player's investment for collecting used products depends on its own investment as well as its rival's investment *i.e.* the manufacturer and the retailer have to invest $\frac{(H_1\tau_1^2+\epsilon H_2\tau_2^2)}{1-\epsilon^2}$ and $\frac{(H_2\tau_2^2+\epsilon H_1\tau_1^2)}{1-\epsilon^2}$, respectively (Wei et al., 2018). For simplicity, we assume $H_1 = H_2 = H$. For single collection mode, $\epsilon = 0$.

## 4.1.2 Model formulation

In this section, a centralized model and three decentralized models with different collection options will be considered. The manufacturer divides his selling season into two successive periods while selling the product. During the first period, the manufacturer produces the green product with greening level $\theta_1$ at a manufacturing cost $c_m$ per unit and sells it to the retailer at a wholesale price $w_1$ per unit. The retailer then sells it to customers at a price $p_1$ per unit with marketing effort $e_1$. However, in the second period, besides producing and selling new product, the manufacturer collects used products from the end customers and remanufactures those products at a cost of $c_r$ per unit. The collection of used products may be done in three ways: (1) the manufacturer only collects used products with a rate $\tau_1$ by paying $A$ per unit to customers, (2) the retailer only collects with a rate $\tau_2$ by paying $A$ per unit to customers and then transfers it to the manufacturer with transfer price $B$ per unit, and (3) both the manufacturer and the retailer collect used products. Only a small portion $\rho$ of the remanufactured products has the same quality with the new one with greening level $\theta_2$ and both are sold at a wholesale price $w_2$ per unit; the remaining portion is sold in the secondary market with a price $w_R$ per unit. The retailer sells the product at a price $p_2$ per unit with marketing effort $e_2$. The manufacturer and the retailer can choose their decisions in two ways: (1) they may choose their corresponding decisions for both the periods at the beginning of the first period, and (2) each player decides optimal decisions for the respective periods independently. Giri et al. (2019) showed that the manufacturer and the retailer can get better result for their first type of choice. Here also we consider the first type of decision strategy. So, the profit functions of the manufacturer and the retailer for periods 1 and 2 are given by

$$\Pi_{m_1}(w_1, \theta_1) = (w_1 - c_m)D_1 - \lambda_1\theta_1^2, \tag{4.1.1}$$

$$\begin{aligned}\Pi_{m_2}(w_2, \theta_2, \tau_1) &= w_2D_2 - c_m(D_2 - \rho D_r) + w_R(1-\rho)D_r - (A + c_r)\tau_1 D_1 \\ &\quad -(B + c_r)\tau_2 D_1 - \lambda_2\theta_2^2 - \frac{H(\tau_1^2 + \epsilon\tau_2^2)}{1-\epsilon^2}\end{aligned} \tag{4.1.2}$$

$$\Pi_{r_1}(p_1, e_1) = (p_1 - w_1)D_1 - G_1e_1^2, \tag{4.1.3}$$

$$\Pi_{r_2}(p_2, e_2, \tau_2) = (p_2 - w_2)D_2 + (B - A)\tau_2 D_1 - \frac{H(\tau_2^2 + \epsilon\tau_1^2)}{1 - \epsilon^2} - G_2 e_2^2 \quad (4.1.4)$$

Total profits of the manufacturer and the retailer are given by

$$\Pi_m(w_1, w_2, \theta_1, \theta_2, \tau_1) = \Pi_{m_1}(w_1, \theta_1) + \delta\Pi_{m_2}(w_2, \theta_2, \tau_1) \quad (4.1.5)$$

$$\text{and } \Pi_r(p_1, p_2, e_1, e_2, \tau_2) = \Pi_{r_1}(p_1, e_1) + \delta\Pi_{r_2}(p_2, e_2, \tau_2) \quad (4.1.6)$$

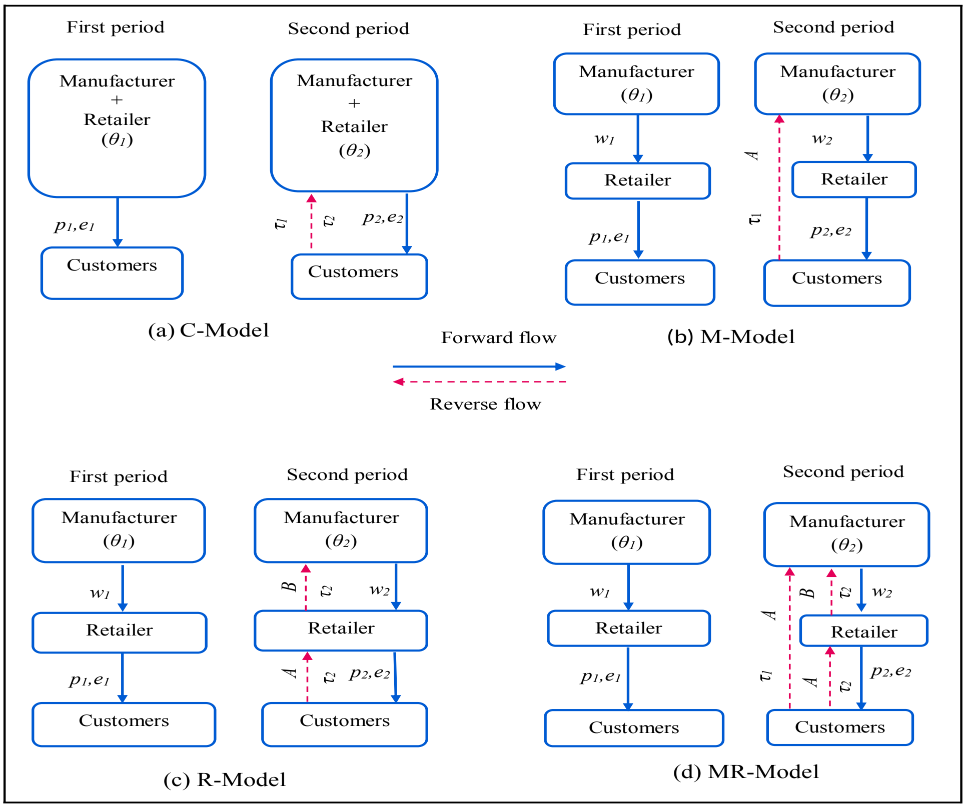



**Fig. 4.1.1:** Structure of the proposed two-period closed-loop supply chain.

## 4.1.2.1 The centralized model (C-Model)

In centralized model, there is a single entity responsible for decision-making, whose aim is to maximize the total profit of the whole supply chain with respect to all the decisions viz. the selling prices, greening levels, marketing efforts and collection rate of used products. Due to single decision maker, wholesale prices and internal transfer price do not play any role in this model (see Fig. 4.1.1(a)). So, for the centralized model, the objective function is given as follows:

$$\max_{(p_1,p_2,\theta_1,\theta_2,e_1,e_2,\tau_1,\tau_2)} \Pi^C = (p_1 - c_m)D_1 - \lambda_1\theta_1^2 - G_1e_1^2 + \delta[p_2D_2 - c_m(D_2 - \rho D_r) + w_R(1-\rho)D_r$$
$$-(A + c_r)(\tau_1 + \tau_2)D_1 - \frac{H(\tau_1^2 + \tau_2^2)}{1 - \epsilon} - \lambda_2\theta_2^2 - G_2e_2^2] \quad (4.1.7)$$

Solving the first order necessary conditions for optimality, we get the optimal decisions of the centralized model as given in the following proposition:

**Proposition 4.1.1.** *If* $\Xi_1 > 0$, $\Xi_2 > 0$ *and* $H\Xi_1 - 2\alpha_1^2\lambda_1 G_1\delta C_1^2(1-\epsilon) > 0$ *then, at the equilibrium, the greening levels, the selling prices, the marketing efforts and collection rate of used products for the C-Model are given respectively by*

$$\begin{aligned}
\theta_1^{*C} &= \frac{G_1 H\beta_1 N_1}{H\Xi_1 - 2\alpha_1^2\lambda_1 G_1\delta C_1^2(1-\epsilon)}, \quad \theta_2^{*C} = \frac{G_2\beta_2 N_2}{\Xi_2},\\
p_1^{*C} &= c_m + \frac{2\lambda_1 G_1 N_1\big(H - \alpha_1\delta C_1^2(1-\epsilon)\big)}{H\Xi_1 - 2\alpha_1^2\lambda_1 G_1\delta C_1^2(1-\epsilon)}, \quad p_2^{*C} = c_m + \frac{2\lambda_2 G_2 N_2}{\Xi_2},\\
e_1^{*C} &= \frac{H\gamma_1\lambda_1 N_1}{H\Xi_1 - 2\alpha_1^2\lambda_1 G_1\delta C_1^2(1-\epsilon)}, \quad e_2^{*C} = \frac{\gamma_2\lambda_2 N_2}{\Xi_2},\\
\tau_1^{*C} &= \frac{G_1\alpha_1\lambda_1 N_1 C_1(1-\epsilon)}{H\Xi_1 - 2\alpha_1^2\lambda_1 G_1\delta C_1^2(1-\epsilon)}, \quad \tau_2^{*C} = \frac{G_1\alpha_1\lambda_1 N_1 C_1(1-\epsilon)}{H\Xi_1 - 2\alpha_1^2\lambda_1 G_1\delta C_1^2(1-\epsilon)}.\\
\textit{where } N_i &= (d_i - c_m\alpha_i);\ \Xi_i = \lambda_i(4\alpha_i G_i - \gamma_i^2) - \beta_i^2 G_i,\ i = 1,2;\ \textit{and } C_1 = X - A.
\end{aligned}$$

**Proof.** The Hessian matrix associated with the profit function of the centralized model is given by

$$H^C = \begin{pmatrix}
\frac{\partial^2\Pi^C}{\partial p_1^2} & \frac{\partial^2\Pi^C}{\partial p_1\partial p_2} & \frac{\partial^2\Pi^C}{\partial p_1\partial\theta_1} & \frac{\partial^2\Pi^C}{\partial p_1\partial\theta_2} & \frac{\partial^2\Pi^C}{\partial p_1\partial e_1} & \frac{\partial^2\Pi^C}{\partial p_1\partial e_2} & \frac{\partial^2\Pi^C}{\partial p_1\partial\tau_1} & \frac{\partial^2\Pi^C}{\partial p_1\partial\tau_2}\\
\frac{\partial^2\Pi^C}{\partial p_2\partial p_1} & \frac{\partial^2\Pi^C}{\partial p_2^2} & \frac{\partial^2\Pi^C}{\partial p_2\partial\theta_1} & \frac{\partial^2\Pi^C}{\partial p_2\partial\theta_2} & \frac{\partial^2\Pi^C}{\partial p_2\partial e_1} & \frac{\partial^2\Pi^C}{\partial p_2\partial e_2} & \frac{\partial^2\Pi^C}{\partial p_2\partial\tau_1} & \frac{\partial^2\Pi^C}{\partial p_2\partial\tau_2}\\
\frac{\partial^2\Pi^C}{\partial\theta_1\partial p_1} & \frac{\partial^2\Pi^C}{\partial\theta_1\partial p_2} & \frac{\partial^2\Pi^C}{\partial\theta_1^2} & \frac{\partial^2\Pi^C}{\partial\theta_1\partial\theta_2} & \frac{\partial^2\Pi^C}{\partial\theta_1\partial e_1} & \frac{\partial^2\Pi^C}{\partial\theta_1\partial e_2} & \frac{\partial^2\Pi^C}{\partial\theta_1\partial\tau_1} & \frac{\partial^2\Pi^C}{\partial\theta_1\partial\tau_2}\\
\frac{\partial^2\Pi^C}{\partial\theta_2\partial p_1} & \frac{\partial^2\Pi^C}{\partial\theta_2\partial p_2} & \frac{\partial^2\Pi^C}{\partial\theta_2\partial\theta_1} & \frac{\partial^2\Pi^C}{\partial\theta_2^2} & \frac{\partial^2\Pi^C}{\partial\theta_2\partial e_1} & \frac{\partial^2\Pi^C}{\partial\theta_2\partial e_2} & \frac{\partial^2\Pi^C}{\partial\theta_2\partial\tau_1} & \frac{\partial^2\Pi^C}{\partial\theta_2\partial\tau_2}\\
\frac{\partial^2\Pi^C}{\partial e_1\partial p_1} & \frac{\partial^2\Pi^C}{\partial e_1\partial p_2} & \frac{\partial^2\Pi^C}{\partial e_1\partial\theta_1} & \frac{\partial^2\Pi^C}{\partial e_1\partial\theta_2} & \frac{\partial^2\Pi^C}{\partial e_1^2} & \frac{\partial^2\Pi^C}{\partial e_1\partial e_2} & \frac{\partial^2\Pi^C}{\partial e_1\partial\tau_1} & \frac{\partial^2\Pi^C}{\partial e_1\partial\tau_2}\\
\frac{\partial^2\Pi^C}{\partial e_2\partial p_1} & \frac{\partial^2\Pi^C}{\partial e_2\partial p_2} & \frac{\partial^2\Pi^C}{\partial e_2\partial\theta_1} & \frac{\partial^2\Pi^C}{\partial e_2\partial\theta_2} & \frac{\partial^2\Pi^C}{\partial e_2\partial e_1} & \frac{\partial^2\Pi^C}{\partial e_2^2} & \frac{\partial^2\Pi^C}{\partial e_2\partial\tau_1} & \frac{\partial^2\Pi^C}{\partial e_2\partial\tau_2}\\
\frac{\partial^2\Pi^C}{\partial\tau_1\partial p_1} & \frac{\partial^2\Pi^C}{\partial\tau_1\partial p_2} & \frac{\partial^2\Pi^C}{\partial\tau_1\partial\theta_1} & \frac{\partial^2\Pi^C}{\partial\tau_1\partial\theta_2} & \frac{\partial^2\Pi^C}{\partial\tau_1\partial e_1} & \frac{\partial^2\Pi^C}{\partial\tau_1\partial e_2} & \frac{\partial^2\Pi^C}{\partial\tau_1^2} & \frac{\partial^2\Pi^C}{\partial\tau_1\partial\tau_2}\\
\frac{\partial^2\Pi^C}{\partial\tau_2\partial p_1} & \frac{\partial^2\Pi^C}{\partial\tau_2\partial p_2} & \frac{\partial^2\Pi^C}{\partial\tau_2\partial\theta_1} & \frac{\partial^2\Pi^C}{\partial\tau_2\partial\theta_2} & \frac{\partial^2\Pi^C}{\partial\tau_2\partial e_1} & \frac{\partial^2\Pi^C}{\partial\tau_2\partial e_2} & \frac{\partial^2\Pi^C}{\partial\tau_2\partial\tau_1} & \frac{\partial^2\Pi^C}{\partial\tau_2^2}
\end{pmatrix}$$

$$= \begin{pmatrix}
A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} & A_{17} & A_{18}\\
A_{21} & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} & A_{27} & A_{28}\\
A_{31} & A_{32} & A_{33} & A_{34} & A_{35} & A_{36} & A_{37} & A_{38}\\
A_{41} & A_{42} & A_{43} & A_{44} & A_{45} & A_{46} & A_{47} & A_{48}\\
A_{51} & A_{52} & A_{53} & A_{54} & A_{55} & A_{56} & A_{57} & A_{58}\\
A_{61} & A_{62} & A_{63} & A_{64} & A_{65} & A_{66} & A_{67} & A_{68}\\
A_{71} & A_{72} & A_{73} & A_{74} & A_{75} & A_{76} & A_{77} & A_{78}\\
A_{81} & A_{82} & A_{83} & A_{84} & A_{85} & A_{86} & A_{87} & A_{88}
\end{pmatrix}$$

where, $A_{11} = -2\alpha_1, A_{13} = A_{31} = \beta_1, A_{15} = A_{51} = \gamma_1, A_{17} = A_{71} = A_{18} = A_{81} = -\alpha_1\delta C_1, A_{22} = -2\alpha_2\delta, A_{24} = A_{42} = \delta\beta_2, A_{26} = A_{62} = \delta\gamma_2, A_{33} = -2\lambda_1, A_{37} = A_{73} = A_{38} = A_{83} = \beta_1\delta C_1, A_{44} = -2\lambda_2\delta, A_{55} = -2G_1, A_{57} = A_{75} = A_{58} = A_{85} = \gamma_1\delta C_1, A_{66} = -2\delta G_2, A_{77} = A_{88} = -\frac{2H\delta}{1-\epsilon}$ and all other elements are zero.

Now, the principal minors are: $|M_1| = -2\alpha_1 < 0$, $|M_2| = 4\delta\alpha_1\alpha_2 > 0$, $|M_3| = -2\delta\alpha_2(4\alpha_1\lambda_1 - \beta_1^2) < 0$, if $\lambda_1 > \frac{\beta_1^2}{4\alpha_1}$, $|M_4| = \delta^2(4\alpha_1\lambda_1 - \beta_1^2)(4\alpha_2\lambda_2 - \beta_2^2) > 0$, if $\lambda_2 > \frac{\beta_2^2}{4\alpha_2}$, $|M_5| = -2\delta^2(4\alpha_2\lambda_2 - \beta_2^2)\Xi_1 < 0$, if $\lambda_1 > \frac{\beta_1^2 G_1}{4\alpha_1 G_1 - \gamma_1^2}$, $|M_6| = 4\delta^3\Xi_1\Xi_2 > 0$ if $\lambda_2 > \frac{\beta_1^2 G_1}{4\alpha_1 G_1 - \gamma_1^2}$, $|M_7| = -\frac{8\delta^4\Xi_2}{1-\epsilon}[H\Xi_1 - \alpha_1^2\lambda_1 G_1\delta C_1^2(1-\epsilon)] < 0$, if $H > \frac{\alpha_1^2\lambda_1 G_1\delta C_1^2(1-\epsilon)}{\Xi_1}$ and $|H^C| = \frac{16H\delta^5\Xi_2}{(1-\epsilon)^2}[H\Xi_1 - 2\alpha_1^2\lambda_1 G_1\delta C_1^2(1-\epsilon)] > 0$. Under these conditions, the Hessian matrix $H^C$ becomes negative definite. Using the first order necessary conditions for optimality of $\Pi^C$, we can get unique optimal solution of the centralized model. ■

#### 4.1.2.2 *Manufacturer collects used products (M-Model)*

In this subsection, we assume that besides producing and selling green product to the potential customers through the retailer, the manufacturer also involves in collecting used products directly from the customers at the beginning of the second period. This strategy of collecting used products can be seen in many companies. Xerox collects used products from the customers directly by providing prepaid mailboxes (Savaskan et al., 2004). Apple has launched a free recycling policy through a competitive trade-in estimate for an Apple Store Gift Card or instant credit at an Apple Store. It provides a prepaid trade-in kit or shipping label to participate in the recycling program (`https://www.apple.com/shop/trade-in`). Sony offers free take back of its products in North America.

The manufacturer as a Stackelberg leader maximizes his total profit for the whole selling season and announces the wholesale prices ($w_1^M$ and $w_2^M$) for the product with the greening levels $\theta_1^M$ and $\theta_2^M$, respectively. The retailer (Stackelberg follower) then sets the selling prices $p_1^M$ and $p_2^M$ for the green product with marketing efforts $e_1^M$ and $e_2^M$, respectively. Also, at the beginning of the second period, the manufacturer collects used products, which is a fraction ($\tau_1^M$) of the demand of the first period (see Fig. 4.1.1(b)). So, the objective functions of the manufacturer and the retailer are given by

$$
\begin{aligned}
\max_{(w_1,w_2,\theta_1,\theta_2,\tau_1)} \Pi_m^M &= \Pi_{m_1}^M + \delta\Pi_{m_2}^M,\\
\text{where } \Pi_{m_1}^M(w_1,\theta_1,\tau_1) &= (w_1 - c_m)D_1 - \lambda_1\theta_1^2,\\
\Pi_{m_2}^M(w_2,\theta_2) &= w_2D_2 - c_m(D_2 - \rho D_r) + w_R(1-\rho)D_r - (A_1 + c_r)D_r - \lambda_2\theta_2^2 - H\tau_1^2,\\
\max_{(p_1,p_2,e_1,e_2)} \Pi_r^M &= \Pi_{r_1}^M + \delta\Pi_{r_2}^M,\\
\text{where } \Pi_{r_1}^M(p_1,e_1) &= (p_1 - w_1)D_1 - G_1e_1^2\\
\Pi_{r_2}^M(p_2,e_2) &= (p_2 - w_2)D_2 - G_2e_2^2
\end{aligned}
$$

Now, we determine the retailer's best responses by solving the first order necessary conditions for optimality of the retailer's objective function simultaneously, and the responses are given as follows:

$$\begin{aligned} p_1^M(w_1,\theta_1) &= \frac{2G_1(d_1+\alpha_1 w_1+\beta_1\theta_1)-w_1\gamma_1^2}{4\alpha_1 G_1-\gamma_1^2}, \quad p_2^M(w_2,\theta_2)=\frac{2G_2(d_2+\alpha_2 w_2+\beta_2\theta_2)-w_2\gamma_2^2}{4\alpha_2 G_2-\gamma_2^2},\\ e_1^M(w_1,\theta_1) &= \frac{\gamma_1(d_1-\alpha_1 w_1+\beta_1\theta_1)}{4\alpha_1 G_1-\gamma_1^2}, \quad e_2^M(w_2,\theta_2)=\frac{\gamma_2(d_2-\alpha_2 w_2+\beta_2\theta_2)}{4\alpha_2 G_2-\gamma_2^2}. \end{aligned}$$

The positivity of the retailer's decisions demands $4\alpha_1 G_1-\gamma_1^2>0$ and $4\alpha_2 G_2-\gamma_2^2>0$. With these reactions of the retailer, the manufacturer will optimize his objective function. The optimal solution can be obtained as given in the following proposition:

**Proposition 4.1.2.** *If* $\Psi_1>0, \Psi_2>0$, *and* $H\Psi_1-\alpha_1^2 G_1\lambda_1\delta C_1^2>0$ *then, at the equilibrium, the manufacturer's wholesale prices, greening levels, collection rate of used products, and the retailer's selling prices and marketing efforts for the M-Model are given respectively by*

$$\begin{aligned} w_1^{*M} &= c_m+\frac{\lambda_1 N_1\big(H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1^2 G_1\delta C_1^2\big)}{\alpha_1(H\Psi_1-\alpha_1^2 G_1\lambda_1\delta C_1^2)}, \quad w_2^{*M}=c_m+\frac{\lambda_2 N_2(4\alpha_2 G_2-\gamma_2^2)}{\alpha_2\Psi_2},\\ \theta_1^{*M} &= \frac{G_1 H\beta_1 N_1}{H\Psi_1-\alpha_1^2 G_1\lambda_1\delta C_1^2}, \quad \theta_2^{*M}=\frac{G_2\beta_2 N_2}{\Psi_2}, \quad \tau_1^{*M}=\frac{G_1\alpha_1\lambda_1 N_1 C_1}{H\Psi_1-\alpha_1^2 G_1\lambda_1\delta C_1^2},\\ p_1^{*M} &= c_m+\frac{\lambda_1 N_1\big(H(6\alpha_1 G_1-\gamma_1^2)-\alpha_1^2 G_1\delta C_1^2\big)}{\alpha_1(H\Psi_1-\alpha_1^2 G_1\lambda_1\delta C_1^2)}, \quad p_2^{*M}=c_m+\frac{\lambda_2 N_2(6\alpha_2 G_2-\gamma_2^2)}{\alpha_2\Psi_2},\\ e_1^{*M} &= \frac{H\gamma_1\lambda_1 N_1}{H\Psi_1-\alpha_1^2 G_1\lambda_1\delta C_1^2}, \quad e_2^{*M}=\frac{\gamma_2\lambda_2 N_2}{\Psi_2},\\ \text{where}\quad \Psi_i &= 2\lambda_i(4\alpha_i G_i-\gamma_i^2)-\beta_i^2 G_i, i=1,2. \end{aligned}$$

**Proof.** *The retailer's reaction*

The Hessian matrix associated with the retailer's profit function is given by

$$H_R^M=\begin{pmatrix} \frac{\partial^2\Pi_r^M}{\partial p_1^2} & \frac{\partial^2\Pi_r^M}{\partial p_1\partial p_2} & \frac{\partial^2\Pi_r^M}{\partial p_1\partial e_1} & \frac{\partial^2\Pi_r^M}{\partial p_1\partial e_2}\\ \frac{\partial^2\Pi_r^M}{\partial p_2\partial p_1} & \frac{\partial^2\Pi_r^M}{\partial p_2^2} & \frac{\partial^2\Pi_r^M}{\partial p_2\partial e_1} & \frac{\partial^2\Pi_r^M}{\partial p_2\partial e_2}\\ \frac{\partial^2\Pi_r^M}{\partial e_1\partial p_1} & \frac{\partial^2\Pi_r^M}{\partial e_1\partial p_2} & \frac{\partial^2\Pi_r^M}{\partial e^2} & \frac{\partial^2\Pi_r^M}{\partial e_1\partial e_2}\\ \frac{\partial^2\Pi_r^M}{\partial e_2\partial p_1} & \frac{\partial^2\Pi_r^M}{\partial e_2\partial p_1} & \frac{\partial^2\Pi_r^M}{\partial e_2\partial e_1} & \frac{\partial^2\Pi_r^M}{\partial e^2} \end{pmatrix}=\begin{pmatrix} -2\alpha_1 & 0 & \gamma_1 & 0\\ 0 & -2\alpha_2\delta & 0 & \delta\gamma_2\\ \gamma_1 & 0 & -2G_1 & 0\\ 0 & \delta\gamma_2 & 0 & -2G_2\delta \end{pmatrix}$$

Now, the principal minors are: $|M_1|=-2\alpha_1<0$, $|M_2|=4\alpha_1\alpha_2\delta>0$, $|M_3|=-2\alpha_2\delta(4\alpha_1 G_1-\gamma_1^2)<0$, if $4\alpha_1 G_1-\gamma_1^2>0$ and $|H_R^M|=\delta^2(4\alpha_1 G_1-\gamma_1^2)(4\alpha_2 G_2-\gamma_2^2)>0$, if $4\alpha_2 G_2-\gamma_2^2>0$. These conditions demonstrate the concavity of $H_R^M$ and guarantee the positivity of equilibrium solution. From the first order necessary conditions for optimality of $\Pi_r^M$, we can get the optimal decisions of the retailer.

*The manufacturer's reaction*

With the optimal decisions of the retailer, the Hessian matrix associated with the manufacturer's profit function is given by

$$H_M^M = \begin{pmatrix} \frac{\partial^2\Pi_m^M}{\partial w_1^2} & \frac{\partial^2\Pi_m^M}{\partial w_1\partial w_2} & \frac{\partial^2\Pi_m^M}{\partial w_1\partial\theta_1} & \frac{\partial^2\Pi_m^M}{\partial w_1\partial\theta_2} & \frac{\partial^2\Pi_m^M}{\partial w_1\partial\tau_1} \\ \frac{\partial^2\Pi_m^M}{\partial w_2\partial w_1} & \frac{\partial^2\Pi_m^M}{\partial w_2^2} & \frac{\partial^2\Pi_m^M}{\partial w_2\partial\theta_1} & \frac{\partial^2\Pi_m^M}{\partial w_2\partial\theta_2} & \frac{\partial^2\Pi_m^M}{\partial w_2\partial\tau_1} \\ \frac{\partial^2\Pi_m^M}{\partial\theta_1\partial w_1} & \frac{\partial^2\Pi_m^M}{\partial\theta_1\partial w_2} & \frac{\partial^2\Pi_m^M}{\partial\theta^2} & \frac{\partial^2\Pi_m^M}{\partial\theta_1\partial w_2} & \frac{\partial^2\Pi_m^M}{\partial\theta_1\partial\tau_1} \\ \frac{\partial^2\Pi_m^M}{\partial\theta_2\partial w_1} & \frac{\partial^2\Pi_m^M}{\partial\theta_2\partial w_2} & \frac{\partial^2\Pi_m^M}{\partial\theta_2\partial\theta_1} & \frac{\partial^2\Pi_m^M}{\partial\theta^2} & \frac{\partial^2\Pi_m^M}{\partial\theta_2\partial\tau_1} \\ \frac{\partial^2\Pi_m^M}{\partial\tau_1\partial w_1} & \frac{\partial^2\Pi_m^M}{\partial\tau_1\partial w_2} & \frac{\partial^2\Pi_m^M}{\partial\tau_1\partial\theta_1} & \frac{\partial^2\Pi_m^M}{\partial\tau_1\partial\theta_2} & \frac{\partial^2\Pi_m^M}{\partial\tau_1^2} \end{pmatrix}$$

$$= \begin{pmatrix} \frac{-4\alpha_1^2 G_1}{4\alpha_1 G_1-\gamma_1^2} & 0 & \frac{2\alpha_1\beta_1 G_1}{4\alpha_1 G_1-\gamma_1^2} & 0 & \frac{-2\alpha_1^2 G_1\delta C_1}{4\alpha_1 G_1-\gamma_1^2} \\ 0 & \frac{-4\alpha_2^2 G_2\delta}{4\alpha_2 G_2-\gamma_2^2} & 0 & \frac{2\alpha_2\beta_2 G_2\delta}{4\alpha_2 G_2-\gamma_2^2} & 0 \\ \frac{2\alpha_1\beta_1 G_1}{4\alpha_1 G_1-\gamma_1^2} & 0 & -2\lambda_1 & 0 & \frac{2\alpha_1\beta_1 G_1\delta C_1}{4\alpha_1 G_1-\gamma_1^2} \\ 0 & \frac{2\alpha_2 G_2\delta}{4\alpha_2 G_2-\gamma_2^2} & 0 & -2\lambda_2\delta & 0 \\ \frac{-2\alpha_1^2 G_1\delta C_1}{4\alpha_1 G_1-\gamma_1^2} & 0 & \frac{2\alpha_1\beta_1 G_1\delta C_1}{4\alpha_1 G_1-\gamma_1^2} & 0 & -2H\delta \end{pmatrix}$$

Now, the principal minors are: $|M_1| = \frac{-4\alpha_1^2 G_1}{4\alpha_1 G_1-\gamma_1^2} < 0$, $|M_2| = \frac{16\alpha_1^2\alpha_2^2 G_1 G_2\delta}{(4\alpha_1 G_1-\gamma_1^2)(4\alpha_2 G_2-\gamma_2^2)} > 0$, $|M_3| = \frac{-16\alpha_1^2\alpha_2^2 G_1 G_2\delta}{(4\alpha_1 G_1-\gamma_1^2)(4\alpha_2 G_2-\gamma_2^2)}[2\lambda_1 - \frac{\beta_1^2 G_1}{(4\alpha_1 G_1-\gamma_1^2)}] < 0$, if $2\lambda_1 - \frac{\beta_1^2 G_1}{(4\alpha_1 G_1-\gamma_1^2)} > 0$ *i.e.* $2\lambda_1(4\alpha_1 G_1 - \gamma_1^2) - \beta_1^2 G_1 > 0$. $|M_4| = \frac{16\alpha_1^2\alpha_2^2 G_1 G_2\delta^2}{(4\alpha_1 G_1-\gamma_1^2)(4\alpha_2 G_2-\gamma_2^2)}[2\lambda_1 - \frac{\beta_1^2 G_1}{(4\alpha_1 G_1-\gamma_1^2)}][2\lambda_2 - \frac{\beta_2^2 G_2}{(4\alpha_2 G_2-\gamma_2^2)}] > 0$, if $[2\lambda_2 - \frac{\beta_2^2 G_2}{(4\alpha_2 G_2-\gamma_2^2)}] > 0$ *i.e.* $2\lambda_2(4\alpha_2 G_2 - \gamma_2^2) - \beta_2^2 G_2 > 0$. $|H_M^M| = -\frac{32\alpha_1^2\alpha_2^2 G_1 G_2\delta^3}{(4\alpha_1 G_1-\gamma_1^2)^2(4\alpha_2 G_2-\gamma_2^2)^3}[2\lambda_2 - \frac{\beta_2^2 G_2}{(4\alpha_2 G_2-\gamma_2^2)}][H\Psi_1 - \alpha_1^2 G_1\lambda_1\delta C_1^2] < 0$, if $H\Psi_1 - \alpha_1^2 G_1\lambda_1\delta C_1^2 > 0$ *i.e.* $H > \frac{\alpha_1^2 G_1\lambda_1\delta C_1^2}{\Psi_1}$. Under these conditions, the Hessian matrix $H_M^M$ becomes negative definite. Therefore, using the first order necessary conditions for optimality of $\Pi_m^M$, we can get unique optimal solution of the manufacturer. ■

Substituting these values in Eqs. (4.1.5) and (4.1.6), the profits of the manufacturer and the retailer, and the whole supply chain can be obtained.

#### 4.1.2.3 Retailer collects used products (R-Model)

In this case, the forward channel activity is the same as previous model. But in the reverse channel, the retailer collects used products from customers at the beginning of the second period, and transfers these used products to the manufacturer on return for a transfer price $B$ per unit (see Fig. 4.1.1(c)). Power tool maker DeWalt ties up with Lowes and Napa Auto Parts, to collect old tools at their stores for recycling (Esposito et al., 2016). Kodak pays a fixed amount to the retailer as a fee for collecting the used disposable cameras (Savaskan et al., 2004). The big appliances like car, refrigerator and furniture are collected by the same retailer who sells them earlier with comparable value, or exchange offer, or for store credit, often on a gift card.

Similar to M-Model, here also the manufacturer first declares his optimal decisions ($w_i, \theta_i, i = 1, 2$) by maximizing his total profit for the whole selling season, and then the retailer sets her optimal decisions ($p_i, e_i, \tau_2, i = 1, 2$) by maximizing her total profit. The objective functions of the manufacturer and the retailer are given by

$$\begin{aligned}
\max_{(w_1,w_2,\theta_1,\theta_2)} \Pi_m^R &= \Pi_{m_1}^R + \delta \Pi_{m_2}^R, \\
\text{where } \Pi_{m_1}^R(w_1,\theta_1) &= (w_1 - c_m)D_1 - \lambda_1\theta_1^2, \\
\Pi_{m_2}^R(w_2,\theta_2) &= w_2 D_2 - c_m(D_2 - \rho D_r) + w_R(1-\rho)D_r - (B + c_r)D_r - \lambda_2\theta_2^2, \\
\max_{(p_1,p_2,e_1,e_2,\tau_2)} \Pi_r^R &= \Pi_{r_1}^R + \delta \Pi_{r_2}^R, \\
\text{where } \Pi_{r_1}^R(p_1,e_1) &= (p_1 - w_1)D_1 - G_1 e_1^2, \\
\Pi_{r_2}^R(p_2,e_2,\tau_2) &= (p_2 - w_2)D_2 + (B - A)\tau_2 D_1 - G_2 e_2^2 - H\tau_2^2
\end{aligned}$$

The retailer's decisions which can be obtained by solving the first order necessary conditions for optimality are given by

$$\begin{aligned}
p_1^R(w_1,\theta_1) &= \frac{H\big(2G_1(d_1 + \alpha_1 w_1 + \beta_1\theta_1) - w_1\gamma_1^2\big) - \alpha_1 G_1\delta(B-A)^2(d_1 + \beta_1\theta_1)}{H(4\alpha_1 G_1 - \gamma_1^2) - \alpha_1^2 G_1\delta(B-A)^2}, \\
p_2^R(w_2,\theta_2) &= \frac{2G_2(d_2 + \alpha_2 w_2 + \beta_2\theta_2) - w_2\gamma_2^2}{4\alpha_2 G_2 - \gamma_2^2}; \ \ \tau_2^R(w_1,\theta_1) = \frac{\alpha_1 G_1(A-B)(d_1 - \alpha_1 w_1 + \beta_1\theta_1)}{H(4\alpha_1 G_1 - \gamma_1^2) - \alpha_1^2 G_1\delta(B-A)^2}, \\
e_1^R(w_1,\theta_1) &= \frac{\gamma_1 H(d_1 - \alpha_1 w_1 + \beta_1\theta_1)}{H(4\alpha_1 G_1 - \gamma_1^2) - \alpha_1^2 G_1\delta(B-A)^2}; \ \ e_2^R(w_2,\theta_2) = \frac{\gamma_2(d_2 - \alpha_2 w_2 + \beta_2\theta_2)}{4\alpha_2 G_2 - \gamma_2^2}.
\end{aligned}$$

Here the positivity of the retailer's decisions demands $H\big(4\alpha_1 G_1 - \gamma_1^2\big) - \alpha_1^2 G_1\delta(B - A_1)^2 > 0$. Under this condition, the Hessian matrix associated with the retailer's profit function can be proved to be negative definite. Substituting the retailer's decisions into the manufacturer's objective function, and then solving the first order conditions for optimality, we can get the optimal decisions of the manufacturer and consequently the optimal decisions of the retailer. The results are given in the following proposition:

**Proposition 4.1.3.** *If* $H > \max\left\{\frac{\alpha_1 G_1\lambda_1\Phi_2}{\Psi_1}, \frac{\alpha_1^2 G_1\delta C_1(B-A_1)}{(4\alpha_1 G_1 - \gamma_1^2)}\right\}$ *then, at the equilibrium, the manufacturer's wholesale prices, greening levels and the retailer's selling prices, marketing efforts, and collection rate of used products for the R-Model are given respectively by*

$$\begin{aligned}
w_1^{*R} &= c_m + \frac{H\lambda_1 N_1(4\alpha_1 G_1 - \gamma_1^2) + \alpha_1\lambda_1 G_1(\Phi_1 - N_1\Phi_2)}{\alpha_1(H\Psi_1 - \alpha_1\lambda_1 G_1\Phi_2)}, \ w_2^{*R} = c_m + \frac{\lambda_2 N_2(4\alpha_2 G_2 - \gamma_2^2)}{\alpha_2\Psi_2}, \\
\theta_1^{*R} &= \frac{G_1 H\beta_1 N_1}{H\Psi_1 - \alpha_1\lambda_1 G_1\Phi_2}, \ \ \theta_2^{*R} = \frac{G_2\beta_2 N_2}{\Psi_2}, \\
p_1^{*R} &= c_m + \frac{\lambda_1 N_1\big(H(6\alpha_1 G_1 - \gamma_1^2) - \alpha_1 G_1\Phi_2\big)}{\alpha_1(H\Psi_1 - \alpha_1\lambda_1 G_1\Phi_2)}, \ \ p_2^{*R} = c_m + \frac{\lambda_2 N_2(6\alpha_2 G_2 - \gamma_2^2)}{\alpha_2\Psi_2}, \\
e_1^{*R} &= \frac{H\gamma_1\lambda_1 N_1}{H\Psi_1 - \alpha_1\lambda_1 G_1\Phi_2}, \ \ e_2^{*R} = \frac{\gamma_2\lambda_2 N_2}{\Psi_2}, \ \ \tau_2^{*R} = \frac{G_1\alpha_1\lambda_1 N_1(B - A_1)}{H\Psi_1 - \alpha_1\lambda_1 G_1\Phi_2}.
\end{aligned}$$

*where* $C_2 = X - B$, $\Phi_1 = N_1\alpha_1\delta(B - A)^2$, *and* $\Phi_2 = 2\alpha_1\delta C_1(B - A)$.

**Proof.** The proof is similar to the proof of Proposition 4.1.2. ■

Substituting these values in Eqs. (4.1.5) and (4.1.6), the profits of the manufacturer and the retailer can be obtained.

#### 4.1.2.4 Manufacturer and retailer collect used products (MR-Model)

In this case, the forward channel activity is also the same as previous models. But in the reverse channel, both the manufacturer and the retailer collect used products from customers at the beginning of the second period (see Fig. 4.1.1(d)). This type of activity can be found in many industries such as automobiles, telecommunications, consumer packaging materials, etc. Due to joint collection of used products, each member's collection cost is affected by other's collection cost.

The objective functions of the manufacturer and the retailer are given by

$$\begin{aligned}
\max_{(w_1,w_2,\theta_1,\theta_2,\tau_1)} \Pi_m^{MR} &= \Pi_{m_1}^{MR} + \delta\Pi_{m_2}^{MR}, \\
\text{where } \Pi_{m_1}^{MR}(w_1,\theta_1) &= (w_1 - c_m)D_1 - \lambda_1\theta_1^2 \\
\Pi_{m_2}^{MR}(w_2,\theta_2,\tau_1) &= w_2D_2 - c_m(D_2 - \rho D_r) + w_R(1-\rho)D_r - (A + c_r)\tau_1 D_1 \\
&\quad -(B + c_r)\tau_2 D_1 - \lambda_2\theta_2^2 - \frac{H(\tau_1^2 + \epsilon\tau_2^2)}{1-\epsilon^2}, \text{ and} \\
\max_{(p_1,p_2,e_1,e_2,\tau_2)} \Pi_r^{MR} &= \Pi_{r_1}^{MR} + \delta\Pi_{r_2}^{MR}, \\
\text{where } \Pi_{r_1}^{MR}(p_1,e_1) &= (p_1 - w_1)D_1 - G_1e_1^2 \\
\Pi_{r_2}^{MR}(p_2,e_2,\tau_2) &= (p_2 - w_2)D_2 + (B - A)\tau_2 D_1 - \frac{H(\tau_2^2 + \epsilon\tau_1^2)}{1-\epsilon^2} - G_2e_2^2
\end{aligned}$$

The retailer's decisions which can be obtained by solving the first order necessary conditions for optimality are given by

$$\begin{aligned}
p_1^{MR}(w_1,\theta_1) &= \frac{H(2G_1(d_1 + \alpha_1 w_1 + \beta_1\theta_1) - w_1\gamma_1^2) - \alpha_1 G_1\delta(B-A)^2(d_1 + \beta_1\theta_1)(1-\epsilon^2)}{H(4\alpha_1G_1 - \gamma_1^2) - \alpha_1^2G_1\delta(B-A)^2(1-\epsilon^2)}, \\
p_2^{MR}(w_2,\theta_2) &= \frac{2G_2(d_2 + \alpha_2w_2 + \beta_2\theta_2) - w_2\gamma_2^2}{4\alpha_2G_2 - \gamma_2^2}, \\
\tau_2^{MR}(w_1,\theta_1) &= \frac{\alpha_1G_1(B-A)(d_1 - \alpha_1w_1 + \beta_1\theta_1)(1-\epsilon^2)}{H(4\alpha_1G_1 - \gamma_1^2) - \alpha_1^2G_1\delta(B-A)^2(1-\epsilon^2)}, \\
e_1^{MR}(w_1,\theta_1) &= \frac{\gamma_1H(d_1 - \alpha_1w_1 + \beta_1\theta_1)}{H(4\alpha_1G_1 - \gamma_1^2) - \alpha_1^2G_1\delta(B-A)^2(1-\epsilon^2)};\ e_2^{MR}(w_2,\theta_2) = \frac{\gamma_2(d_2 - \alpha_2w_2 + \beta_2\theta_2)}{4\alpha_2G_2 - \gamma_2^2}.
\end{aligned}$$

Here the positivity of the retailer's decisions demands $H\big(4\alpha_1G_1 - \gamma_1^2\big) - \alpha_1^2G_1\delta(B - A_1)^2(1-\epsilon^2) > 0$. Under this condition, the Hessian matrix associated with the retailer's profit function can be proved to be negative definite. Substituting the retailer's decisions into the manufacturer's objective function, and then solving the first order conditions for optimality, we can get the optimal decisions of the manufacturer and consequently the optimal decisions of the retailer. The results are given in the following proposition:

**Proposition 4.1.4.** *If* $H > \max\left\{\frac{\alpha_1 G_1 \lambda_1 \Phi_3}{\Psi_1}, \frac{\alpha_1^2 G_1 \delta \lambda_1 (B-A)\left(2C_2+(2-\epsilon)(B-A)\right)(1-\epsilon^2)}{\Psi_1}, \frac{\alpha_1^2 G_1 \delta (B-A)\left(2C_1-\epsilon(B-A)\right)(1-\epsilon^2)}{2(4\alpha_1 G_1-\gamma_1^2)}\right\}$ *then, at the equilibrium, the manufacturer's wholesale prices, greening levels, collection rate of used products and the retailer's selling prices, marketing efforts, and collection rate of used products for the MR-Model are given respectively by*

$$\begin{aligned}
w_1^{*MR} &= c_m + \frac{\lambda_1 N_1\left(H(4\alpha_1 G_1 - \gamma_1^2) - \alpha_1 G_1 \Phi_3\right) + \alpha_1 \lambda_1 G_1 \Phi_1 (1-\epsilon^2)}{\alpha_1 (H\Psi_1 - \alpha_1 \lambda_1 G_1 \Phi_3)}, \\
w_2^{*MR} &= c_m + \frac{\lambda_2 N_2 (4\alpha_2 G_2 - \gamma_2^2)}{\alpha_2 \Psi_2}, \\
\theta_1^{*MR} &= \frac{G_1 H \beta_1 N_1}{H\Psi_1 - \alpha_1 \lambda_1 G_1 \Phi_3}, \ \theta_2^{*MR} = \frac{G_2 \beta_2 N_2}{\Psi_2}, \ \tau_1^{*MR} = \frac{\alpha_1 G_1 \lambda_1 N_1 C_1 (1-\epsilon^2)}{H\Psi_1 - \alpha_1 \lambda_1 G_1 \Phi_3}, \\
p_1^{*MR} &= c_m + \frac{\lambda_1 N_1\left(H(6\alpha_1 G_1 - \gamma_1^2) - \alpha_1 G_1 \Phi_3\right)}{\alpha_1 (H\Psi_1 - \alpha_1 \lambda_1 G_1 \Phi_3)}, \ p_2^{*MR} = c_m + \frac{\lambda_2 N_2 (6\alpha_2 G_2 - \gamma_2^2)}{\alpha_2 \Psi_2}, \\
e_1^{*MR} &= \frac{H\gamma_1 \lambda_1 N_1}{H\Psi_1 - \alpha_1 \lambda_1 G_1 \Phi_3}, \ e_2^{*MR} = \frac{\gamma_2 \lambda_2 N_2}{\Psi_2}, \ \tau_2^{*MR} = \frac{\alpha_1 G_1 \lambda_1 N_1 (B-A)(1-\epsilon^2)}{H\Psi_1 - \alpha_1 \lambda_1 G_1 \Phi_3}, \text{where} \\
\Phi_3 &= \alpha_1 \delta (1-\epsilon^2)[C_1^2 + (B-A)\left((2-\epsilon)(B-A) + 2C_2\right)].
\end{aligned}$$

**Proof.** The proof is similar to the proof of Proposition 4.1.2. ■

Substituting these values in Eqs. (4.1.5) and (4.1.6), the profits of the manufacturer and the retailer can be obtained.

**Corollary 4.1.1.** *In any model, if the manufacturer and/or the retailer has to pay higher collection price to collect used products, then the collection rate of used products decreases* ($\frac{\partial \tau_*}{\partial A} < 0$)*. This is because, a higher value of A decreases the profits of the manufacturer and the retailer. Again, if the manufacturer agrees to pay higher transfer price to the retailer for transferring used products, the collection rate of used products to the retailer increases* ($\frac{\partial \tau_*}{\partial B} > 0$)*, since it causes more profit to the retailer. So, if a player has to pay more to collect used products, s/he disagrees to collect.*

**Corollary 4.1.2.** *The optimal wholesale price, selling price, greening level and marketing effort in the second period have same values in the three models. This means that these decisions do not depend on whether the manufacturer only collects used products or the* *retailer only collects used products or both the manufacturer and the retailer collect used products. So, the manufacturer's decision of implementing single or dual collection mode does not affect the optimal decisions of the second period. This means that any difference in players' outcomes has happened only in the first period.*

### 4.1.3 Model analysis

#### 4.1.3.1 *Comparison of the optimal results*

In this subsection, we make a comparison of the optimal results of the proposed models analytically. Proposition 4.1.5 presents a comparison of the optimal collection rate of used products, greening levels, and marketing efforts of the proposed decentralized models.

**Proposition 4.1.5.** *At the equilibrium, the collection rate of used products, the greening levels and the marketing efforts in the first period have the following relationships:*

*(i)* $\tau_1^{MR} \geq \tau_1^{M}$, *when* $H \leq \frac{\alpha_1^2\lambda_1 G_1\delta(B-A)(1-\epsilon^2)[2C_1-\epsilon(B-A)]}{\Psi_1\epsilon^2}$; $\tau_2^{MR} \geq \tau_2^{R}$, *when* $H \leq \frac{\alpha_1^2\lambda_1 G_1\delta(1-\epsilon^2)[C_1^2-\epsilon(B-A)^2]}{\Psi_1\epsilon^2}$; *and* $\tau_1^{M} \geq \tau_2^{R}$, *when* $H \geq \frac{\alpha_1^2\lambda_1 G_1\delta(B-A)C_1^2}{C_2\Psi_1}$; *otherwise, the direction of the inequality will be reversed.*

*(ii)* $\theta_1^{MR} > \theta_1^{M} \geq \theta_1^{R}$, *when* $\Phi_3 > \alpha_1\delta C_1^2$ *and* $C_2 \geq (B-A)$,

*(iii)* $e_1^{MR} > e_1^{M} \geq e_1^{R}$, *when* $\Phi_3 > \alpha_1\delta C_1^2$ *and* $C_2 \geq (B-A)$.

**Proof.** First, we compare the greening levels of M-Model and R-Model. We have $\theta_1^M - \theta_1^R = \frac{G_1 H\beta_1 N_1}{H\Psi_1-\alpha_1^2\lambda_1 G_1\delta C_1^2} - \frac{G_1 H\beta_1 N_1}{H\Psi_1-\alpha_1\lambda_1 G_1\Phi_2}$. The denominators of both $\theta_1^M$ and $\theta_1^R$ are positive. On simplification, we get $\theta_1^M - \theta_1^R = \frac{\alpha_1^2\beta_1\lambda_1\delta G_1^2 H N_1 C_1(C_2-(B-A))}{(H\Psi_1-\alpha_1^2\lambda_1 G_1\delta C_1^2)(H\Psi_1-\alpha_1\lambda_1 G_1\Phi_2)} \geq 0$, if $C_2 \geq (B-A)$.

Now, we compare the greening levels of MR-Model and M-Model. We have $\theta_1^{MR} - \theta_1^{M} = \frac{G_1 H\beta_1 N_1}{H\Psi_1-\alpha_1\lambda_1 G_1\Phi_3} - \frac{G_1 H\beta_1 N_1}{H\Psi_1-\alpha_1^2\lambda_1 G_1\delta C_1^2}$. Denominators of both $\theta_1^{MR}$ and $\theta_1^{M}$ are positive. On simplification, we get $\theta_1^{MR} - \theta_1^{M} = \frac{\alpha_1\beta_1\lambda_1 G_1^2 H N_1(\Phi_3-\alpha_1\delta C_1^2)}{(H\Psi_1-\alpha_1\lambda_1 G_1\Phi_3)(H\Psi_1-\alpha_1^2\lambda_1 G_1\delta C_1^2)} > 0$, whenever $\Phi_3 - \alpha_1\delta C_1^2 > 0$. Therefore, $\theta_1^{MR} > \theta_1^{M} \geq \theta_1^{R}$, if $\Phi_3 > \alpha_1\delta C_1^2$ and $C_2 \geq (B-A)$. Proofs for the marketing efforts are analogous.

Comparison of the collection rate of used products in different models are given as follows:

$\tau_1^{MR} - \tau_1^{M} = \frac{G_1\alpha_1\lambda_1N_1C_1(1-\epsilon^2)}{H\Psi_1-\alpha_1\lambda_1G_1\Phi_3} - \frac{G_1\alpha_1\lambda_1N_1C_1}{H\Psi_1-\alpha_1^2\lambda_1G_1\delta C_1^2}$. Denominators of both $\tau_1^{MR}$ and $\tau_1^{M}$ are positive. On simplification, we get

$\tau_1^{MR} - \tau_1^{M} = \frac{G_1\alpha_1\lambda_1N_1C_1[\alpha_1^2\lambda_1G_1\delta(B-A)(1-\epsilon^2)\left(2C_1-\epsilon(BA_1)\right)-H\Psi_1\epsilon^2]}{(H\Psi_1-\alpha_1\lambda_1G_1\Phi_3)(H\Psi_1-\alpha_1^2\lambda_1G_1\delta C_1^2)} \geq 0$, whenever $H \leq \frac{\alpha_1^2\lambda_1G_1\delta(B-A)(1-\epsilon^2)\left(2C_1-\epsilon(B-A)\right)}{\Psi_1\epsilon^2}$.

$\tau_2^{MR} - \tau_2^{R} = \frac{G_1\alpha_1\lambda_1N_1(B-A)(1-\epsilon^2)}{H\Psi_1-\alpha_1\lambda_1G_1\Phi_3} - \frac{G_1\alpha_1\lambda_1N_1(B-A)}{H\Psi_1-\alpha_1\lambda_1G_1\Phi_2}$. Denominators of both $\tau_2^{MR}$ and $\tau_2^{R}$ are positive. On simplification, we get

$\tau_2^{MR} - \tau_2^{R} = \frac{G_1\alpha_1\lambda_1N_1(B-A)[\alpha_1^2\lambda_1G_1\delta(1-\epsilon^2)\left(C_1^2-\epsilon(B-A)^2\right)-H\Psi_1\epsilon^2]}{(H\Psi_1-\alpha_1\lambda_1G_1\Phi_3)(H\Psi_1-\alpha_1^2\lambda_1G_1\delta C_1^2)} \geq 0$, whenever $H \leq \frac{\alpha_1^2\lambda_1G_1\delta(1-\epsilon^2)\left(C_1^2-\epsilon(B-A)^2\right)}{\Psi_1\epsilon^2}$.

$\tau_1^{M} - \tau_2^{R} = \frac{G_1\alpha_1\lambda_1N_1C_1}{H\Psi_1-\alpha_1^2\lambda_1G_1\delta C_1^2} - \frac{G_1\alpha_1\lambda_1N_1(B-A)}{H\Psi_1-\alpha_1\lambda_1G_1\Phi_2}$. Denominators of both $\tau_1^{M}$ and $\tau_2^{R}$ are positive. On simplification, we get $\tau_1^{M} - \tau_2^{R} = \frac{G_1\alpha_1\lambda_1N_1[HC_2\Psi_1-\alpha_1^2\lambda_1G_1\delta(B-A)C_1^2]}{(H\Psi_1-\alpha_1^2\lambda_1G_1\delta C_1^2)(H\Psi_1-\alpha_1\lambda_1G_1\Phi_2)} \geq 0$, if $H \geq \frac{\alpha_1^2\lambda_1G_1\delta(B-A)C_1^2}{\Psi_1C_2}$. ∎

Proposition 4.1.5($i$) shows that the optimal collection rate of used products depends on the collection options (only manufacturer collects, only retailer collects, both manufacturer and retailer collect) of used products in the second period. When both the manufacturer and the retailer collect used products, the rate of collection is higher than the case when only the manufacturer or the retailer collects used products whenever $H$ is lower than some threshold value. Again, collection rate of used products and $H$ are inversely propositional. So, for lower values of $H$, collection quantity of used products may exceed the total market demand which is not acceptable. Therefore, when both the manufacturer and the retailer collect used products simultaneously and there is a competition between them, the collection rate of used products in dual collection mode becomes lower than the single collection mode. But, if there is no competition between them while collecting used products, dual collection modes gives better result. In single collection mode, the collection rate of used products in M-Model is higher than that in R-Model when $H$ is greater than a threshold value. Otherwise, the collection rate of used products in R-Model is higher than that in M-Model. Therefore, the collection rate of used products in single collection mode depends on how much the manufacturer/retailer invests in used products collection.

A higher collection rate in M-Model encourages the manufacturer to produce higher green product than R-Model when the marginal profit of the manufacturer obtained by collecting used products from the retailer is higher than that of the retailer obtained by collecting used products from the end customers, which is given in Proposition 4.1.5$(ii)$. In case of dual collection mode, as the collection rate of used products is lower than M-Model and R-Model, the manufacturer produces higher green product in the first period to gain more profit from increased market demand when the condition given in Proposition 4.1.5$(ii)$ holds.

Proposition 4.1.5$(iii)$ reveals that the marketing effort of the retailer in the first period also depends on the collection option of the manufacturer. As the greening level of the product in MR-Model is higher than other models, the retailer also increases the marketing effort of the higher green product to increase the market demand, and the marketing effort of different models follows the similar pattern of the greening level.

**Proposition 4.1.6.** *If the condition* $\lambda_1 > \frac{\beta_1^2 G_1}{4\alpha_1 G_1 - \gamma_1^2}$ *holds, then the wholesale prices in the first period follow the relationship:* $w_1^{MR} < w_1^M < w_1^R$*; and if the condition* $G_1 > \frac{\gamma_1^2 \lambda_1}{2\alpha_1\lambda_1 - \beta_1^2}$ *holds, then the selling prices in the first period follow the relationship:* $p_1^{MR} < p_1^M < p_1^R$*; Otherwise, the direction of the inequality will be reversed.*

**Proof.** First, we compare the wholesale prices of M-Model and R-Model. We have $w_1^R - w_1^M = \frac{H\lambda_1 N_1(4\alpha_1 G_1 - \gamma_1^2) + \alpha_1\lambda_1 G_1(\Phi_1 - N_1\Phi_2)}{\alpha_1(H\Psi_1 - \alpha_1\lambda_1 G_1\Phi_2)} - \frac{\lambda_1 N_1\left(H(4\alpha_1 G_1 - \gamma_1^2) - \alpha_1^2 G_1\delta C_1^2\right)}{\alpha_1(H\Psi_1 - \alpha_1^2\lambda_1 G_1\delta C_1^2)}$.
After simplification, the numerator of $w_1^R - w_1^M$ becomes $H\alpha_1^2\delta\lambda_1 N_1 G_1 C_1(C_2 - (B-A))\left(\lambda_1(4\alpha_1 G_1 - \gamma_1^2) - \beta_1^2 G_1\right) + \alpha_1\lambda_1 G_1\Phi_1(H\Psi_1 - \alpha_1^2\lambda_1 G_1\delta C_1^2)$. Therefore, $H\alpha_1^2\delta\lambda_1 N_1 G_1 C_1(C_2 - (B-A))\left(\lambda_1(4\alpha_1 G_1 - \gamma_1^2) - \beta_1^2 G_1\right)$ is positive if $\lambda_1 > \frac{\beta_1^2 G_1}{4\alpha_1 G_1 - \gamma_1^2}$ (using the condition of Proposition 4.1.5) and $H\Psi_1 - \alpha_1^2\lambda_1 G_1\delta C_1^2 > 0$ (see Proposition 4.1.2). Now, we compare the selling prices of MR-Model and M-Model. Under the previous condition, $w_1^M > w_1^{MR}$. Hence, $w_1^{MR} < w_1^M < w_1^R$, when $\lambda_1 > \frac{\beta_1^2 G_1}{4\alpha_1 G_1 - \gamma_1^2}$ and $H$ is sufficiently large.

Now, we compare the selling prices of M-Model and R-Model. We have $p_1^R - p_1^M = \frac{\lambda_1 N_1(H(6\alpha_1 G_1 - \gamma_1^2) - \alpha_1 G_1\Phi_2)}{\alpha_1(H\Psi_1 - \alpha_1\lambda_1 G_1\Phi_2)} - \frac{\lambda_1 N_1(H(6\alpha_1 G_1 - \gamma_1^2) - \alpha_1^2 G_1\delta C_1^2)}{\alpha_1(H\Psi_1 - \alpha_1^2\lambda_1 G_1\delta C_1^2)}$. On simplification, the numerator of $p_1^R - p_1^M$ becomes $H\alpha_1^2\delta\lambda_1 N_1 G_1 C_1(C_2 - (B-A))\left(G_1(2\alpha_1\lambda_1 - \beta_1^2) - \gamma_1^2\lambda_1\right)$ and this is positive if $G_1 > \frac{\gamma_1^2\lambda_1}{2\alpha_1\lambda_1 - \beta_1^2}$. Now, we compare the selling prices of MR-Model and M-Model. Under the previous condition, $p_1^M > p_1^{MR}$. So, $p_1^{MR} < p_1^M < p_1^R$, when $G_1 > \frac{\gamma_1^2\lambda_1}{2\alpha_1\lambda_1 - \beta_1^2}$. ■

Although the greening level in MR-Model is higher, the manufacturer sets a lower wholesale price in MR-Model than other two models when green innovation efficiency coefficient ($\lambda_1$) is higher than a threshold value. As per our assumption, $\lambda_1$

and $\theta_1$ are inversely proportional. So, for lower value of $\lambda_1$, greening level increases rapidly. It increases the extra cost for green innovation, which again decreases the profit of the manufacturer. To maintain the profit, the manufacturer has to increase the wholesale price. As the manufacturer sells the higher green product with a lower wholesale price in MR-Model, the retailer also sets lower selling price in MR-Model when $G_1$ is higher than a threshold value, which is beneficial to the customers. So, the market demand increases, which increases the profits of the manufacturer, the retailer and the whole supply chain.

**Proposition 4.1.7.** *At the equilibrium, the greening levels, the marketing efforts, collection rate of used products and selling prices of the centralized model and MR-Model bear the following relationships:*

*(i)* $\theta_1^C > \theta_1^{MR}$*, and* $\theta_2^C > \theta_2^{MR}$*;* $e_1^C > e_1^{MR}$*, and* $e_2^C > e_2^{MR}$*;* $\tau^C > \tau^{MR}$.

*(ii)* $p_1^{MR} > p_1^C$*, if* $G_1 > \frac{\gamma_1^2\lambda_1}{2\alpha_1\lambda_1-\beta_1^2}$*, and* $p_2^{MR} > p_2^C$*, if* $G_2 > \frac{\gamma_2^2\lambda_2}{2\alpha_2\lambda_2-\beta_2^2}$.

**Proof.** First, we compare the greening levels of the centralized model and MR-Model in the first period. $\theta_1^C - \theta_1^{MR} = \frac{G_1H\beta_1N_1}{H\Xi_1-2\alpha_1^2\lambda_1G_1\delta C_1(1-\epsilon)} - \frac{G_1H\beta_1N_1}{H\Psi_1-\alpha_1\lambda_1G_1\Phi_3}$. On simplification, the numerator of this difference becomes $G_1H\beta_1N_1\big(H\lambda_1(4\alpha_1G_1 - \gamma_1^2) - \alpha_1\lambda_1G_1(\Phi_3 - 2\alpha_1\delta C_1^2(1-\epsilon))\big)$ and this is positive for the large value of $H$. So, $\theta_1^C > \theta_1^{MR}$. Now, we compare the results for the second period. We have $\theta_2^C - \theta_2^{MR} = \frac{G_2\beta_2N_2}{\Xi_2} - \frac{G_2\beta_2N_2}{\Psi_2}$. The numerator of this difference is $G_2\beta_2N_2\lambda_2(4\alpha_2G_2 - \gamma_2^2) > 0$. So, $\theta_2^C > \theta_2^{MR}$. The proof for the marketing effort is analogous. $\tau_1^C > \tau_1^{MR}$ can be obtained using the proof of greening level. Now, $\tau^C - \tau^{MR} = \frac{2G_1\alpha_1\lambda_1N_1C_1(1-\epsilon)}{H\Xi_1-2\alpha_1^2\lambda_1G_1\delta C_1^2(1-\epsilon)} - \frac{G_1\alpha_1\lambda_1N_1C_2(1-\epsilon^2)}{H\Psi_1-\alpha_1\lambda_1G_1\Phi_3}$. After simplification, the numerator of this difference becomes $\alpha_1\lambda_1G_1N_1(1-\epsilon)\Big(H[2C_1\Psi_1 - C_2(1+\epsilon)\Xi_1] - 2C_1\alpha_1\lambda_1G_1\Phi_3 + 2\alpha_1^2\lambda_1G_1\delta C_1^2C_2(1-\epsilon^2)\Big)$ and this is positive because of higher value of $H$. So, obviously $\tau^C > \tau^{MR}$. $p_1^{MR} - p_1^C = \frac{\lambda_1N_1[(6\alpha_2G_2-\gamma_2^2)-\alpha_1G_1\Phi_3]}{\alpha_1(H\Psi_1-\alpha_1\lambda_1G_1\Phi_3)} - \frac{2\lambda_1G_1N_1(H-\alpha_1\delta C_1^2(1-\epsilon))}{H\Xi_2-2\alpha_1^2\lambda_1G_1\delta C_1^2(1-\epsilon)}$. On simplification, the numerator of this difference becomes $\lambda_1N_1H[H(4\alpha_1G_1 - \gamma_1^2) - (\alpha_1G_1\Phi_3 - 2\alpha_1^2G_1\delta C_1^2(1-\epsilon))][\lambda_1(2\alpha_1G_1 - \gamma_1^2) - \beta_1^2G_1]$. It is positive if $G_1 > \frac{\gamma_1^2\lambda_1}{2\alpha_1\lambda_1-\beta_1^2}$. So, $p_1^{MR} > p_1^C$. Now, $p_2^{MR} - p_2^C = \frac{\lambda_2N_2(6\alpha_2G_2-\gamma_2^2)}{\alpha_2\Psi_2} - \frac{2\lambda_2G_2N_2}{\Xi_2}$. On simplification, the numerator of this difference becomes $(4\alpha_2G_2 - \gamma_2^2)[\lambda_2(2\alpha_2G_2 - \gamma_2^2) - \beta_2^2G_2]$. It is positive if $G_2 > \frac{\gamma_2^2\lambda_2}{2\alpha_2\lambda_2-\beta_2^2}$. So, $p_2^{MR} > p_2^C$. ■

Proposition 4.1.7 illustrates that the greening level and the marketing effort in both the first and the second periods are higher in the centralized model than those in the MR-Model. The collection rate of used products in the centralized model is also higher than those in the MR-Model. The comparison of selling price in the first period depends on the value of $G_1$ and that in second period depends on the value of $G_2$. If the values of these parameters are greater than a threshold value then the selling price in MR-Model is higher than that in the centralized model. Otherwise, the result will be reversed. So, the centralized model gives the best possible result than the decentralized models. The reason behind this type of result is the non-existence of double-marginalization effect. Due to single decision maker, double-marginalization effect does not play any role in the centralized model.

#### 4.1.3.2 Cost sharing (CS) contract

Although the retailer benefits from the green marketing, the manufacturer only bears the green expenditure. This shows the importance of contract analysis, and a cost sharing contract can play a significant role in this situation. So, in order to encourage the manufacturer to engage in green production and to produce more green products, in this subsection we implement a cost sharing contract in which the retailer agrees to share a portion ($\mu_1$ $(0 \leq \mu_1 \leq 1)$ in the first period and $\mu_2$ $(0 \leq \mu_2 \leq 1)$ in the second period) of total greening cost with the manufacturer. This type of cost sharing can be seen in big companies like Coca-Cola, Dell, Tesco, etc. The objective functions of the manufacturer and the retailer are given by

$$\begin{aligned}
\max_{(w_1,w_2,\theta_1,\theta_2,\tau_1)} \Pi_m^{CS} &= \Pi_{m_1}^{CS} + \delta \Pi_{m_2}^{CS}, \\
\text{where } \Pi_{m_1}^{CS}(w_1,\theta_1,\tau_1) &= (w_1 - c_m)D_1 - (1-\mu_1)\lambda_1\theta_1^2, \\
\Pi_{m_2}^{CS}(w_2,\theta_2) &= w_2 D_2 - c_m(D_2 - \rho D_r) + w_R(1-\rho)D_r - (A+c_r)\tau_1 D_1 \\
&\quad -(B+c_r)\tau_2 D_1 - (1-\mu_2)\lambda_2\theta_2^2 - \frac{H(\tau_1^2 + \epsilon\tau_2^2)}{1-\epsilon^2}, \text{ and} \\
\max_{(p_1,p_2,e_1,e_2,\tau_2)} \Pi_r^{CS} &= \Pi_{r_1}^{CS} + \delta \Pi_{r_2}^{CS}, \\
\text{where } \Pi_{r_1}^{CS}(p_1,e_1,\tau_2) &= (p_1 - w_1)D_1 - G_1 e_1^2 - \mu_1\lambda_1\theta_1^2 \\
\Pi_{r_2}^{CS}(p_2,e_2) &= (p_2 - w_2)D_2 + (B-A)\tau_2 D_1 - \frac{H(\tau_2^2 + \epsilon\tau_1^2)}{1-\epsilon^2} - G_2 e_2^2 - \mu_2\lambda_2\theta_2^2
\end{aligned}$$

Using the approach similar to MR-Model, the optimal decisions of the manufacturer and the retailer for CS-Model can be obtained as given in the following proposition:

**Proposition 4.1.8.** *At the equilibrium, the manufacturer's wholesale prices, collection rate of used products, greening levels, and the retailer's selling prices, collection rate of used* *products, marketing efforts for the CS-Model are given respectively by*

$$
\begin{aligned}
w_1^{*CS} &= c_m + \frac{(1-\mu_1)\Big(\lambda_1 N_1\big(H(4\alpha_1 G_1 - \gamma_1^2) - \alpha_1 G_1 \Phi_3\big) + \alpha_1 \lambda_1 G_1 \Phi_1 (1-\epsilon^2)\Big)}{\alpha_1\Big((1-\mu_1)(H\Psi_1 - \alpha_1\lambda_1 G_1 \Phi_3) - \mu_1 H \beta_1^2 G_1\Big)}, \\
w_2^{*CS} &= c_m + \frac{(1-\mu_2)\lambda_2 N_2 (4\alpha_2 G_2 - \gamma_2^2)}{\alpha_2\Big((1-\mu_2)\Psi_2 - \mu_2 \beta_2^2 G_2\Big)}, \\
\tau_1^{*CS} &= \frac{G_1 \alpha_1 \lambda_1 N_1 C_1 (1-\mu_1)(1-\epsilon^2)}{(1-\mu_1)(H\Psi_1 - \alpha_1\lambda_1 G_1\Phi_3) - \mu_1 H\beta_1^2 G_1}, \\
\theta_1^{*CS} &= \frac{G_1 H \beta_1 N_1}{(1-\mu_1)(H\Psi_1 - \alpha_1\lambda_1 G_1\Phi_3) - \mu_1 H\beta_1^2 G_1}, \ \theta_2^{*CS} = \frac{G_2\beta_2 N_2}{(1-\mu_2)\Psi_2 - \mu_2\beta_2^2 G_2}, \\
p_1^{*CS} &= c_m + \frac{(1-\mu_1)\lambda_1 N_1\big(H(6\alpha_1 G_1 - \gamma_1^2) - \alpha_1 G_1 \Phi_3\big)}{\alpha_1\Big((1-\mu_1)(H\Psi_1 - \alpha_1\lambda_1 G_1\Phi_3) - \mu_1 H\beta_1^2 G_1\Big)}, \\
p_2^{*CS} &= c_m + \frac{(1-\mu_2)\lambda_2 N_2 (6\alpha_2 G_2 - \gamma_2^2)}{\alpha_2\Big((1-\mu_2)\Psi_2 - \mu_2\beta_2^2 G_2\Big)}, \\
\tau_2^{*CS} &= \frac{G_1\alpha_1\lambda_1 N_1 (B-A)(1-\mu_1)(1-\epsilon^2)}{(1-\mu_1)(H\Psi_1 - \alpha_1\lambda_1 G_1\Phi_3) - \mu_1 H\beta_1^2 G_1)}, \\
e_1^{*CS} &= \frac{H\gamma_1\lambda_1 N_1(1-\mu_1)}{(1-\mu_1)(H\Psi_1 - \alpha_1\lambda_1 G_1\Phi_3) - \mu_1 H\beta_1^2 G_1)}, \ e_2^{*CS} = \frac{\gamma_2\lambda_2 N_2(1-\mu_2)}{(1-\mu_2)\Psi_2 - \mu_2\beta_2^2 G_2}, \text{ where} \\
\mu_1 &= \frac{G_1\Big(H\beta_1^2 + \alpha_1^2\lambda_1\delta(1-\epsilon^2)[C_1^2(1-2\epsilon) - (B-A)\big((B-A)\epsilon - 2C_2)\big]\Big)}{\lambda_1\Big(4H(4\alpha_1 G_1 - \gamma_1^2) - \alpha_1^2 G_1 \delta(1-\epsilon^2) X_1\Big)} \\
X_1 &= C_1^2(1-2\epsilon) + (B-A)[2(B-A_1+C_1) + \epsilon(B-A)] \text{ and } \mu_2 = \frac{\beta_2^2 G_2}{4\lambda_2(4\alpha_2 G_2 - \gamma_2^2)}.
\end{aligned}
$$

**Corollary 4.1.3.** $\frac{\partial \theta_i^{CS}}{\partial \mu_i} > 0, for\ i = 1, 2.$

It is obvious that if the retailer provides more cost sharing fraction to the manufacturer for the respective period, the manufacturer increases the greening level of the product since it diminishes the cost burden due to green innovation.

**Proposition 4.1.9.** *At the equilibrium, the optimal decisions of CS-Model and MR-Model are connected by the following relations:*

*(i)* $w_1^{CS} > w_1^{MR}$*, and* $w_2^{CS} > w_2^{MR}$*;* $p_1^{CS} > p_1^{MR}$*, and* $p_2^{CS} > p_2^{MR}$*.*

*(ii)* $\theta_1^{CS} > \theta_1^{MR}$*, and* $\theta_2^{CS} > \theta_2^{MR}$*;* $e_1^{CS} > e_1^{MR}$*, and* $e_2^{CS} > e_2^{MR}$*;* $\tau_1^{CS} > \tau_1^{MR}$*, and* $\tau_2^{CS} > \tau_2^{MR}$*.*

**Proof.** After simplification, the numerator of the difference $(w_1^{CS} - w_1^{MR})$ becomes $H\mu_1\beta_1^2 G_1\big(\lambda_1 N_1[H(4\alpha_1 G_1 - \gamma_1^2) - \alpha_1 G_1\Phi_3] + \alpha_1\lambda_1 G_1 \Phi_1(1-\epsilon^2)\big) > 0$. So, $w_1^{CS} >$

$w_1^{MR}$.
Similarly, the numerator of $(w_2^{CS} - w_2^{MR})$ becomes $\beta_2^2 G_2 \lambda_2 \mu_2 N_2 (4\alpha_2 G_2 - \gamma_2^2) > 0$. Therefore, $w_2^{CS} > w_2^{MR}$.
Again, the numerator of $\tau_1^{CS} - \tau_1^{MR}$ becomes $H\alpha_1 \beta_1^2 G_1^2 \lambda_1 N_1 \mu_1 C_1 (1 - \epsilon^2) > 0$. So, $\tau_1^{CS} > \tau_1^{MR}$. In the similar way, the remaining results can be proved. ■

Proposition 4.1.9 shows that, under cost sharing contract, the manufacturer is able to produce higher green product as compared to MR-Model. This is because, the cost sharing with the retailer helps the manufacturer to reduce the cost burden due to green innovation. The higher green product forces the manufacturer to increase the wholesale prices in both the periods which again forces the retailer to increase the selling price. The retailer simultaneously increases the marketing effort. Although the selling price increases due to higher greening level and higher marketing effort, market demand increases which increases the profits of the manufacturer, the retailer and the whole supply chain (due to algebraic complexity we prefer to show it numerically). Therefore, cost sharing is profitable for the manufacturer, the retailer and the whole supply chain and beneficial for the environment.

### 4.1.3.3 Special cases

Here, we present some special cases which can be obtained from our proposed models. Tables 4.1.1, 4.1.2, and 4.1.3 present the models without both marketing effort and greening level, with only greening level, and with only marketing effort, respectively. We use the subscripts $(\theta, e)$, $(\theta, 0)$, $(0, e)$, and $(0, 0)$ for our proposed models, the models with only greening level, the models with only marketing effort, and the models without both greening level and marketing effort, respectively.

**Table 4.1.1:** Optimal results of M, R, and MR models without both greening level and marketing effort.

| | M-Model | R-Model | MR-Model |
|---|---|---|---|
| $w_{1(0,0)}$ | $c_m + \frac{N_1(4H-\alpha_1\delta C_1^2)}{\alpha_1(8H-\alpha_1\delta C_1^2)}$ | $c_m + \frac{N_1(4H-\Phi_2)+\Phi_1}{\alpha_1(8H-\Phi_2)}$ | $c_m + \frac{N_1(4H-\Phi_3)+\Phi_1(1-\epsilon^2)}{\alpha_1(8H-\Phi_3)}$ |
| $w_{2(0,0)}$ | $c_m + \frac{N_2}{2\alpha_2}$ | $c_m + \frac{N_2}{2\alpha_2}$ | $c_m + \frac{N_2}{2\alpha_2}$ |
| $\tau_{1(0,0)}$ | $\frac{N_1 C_1}{8H-\alpha_1\delta C_1^2}$ | N/A | $\frac{N_1 C_1(1-\epsilon^2)}{8H-\Phi_3}$ |
| $p_{1(0,0)}$ | $c_m + \frac{N_1(6H-\alpha_1\delta C_1^2)}{\alpha_1(8H-\alpha_1\delta C_1^2)}$ | $c_m + \frac{N_1(6H-\Phi_2)}{\alpha_1(8H-\Phi_2)}$ | $c_m + \frac{N_1(6H-\Phi_3)}{\alpha_1(8H-\Phi_3)}$ |
| $p_{2(0,0)}$ | $c_m + \frac{3N_2}{4\alpha_2}$ | $c_m + \frac{3N_2}{4\alpha_2}$ | $c_m + \frac{3N_2}{4\alpha_2}$ |
| $\tau_{2(0,0)}$ | N/A | $\frac{N_1(B-A)}{8H-\Phi_2}$ | $\frac{N_1(B-A)(1-\epsilon^2)}{8H-\Phi_3}$ |

**Table 4.1.2:** Optimal results of M, R, and MR models with only greening level.

| | M-Model | R-Model | MR-Model |
|---|---|---|---|
| $w_{1_{(\theta,0)}}$ | $c_m + \frac{\lambda_1 N_1(4H-\alpha_1\delta C_1^2)}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1^2\lambda_1\delta C_1^2}$ | $c_m + \frac{\lambda_1 N_1(4H-\Phi_2)+\lambda_1\Phi_1}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_2}$ | $c_m + \frac{\lambda_1 N_1(4H-\Phi_3)+\lambda_1\Phi_1(1-\epsilon^2)}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3}$ |
| $w_{2_{(\theta,0)}}$ | $c_m + \frac{4\lambda_2 N_2}{8\alpha_2\lambda_2-\beta_2^2}$ | $c_m + \frac{4\lambda_2 N_2}{8\alpha_2\lambda_2-\beta_2^2}$ | $c_m + \frac{4\lambda_2 N_2}{8\alpha_2\lambda_2-\beta_2^2}$ |
| $\theta_{1_{(\theta,0)}}$ | $\frac{H\beta_1 N_1}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1^2\lambda_1\delta C_1^2}$ | $\frac{H\beta_1 N_1}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_2}$ | $\frac{H\beta_1 N_1}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3}$ |
| $\theta_{2_{(\theta,0)}}$ | $\frac{\beta_2 N_2}{8\alpha_2\lambda_2-\beta_2^2}$ | $\frac{\beta_2 N_2}{8\alpha_2\lambda_2-\beta_2^2}$ | $\frac{\beta_2 N_2}{8\alpha_2\lambda_2-\beta_2^2}$ |
| $\tau_{1_{(\theta,0)}}$ | $\frac{\alpha_1\lambda_1 N_1 C_1}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1^2\lambda_1\delta C_1^2}$ | N/A | $\frac{\alpha_1\lambda_1 N_1 C_1(1-\epsilon^2)}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3}$ |
| $p_{1_{(\theta,0)}}$ | $c_m + \frac{\lambda_1 N_1(6H-\alpha_1\delta C_1^2)}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1^2\lambda_1\delta C_1^2}$ | $c_m + \frac{\lambda_1 N_1(6H-\Phi_2)}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_2}$ | $c_m + \frac{\lambda_1 N_1(6H-\Phi_3)}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3}$ |
| $p_{2_{(\theta,0)}}$ | $c_m + \frac{6\lambda_2 N_2}{8\alpha_2\lambda_2-\beta_2^2}$ | $c_m + \frac{6\lambda_2 N_2}{8\alpha_2\lambda_2-\beta_2^2}$ | $c_m + \frac{6\lambda_2 N_2}{8\alpha_2\lambda_2-\beta_2^2}$ |
| $\tau_{2_{(\theta,0)}}$ | N/A | $\frac{\alpha_1\lambda_1 N_1(B-A)}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_2}$ | $\frac{\alpha_1\lambda_1 N_1(B-A)(1-\epsilon^2)}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3}$ |

**Table 4.1.3:** Optimal results of M, R, and MR models with only marketing effort.

| | M-Model | R-Model | MR-Model |
|---|---|---|---|
| $w_{1_{(0,e)}}$ | $c_m + \frac{N_1\left(H(4\alpha_1 G_1-\gamma_1^2)-G_1\alpha_1^2\delta C_1^2\right)}{\alpha_1\left(2H(4\alpha_1 G_1-\gamma_1^2)-G_1\alpha_1^2\delta C_1^2\right)}$ | $c_m + \frac{N_1\left(H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_2\right)+\alpha_1 G_1\Phi_1}{\alpha_1\left(2H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_2\right)}$ | $c_m + \frac{N_1\left(H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_3\right)+\alpha_1 G_1\Phi_1(1-\epsilon^2)}{\alpha_1\left(2H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_3\right)}$ |
| $w_{2_{(0,e)}}$ | $c_m + \frac{N_2}{2\alpha_2}$ | $c_m + \frac{N_2}{2\alpha_2}$ | $c_m + \frac{N_2}{2\alpha_2}$ |
| $\tau_{1_{(0,e)}}$ | $\frac{\alpha_1 G_1 N_1 C_1}{2H(4\alpha_1 G_1-\gamma_1^2)-G_1\alpha_1^2\delta C_1^2}$ | N/A | $\frac{\alpha_1 G_1 N_1 C_1(1-\epsilon^2)}{2H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_3}$ |
| $p_{1_{(0,e)}}$ | $c_m + \frac{N_1\left(H(6\alpha_1 G_1-\gamma_1^2)-G_1\alpha_1^2\delta C_1^2\right)}{\alpha_1\left(2H(4\alpha_1 G_1-\gamma_1^2)-G_1\alpha_1^2\delta C_1^2\right)}$ | $c_m + \frac{N_1\left(H(6\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_2\right)}{\alpha_1\left(2H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_2\right)}$ | $c_m + \frac{N_1\left(H(6\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_3\right)}{\alpha_1\left(2H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_3\right)}$ |
| $p_{2_{(0,e)}}$ | $c_m + \frac{N_2(6\alpha_2 G_2-\gamma_2^2)}{2\alpha_2(4\alpha_2 G_2-\gamma_2^2)}$ | $c_m + \frac{N_2(6\alpha_2 G_2-\gamma_2^2)}{2\alpha_2(4\alpha_2 G_2-\gamma_2^2)}$ | $c_m + \frac{N_2(6\alpha_2 G_2-\gamma_2^2)}{2\alpha_2(4\alpha_2 G_2-\gamma_2^2)}$ |
| $e_{1_{(0,e)}}$ | $\frac{H\gamma_1 N_1}{2H(4\alpha_1 G_1-\gamma_1^2)-G_1\alpha_1^2\delta C_1^2}$ | $\frac{H\gamma_1 N_1}{2H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_2}$ | $\frac{H\gamma_1 N_1}{2H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_3}$ |
| $e_{2_{(0,e)}}$ | $\frac{\gamma_2 N_2}{2(4\alpha_2 G_2-\gamma_2^2)}$ | $\frac{\gamma_2 N_2}{2(4\alpha_2 G_2-\gamma_2^2)}$ | $\frac{\gamma_2 N_2}{2(4\alpha_2 G_2-\gamma_2^2)}$ |
| $\tau_{2_{(0,e)}}$ | N/A | $\frac{\alpha_1 G_1 N_1(B-A)}{2H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_2}$ | $\frac{\alpha_1 G_1 N_1(B-A)(1-\epsilon^2)}{2H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_3}$ |

The relationships among the optimal decisions of the proposed models and the models under special cases are presented in Propositions 4.1.10-4.1.14.

**Proposition 4.1.10.** *The relationships among the wholesale prices in the first period are given below:*

*(i) In MR-Model, if the condition* $H \geq \frac{\alpha_1\lambda_1[\Phi_3-2\alpha_1\delta(B-A)^2(1-\epsilon^2)]}{\beta_1^2}$ *holds, then* $w^{MR}_{1_{(\theta,e)}} \geq w^{MR}_{1_{(\theta,0)}} > w^{MR}_{1_{(0,0)}} > w^{MR}_{1_{(0,e)}}$.

*Else if* $\frac{\Phi_3(\beta_1^2 G_1+\gamma_1^2\lambda_1)-(\beta_1^2 G_1+2\gamma_1^2\lambda_1)\alpha_1\delta(B-A)^2(1-\epsilon^2)}{4N_1\beta_1^2 G_1} \leq H < \frac{\alpha_1\lambda_1[\Phi_3-2\alpha_1\delta(B-A)^2(1-\epsilon^2)]}{\beta_1^2}$, *then* $w^{MR}_{1_{(\theta,0)}} > w^{MR}_{1_{(\theta,e)}} \geq w^{MR}_{1_{(0,0)}} > w^{MR}_{1_{(0,e)}}$.

*Else if* $\frac{\alpha_1 G_1[\Phi_3-\alpha_1\delta(B-A)^2(1-\epsilon^2)]}{4\alpha_1 G_1-\gamma_1^2} \leq H < \frac{\Phi_3(\beta_1^2 G_1+\gamma_1^2\lambda_1)-(\beta_1^2 G_1+2\gamma_1^2\lambda_1)\alpha_1\delta(B-A)^2(1-\epsilon^2)}{4N_1\beta_1^2 G_1}$, *then* $w^{MR}_{1_{(\theta,0)}} > w^{MR}_{1_{(0,0)}} > w^{MR}_{1_{(\theta,e)}} \geq w^{MR}_{1_{(0,e)}}$. *Otherwise,* $w^{MR}_{1_{(\theta,0)}} > w^{MR}_{1_{(0,0)}} > w^{MR}_{1_{(0,e)}} > w^{MR}_{1_{(\theta,e)}}$.

*(ii) In M-Model, if the condition* $H \geq \frac{\alpha_1^2\lambda_1\delta C_1^2}{\beta_1^2}$ *holds, then* $w^{M}_{1_{(\theta,e)}} \geq w^{M}_{1_{(\theta,0)}} > w^{M}_{1_{(0,0)}} > w^{M}_{1_{(0,e)}}$.
*Else if* $\frac{\alpha_1\delta C_1^2(\beta_1^2G_1+\gamma_1^2\lambda_1)}{4N_1\beta_1^2G_1} \leq H < \frac{\alpha_1^2\lambda_1\delta C_1^2}{\beta_1^2}$, *then* $w^{M}_{1_{(\theta,0)}} > w^{M}_{1_{(\theta,e)}} \geq w^{M}_{1_{(0,0)}} > w^{M}_{1_{(0,e)}}$.
*Else if* $\frac{\alpha_1^2G_1\delta C_1^2}{4\alpha_1G_1-\gamma_1^2} \leq H < \frac{\alpha_1\delta C_1^2(\beta_1^2G_1+\gamma_1^2\lambda_1)}{4N_1\beta_1^2G_1}$, *then* $w^{M}_{1_{(\theta,0)}} > w^{M}_{1_{(0,0)}} \geq w^{M}_{1_{(\theta,e)}} > w^{M}_{1_{(0,e)}}$.
*Otherwise,* $w^{M}_{1_{(\theta,0)}} > w^{M}_{1_{(0,0)}} > w^{M}_{1_{(0,e)}} > w^{M}_{1_{(\theta,e)}}$.

*(iii) In R-Model, if the condition* $H \geq \frac{\alpha_1\lambda_1[\Phi_2-2\alpha_1\delta(B-A)^2]}{\beta_1^2}$ *holds, then* $w^{R}_{1_{(\theta,e)}} \geq w^{R}_{1_{(\theta,0)}} > w^{R}_{1_{(0,0)}} > w^{R}_{1_{(0,e)}}$.
*Else if* $\frac{\Phi_2(\beta_1^2G_1+\gamma_1^2\lambda_1)-(\beta_1^2G_1+2\gamma_1^2\lambda_1)\alpha_1\delta(B-A)^2}{4N_1\beta_1^2G_1} \leq H < \frac{\alpha_1\lambda_1[\Phi_2-2\alpha_1\delta(B-A)^2]}{\beta_1^2}$, *then* $w^{R}_{1_{(\theta,0)}} > w^{R}_{1_{(\theta,e)}} \geq w^{R}_{1_{(0,0)}} > w^{R}_{1_{(0,e)}}$.
*Else if* $\frac{\alpha_1G_1\Phi_2-\alpha_1^2G_1\delta(B-A)^2}{4\alpha_1G_1-\gamma_1^2} \leq H < \frac{\Phi_2(\beta_1^2G_1+\gamma_1^2\lambda_1)-(\beta_1^2G_1+2\gamma_1^2\lambda_1)\alpha_1\delta(B-A)^2}{4N_1\beta_1^2G_1}$, *then* $w^{R}_{1_{(\theta,0)}} > w^{R}_{1_{(0,0)}} \geq w^{R}_{1_{(\theta,e)}} > w^{R}_{1_{(0,e)}}$. *Otherwise,* $w^{R}_{1_{(\theta,0)}} > w^{R}_{1_{(0,0)}} > w^{R}_{1_{(0,e)}} > w^{R}_{1_{(\theta,e)}}$.

**Proof.** We have

$$\begin{aligned} w^{MR}_{1_{(\theta,e)}} - w^{MR}_{1_{(\theta,0)}} &= \frac{\lambda_1N_1[H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3]+\alpha_1\lambda_1G_1\Phi_1(1-\epsilon^2)}{\alpha_1(H\Psi_1-\alpha_1\lambda_1G_1\Phi_3)} - \frac{\lambda_1N_1(4H-\Phi_3)+\lambda_1\Phi_1(1-\epsilon^2)}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3} \\ &= \frac{H\beta_1^2-\alpha_1\lambda_1\left(\Phi_3-2\alpha_1\delta(B-A)^2(1-\epsilon^2)\right)}{\alpha_1(H\Psi_1-\alpha_1\lambda_1G_1\Phi_3)(H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3)} \geq 0 \\ &\text{if } H \geq \frac{\alpha_1\lambda_1\left(\Phi_3-2\alpha_1\delta(B-A)^2(1-\epsilon^2)\right)}{\beta_1^2}. \end{aligned}$$

$$\begin{aligned} w^{MR}_{1_{(\theta,0)}} - w^{MR}_{1_{(0,0)}} &= \frac{\lambda_1N_1(4H-\Phi_3)+\lambda_1\Phi_1(1-\epsilon^2)}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3} - \frac{N_1(4H-\Phi_3)+\Phi_1(1-\epsilon^2)}{\alpha_1(8H-\Phi_3)} \\ &= \frac{HN_1\beta_1^2(4H-\Phi_3)+H\beta_1^2\Phi_1(1-\epsilon^2)}{\alpha_1(8H-\Phi_3)(H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3)} > 0. \end{aligned}$$

$$\begin{aligned} w^{MR}_{1_{(0,0)}} - w^{MR}_{1_{(0,e)}} &= \frac{N_1(4H-\Phi_3)+\Phi_1(1-\epsilon^2)}{\alpha_1(8H-\Phi_3)} - \frac{N_1[H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3]+\alpha_1G_1\Phi_1(1-\epsilon^2)}{\alpha_1\left(2H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3\right)} \\ &= \frac{HN_1\alpha_1\delta\gamma_1^2(1-\epsilon^2)[C_1^2+(B-A)(2C_2-\epsilon(B-A))]}{\alpha_1(8H-\Phi_3)\left(2H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3\right)} > 0. \end{aligned}$$

$$\begin{aligned} w^{MR}_{1_{(\theta,e)}} - w^{MR}_{1_{(0,0)}} &= \frac{\lambda_1N_1[H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3]+\alpha_1\lambda_1G_1\Phi_1(1-\epsilon^2)}{\alpha_1(H\Psi_1-\alpha_1\lambda_1G_1\Phi_3)} - \frac{N_1(4H-\Phi_3)+\Phi_1(1-\epsilon^2)}{\alpha_1(8H-\Phi_3)} \\ &= \frac{4HN_1G_1\beta_1^2-\Phi_3(\lambda_1\gamma_1^2+G_1\beta_1^2)+\alpha_1\delta(B-A)^2(1-\epsilon^2)(2\lambda_1\gamma_1^2+G_1\beta_1^2)}{\alpha_1(8H-\Phi_3)(H\Psi_1-\alpha_1\lambda_1G_1\Phi_3)} \geq 0 \\ &\text{if } H \geq \frac{\Phi_3(\lambda_1\gamma_1^2+G_1\beta_1^2)-\alpha_1\delta(B-A)^2(1-\epsilon^2)(2\lambda_1\gamma_1^2+G_1\beta_1^2)}{4N_1G_1\beta_1^2}. \end{aligned}$$

$$w^{MR}_{1_{(\theta,e)}} - w^{MR}_{1_{(0,e)}} = \frac{HN_1G_1\beta_1^2[H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3+\alpha_1^2G_1\delta(B-A)^2(1-\epsilon^2)]}{\alpha_1[2H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3](H\Psi_1-\alpha_1\lambda_1G_1\Phi_3)} \geq 0$$

if $H \geq \frac{\alpha_1 G_1\left(\Phi_3-\alpha_1\delta(B-A)^2(1-\epsilon^2)\right)}{4\alpha_1 G_1-\gamma_1^2}$.

This proves the relationship of the wholesale prices for MR-Model in the first period. The proofs of the results for M-Model and R-Model can be obtained in a similar manner. ■

Proposition 4.1.10 shows that the wholesale prices in the first period of our proposed models and the models under special cases depend on the investment coefficient $H$ for collecting used products. For a higher value of $H$, the wholesale price in the model with both greening effort and marketing effort attains the highest value. This is due to consideration of the green product and the marketing effort. According to our assumption, $H$ and $\tau$ are inversely proportional. So, when $H$ takes higher value, the collection rate of used products decreases but the manufacturer and the retailer have to invest more to collect used products. As $H$ decreases, the collection rate of used products increases. So, the manufacturer can decrease the wholesale price in the model with both greening level and marketing effort. But in the model with only greening level, the wholesale price of the product increases. In this model, the retailer does not bear the extra cost for marketing effort. So, the manufacturer increases wholesale price to gain more profit. As $H$ decreases, the wholesale price follows the above sequence, but the collection rate of used products will exceed the demand (at least theoretically), which is not acceptable. So, in numerical analysis, we'll focus on the first part of the results (*i.e.* for higher values of $H$) of all the three models.

**Proposition 4.1.11.** *The selling prices in the first period are connected by the following relationships:*

*(i) In MR-Model, if the condition* $H \geq \frac{\Phi_3}{4}$ *holds, then* $p^{MR}_{1_{(\theta,e)}} > p^{MR}_{1_{(\theta,0)}} > p^{MR}_{1_{(0,e)}} \geq p^{MR}_{1_{(0,0)}}$. *Otherwise,* $p^{MR}_{1_{(\theta,e)}} > p^{MR}_{1_{(\theta,0)}} > p^{MR}_{1_{(0,0)}} > p^{MR}_{1_{(0,e)}}$.

*(ii) In M-Model, if the condition* $H \geq \frac{\alpha_1\delta C_1^2}{4}$ *holds, then* $p^{M}_{1_{(\theta,e)}} > p^{M}_{1_{(\theta,0)}} > p^{M}_{1_{(0,e)}} \geq p^{M}_{1_{(0,0)}}$. *Otherwise,* $p^{M}_{1_{(\theta,e)}} > p^{M}_{1_{(\theta,0)}} > p^{M}_{1_{(0,0)}} > p^{M}_{1_{(0,e)}}$.

*(iii) In R-Model, if the condition* $H \geq \frac{\Phi_2}{4}$ *holds, then* $p^{R}_{1_{(\theta,e)}} > p^{R}_{1_{(\theta,0)}} > p^{R}_{1_{(0,e)}} \geq p^{R}_{1_{(0,0)}}$. *Otherwise,* $p^{R}_{1_{(\theta,e)}} > p^{R}_{1_{(\theta,0)}} > p^{R}_{1_{(0,0)}} > p^{R}_{1_{(0,e)}}$.

**Proof.** We have

$p^{MR}_{1_{(0,e)}} - p^{MR}_{1_{(0,0)}} = \frac{N_1[H(6\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_3]}{\alpha_1[2H(4\alpha_1 G_1-\gamma_1^2)-\alpha_1 G_1\Phi_3]} - \frac{N_1(6H-\Phi_3)}{\alpha_1(8H-\Phi_3)}$

$$= \frac{HN_1\gamma_1^2(4H-\Phi_3)}{\alpha_1(8H-\Phi_3)\left(2H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3\right)} \geq 0, \text{ if } H \geq \frac{\Phi_3}{4}.$$

$$p^{MR}_{1_{(\theta,0)}} - p^{MR}_{1_{(0,e)}} = \frac{\lambda_1N_1(6H-\Phi_3)}{H(8\alpha_1\lambda_1-\beta^2)-\alpha_1\lambda_1\Phi_3} - \frac{N_1[H(6\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3]}{\alpha_1[2H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3]}$$

$$= \frac{HN_1[\alpha_1(\beta_1^2G_1-\gamma_1^2\lambda_1)(4H-\Phi_3)+H\beta_1^2(2\alpha_1G_1-\gamma_1^2)]}{\alpha_1[H(8\alpha_1\lambda_1-\beta^2)-\alpha_1\lambda_1\Phi_3][2H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3]} > 0.$$

$$p^{MR}_{1_{(\theta,e)}} - p^{MR}_{1_{(\theta,0)}} = \frac{\lambda_1N_1[H(6\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3]}{\alpha_1(H\Psi_1-\alpha_1\lambda_1G_1\Phi_3)} - \frac{\lambda_1N_1(6H-\Phi_3)}{H(8\alpha_1\lambda_1-\beta^2)-\alpha_1\lambda_1\Phi_3}$$

$$= \frac{HN_1\lambda_1\gamma_1^2[\alpha_1\lambda_1(4H-\Phi_3)+H\beta_1^2]}{\alpha_1(H\Psi_1-\alpha_1\lambda_1G_1\Phi_3)(H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3)} > 0.$$

So, if $H \geq \frac{\Phi_3}{4}$, then $p^{MR}_{1_{(\theta,e)}} > p^{MR}_{1_{(\theta,0)}} > p^{MR}_{1_{(0,e)}} \geq p^{MR}_{1_{(0,0)}}$. Therefore, the selling prices in the first period in MR-Model follow the relationship as given in Proposition 4.1.11$(i)$. The proofs of the other results can be obtained in a similar manner. ■

Proposition 4.1.11 shows that, similar to the wholesale price, the selling price in the first period also depends on the value of $H$ and it increases with the inclusion of either marketing effort or greening effort or both marketing and greening efforts. The retailer always charges higher selling price in the model with both the greening effort and marketing effort, and lower selling price in the model without greening effort and marketing effort for sufficiently large value of $H$. But, for a lower value of $H$, the selling price in the model without both marketing effort and greening effort is higher than those in model with only marketing effort. For lower values of $H$, the collection rate of used products may exceed the total market demand, which is not possible. So, the selling price in the model without both greening effort and marketing effort is always lower than those of the other models.

**Proposition 4.1.12.** *If the condition* $\frac{G_1}{\lambda_1} \geq \frac{2\gamma_1^2}{\beta_1^2}$ *holds, then the collection rates of used products have the relationships as given below:*

*(i) In MR-Model,* $\tau^{MR}_{1_{(\theta,e)}} > \tau^{MR}_{1_{(\theta,0)}} \geq \tau^{MR}_{1_{(0,e)}} > \tau^{MR}_{1_{(0,0)}}$*; otherwise,* $\tau^{MR}_{1_{(\theta,e)}} > \tau^{MR}_{1_{(0,e)}} > \tau^{MR}_{1_{(\theta,0)}} > \tau^{MR}_{1_{(0,0)}}$*, and* $\tau^{MR}_{2_{(\theta,e)}} > \tau^{MR}_{2_{(\theta,0)}} \geq \tau^{MR}_{2_{(0,e)}} > \tau^{MR}_{2_{(0,0)}}$*; otherwise,* $\tau^{MR}_{2_{(\theta,e)}} > \tau^{MR}_{2_{(0,e)}} > \tau^{MR}_{2_{(\theta,0)}} > \tau^{MR}_{2_{(0,0)}}$.

*(ii) In M-Model,* $\tau^{M}_{1_{(\theta,e)}} > \tau^{M}_{1_{(\theta,0)}} \geq \tau^{M}_{1_{(0,e)}} > \tau^{M}_{1_{(0,0)}}$*. Otherwise,* $\tau^{M}_{1_{(\theta,e)}} > \tau^{M}_{1_{(0,e)}} > \tau^{M}_{1_{(\theta,0)}} > \tau^{M}_{1_{(0,0)}}$.

*(iii) In R-Model,* $\tau^{R}_{2_{(\theta,e)}} > \tau^{R}_{2_{(\theta,0)}} \geq \tau^{R}_{2_{(0,e)}} > \tau^{R}_{2_{(0,0)}}$*. Otherwise,* $\tau^{R}_{2_{(\theta,e)}} > \tau^{R}_{2_{(0,e)}} > \tau^{R}_{2_{(\theta,0)}} > \tau^{R}_{2_{(0,0)}}$.

**Proof.** We have

$$\tau^{MR}_{1_{(\theta,e)}} - \tau^{MR}_{1_{(\theta,0)}} = \frac{G_1\alpha_1\lambda_1N_1C_1(1-\epsilon^2)}{H\Psi_1-\alpha_1\lambda_1G_1\Phi_3} - \frac{\alpha_1\lambda_1N_1C_1(1-\epsilon^2)}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3}$$
$$= \frac{2H\alpha_1\lambda_1^2N_1C_1\gamma_1^2(1-\epsilon^2)}{(H\Psi_1-\alpha_1\lambda_1G_1\Phi_3)(H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3)} > 0.$$
$$\tau^{MR}_{1_{(\theta,0)}} - \tau^{MR}_{1_{(0,e)}} = \frac{\alpha_1\lambda_1N_1C_1(1-\epsilon^2)}{H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3} - \frac{G_1\alpha_1N_1C_1(1-\epsilon^2)}{2H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3}$$
$$= \frac{H\alpha_1N_1C_1(1-\epsilon^2)(G_1\beta_1^2-2\lambda_1\gamma_1^2)}{(H(8\alpha_1\lambda_1-\beta_1^2)-\alpha_1\lambda_1\Phi_3)(2H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3)} \geq 0 \text{ if } \frac{G_1}{\lambda_1} \geq \frac{2\gamma_1^2}{\beta_1^2}.$$
$$\tau^{MR}_{1_{(0,e)}} - \tau^{MR}_{1_{(0,0)}} = \frac{G_1\alpha_1N_1C_1(1-\epsilon^2)}{2H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3} - \frac{N_1C_1(1-\epsilon^2)}{8H-\Phi_3}$$
$$= \frac{2H\alpha_1N_1C_1(1-\epsilon^2)\gamma_1^2}{(2H(4\alpha_1G_1-\gamma_1^2)-\alpha_1G_1\Phi_3)(8H-\Phi_3)} > 0.$$

Therefore, the rate of collection of used products in the first period in MR-Model follows the result as given in Proposition 4.1.12$(i)$. The proofs of the results for M-Model and R-Model can be obtained in a similar manner. ■

Proposition 4.1.12 reveals that the collection rate of used products can be increased by assembling both the greening level and the marketing effort or either of the greening level and the marketing effort. That's why, a higher collection rate of used products occurs when the manufacturer is engaged in product greening and the retailer put effort in green product marketing. Otherwise, the collection rate of used products becomes lower. When the ratio of the marketing cost coefficient and green innovation cost coefficient is greater than a threshold value, the collection rate of used products in the model with only greening level is higher than that of the model with only marketing effort.

**Proposition 4.1.13.** *The wholesale prices in the second period are connected by the relations given below:*

*(i) In MR-Model,* $w^{MR}_{2_{(\theta,e)}} > w^{MR}_{2_{(\theta,0)}} > w^{MR}_{2_{(0,e)}} = w^{MR}_{2_{(0,0)}}$.

*(ii) In M-Model,* $w^{M}_{2_{(\theta,e)}} > w^{M}_{2_{(\theta,0)}} > w^{M}_{2_{(0,e)}} = w^{M}_{2_{(0,0)}}$.

*(iii) In R-Model,* $w^{R}_{2_{(\theta,e)}} > w^{R}_{2_{(\theta,0)}} > w^{R}_{2_{(0,e)}} = w^{R}_{2_{(0,0)}}$.

*and if the condition* $6\beta_2^2\alpha_2G_2 \geq \gamma_2^2(4\alpha_2\lambda_2 + \beta_2^2)$ *holds, then the selling prices in the second period are connected by the following relations:*

*(i) In MR-Model,* $p^{MR}_{2_{(\theta,e)}} > p^{MR}_{2_{(\theta,0)}} \geq p^{MR}_{2_{(0,e)}} > p^{MR}_{2_{(0,0)}}$*; otherwise,* $p^{MR}_{2_{(\theta,e)}} > p^{MR}_{2_{(0,e)}} > p^{MR}_{2_{(\theta,0)}} > p^{MR}_{2_{(0,0)}}$.

*(ii) In M-Model,* $p^{M}_{2_{(\theta,e)}} > p^{M}_{2_{(\theta,0)}} \geq p^{M}_{2_{(0,e)}} > p^{M}_{2_{(0,0)}}$*; otherwise,* $p^{M}_{2_{(\theta,e)}} > p^{M}_{2_{(0,e)}} > p^{M}_{2_{(\theta,0)}} > p^{M}_{2_{(0,0)}}$.

*(iii) In R-Model,* $p^{R}_{2_{(\theta,e)}} > p^{R}_{2_{(\theta,0)}} \geq p^{R}_{2_{(0,e)}} > p^{R}_{2_{(0,0)}}$*; otherwise,* $p^{R}_{2_{(\theta,e)}} > p^{R}_{2_{(0,e)}} > p^{R}_{2_{(\theta,0)}} > p^{R}_{2_{(0,0)}}$.

**Proof.** We have

$p^{MR}_{2_{(\theta,e)}} - p^{MR}_{2_{(\theta,0)}} = \frac{\lambda_2 N_2(6\alpha_2 G_2 - \gamma_2^2)}{\alpha_2 \Psi_2} - \frac{6\lambda_2 N_2)}{8\alpha_2\lambda_2 - \beta_2^2} = \frac{(4\alpha_2\lambda_2 + \beta_2^2)\gamma_2^2}{\alpha_2\Psi_2(8\alpha_2\lambda_2 - \beta_2^2)} > 0.$

$p^{MR}_{2_{(\theta,0)}} - p^{MR}_{2_{(0,e)}} = \frac{6\lambda_2 N_2)}{8\alpha_2\lambda_2 - \beta_2^2} - \frac{N_2(6\alpha_2 G_2 - \gamma_2^2)}{2\alpha_2(4\alpha_2 G_2 - \gamma_2^2)} = \frac{6\alpha_2 G_2 \beta_2^2 - \gamma_2^2(4\alpha_2\lambda_2 + \beta_2^2)}{2\alpha_2(4\alpha_2 G_2 - \gamma_2^2)(8\alpha_2\lambda_2 - \beta_2^2)} \geq 0,$

if $6\alpha_2 G_2 \beta_2^2 - \gamma_2^2(4\alpha_2\lambda_2 + \beta_2^2) > 0$.

$p^{MR}_{2_{(0,e)}} - p^{MR}_{2_{(0,0)}} = \frac{N_2(6\alpha_2 G_2 - \gamma_2^2)}{2\alpha_2(4\alpha_2 G_2 - \gamma_2^2)} - \frac{M_2 + 2d_2}{4\alpha_2} = \frac{N_2\gamma_2^2}{4\alpha_2(4\alpha_2 G_2 - \gamma_2^2)} > 0.$

Therefore, the selling price of MR-Model in the second period follows the result as given in Proposition 4.1.13($i$). The proofs of the results for M-Model and R-Model can be obtained in a similar manner. The results for wholesale prices in the second period can be obtained similarly. ■

In case of wholesale price, it is higher in the model with both the greening level and the marketing effort. The models with only marketing effort, and without greening level and marketing effort have the same wholesale price in the second period and it is lower than that of the model with only greening level. If the condition given in Proposition 4.1.13 holds, then the selling price in the second period follows the similar pattern as that of the first period.

**Proposition 4.1.14.** *The greening level and the marketing effort in the first and second periods are related as given below:*

*(i) In MR-Model,* $\theta^{MR}_{1_{(\theta,e)}} > \theta^{MR}_{1_{(\theta,0)}}$, $e^{MR}_{1_{(\theta,e)}} > e^{MR}_{1_{(0,e)}}$ *and* $\theta^{MR}_{2_{(\theta,e)}} > \theta^{MR}_{2_{(\theta,0)}}$, $e^{MR}_{2_{(\theta,e)}} > e^{MR}_{2_{(0,e)}}$.

*(ii) In M-Model,* $\theta^{M}_{1_{(\theta,e)}} > \theta^{M}_{1_{(\theta,0)}}$, $e^{M}_{1_{(\theta,e)}} > e^{M}_{1_{(0,e)}}$ *and* $\theta^{M}_{2_{(\theta,e)}} > \theta^{M}_{2_{(\theta,0)}}$, $e^{M}_{2_{(\theta,e)}} > e^{M}_{2_{(0,e)}}$.

*(iii) In R-Model,* $\theta^{R}_{1_{(\theta,e)}} > \theta^{R}_{1_{(\theta,0)}}$, $e^{R}_{1_{(\theta,e)}} > e^{R}_{1_{(0,e)}}$ *and* $\theta^{R}_{2_{(\theta,e)}} > \theta^{R}_{2_{(\theta,0)}}$, $e^{R}_{2_{(\theta,e)}} > e^{R}_{2_{(0,e)}}$.

**Proof.** The proof being straight forward, it is omitted. ■

Proposition 4.1.14 shows that the greening level and the marketing effort in both the periods attain the highest value in the model with both greening level and marketing effort and this is an obvious result. So, the models with both the greening level and the marketing effort are more encouraging.

From Propositions 4.1.10-4.1.14, one can easily note that if the manufacturer and the retailer exert effort in green innovation and marketing, respectively, then the environment-friendly customers can spend higher money while buying green product without thinking more about the brand. It also helps the channel members to collect more used products. So, it will help the channel members economically by increasing profit (through demand increase), and environmentally by improving greening level and reducing used products (through collection effort increase).

### 4.1.4 Numerical analysis

In this section, we consider a numerical example and analyze the optimal results of different models proposed. As it is difficult to get access to the actual industry data, we consider the following parameter-values which agree with the assumptions of our study: $d_1 = 80; d_2 = 70; \alpha_1 = 0.23; \alpha_2 = 0.22; \beta_1 = 0.8; \beta_2 = 0.65; \gamma_1 = 0.78; \gamma_2 = 0.63; c_m = 70; c_r = 35; A = 20; B = 25; \lambda_1 = 10; \lambda_2 = 6; G_1 = 12; G_2 = 8; H = 1200; \delta = 0.8; \rho = 0.35; w_R = 100; \epsilon = 0.2;$ in appropriate units.

**Table 4.1.4:** Optimal results of the proposed models.

| Optimal results | C-Model | MR-Model | M-Model | R-Model | CS-Model |
|---|---|---|---|---|---|
| $w_1$ | - | 210.102 | 210.787 | 213.392 | 210.265 |
| $w_2$ | - | 199.585 | 199.585 | 199.585 | 199.710 |
| $p_1$ | 217.859 | 288.710 | 289.066 | 290.119 | 288.966 |
| $p_2$ | 213.690 | 268.249 | 268.249 | 268.249 | 268.439 |
| $\theta_1$ | 6.92553 | 3.15013 | 3.13116 | 3.07501 | 3.24719 |
| $\theta_2$ | 7.78319 | 3.71929 | 3.71929 | 3.71929 | 3.80349 |
| $e_1$ | 5.62700 | 2.55948 | 2.54406 | 2.49845 | 2.56247 |
| $e_2$ | 5.65778 | 2.70364 | 2.70364 | 2.70364 | 2.70623 |
| $\tau_1$ | - | 0.24996 | 0.25881 | - | 0.25026 |
| $\tau_2$ | - | 0.03623 | - | 0.03684 | 0.03627 |
| $\tau$ | 0.91590 | 0.28619 | 0.25881 | 0.03684 | 0.28652 |
| $\Pi_m$ | - | 4015.78 | 4000.63 | 3955.78 | 4020.16 |
| $\Pi_r$ | - | 2117.06 | 2114.69 | 2066.05 | 2117.18 |
| $\Pi$ | 8669.95 | 6132.84 | 6115.31 | 6021.84 | 6137.34 |

Table 4.1.4 presents the optimal results of the proposed models under centralized, decentralized and cost sharing scenarios. As usual, the centralized model gives the best performance. Due to non-existence of double-marginalization effect, the

centralized decision-maker sells the green product of higher greening level at the lowest price in both the periods. It is also noted that the greening level in the second period is higher than that in the first period. This is because of remanufacturing. This result is contrary to the result of Wei et al. (2018), who showed that the manufacturer sells the lower green products at higher price in the second period. This observation is not consistent with the reality. The customers may disagree to buy lower green products by paying higher price in the second period. So, the second period may not be suitable for business. But our results show that the customers may wait for the second period for buying higher green products in lower price. So, second period always exists. The marketing effort and collection rate of used products are also higher in the centralized scenario and all these efforts are more than doubled compared to the decentralized models. Due to lower selling prices, higher marketing effort and higher greening level, the market demand increases and consequently, the entire channel profit increases. Different options for collecting used products have significant effect on consumer surplus. When the retailer only collects used products, the manufacturer charges higher wholesale price for lower green product. The retailer also charges higher selling price with lower marketing effort. But when both the manufacturer and the retailer collect used products, the manufacturer demands lower wholesale price for higher green product. So, the retailer also charges lower selling price with higher marketing effort. It is noted that individual collection rates of used products to the manufacturer and the retailer in case of dual collection mode are lower than those under single collection mode. This phenomena is similar to the result of Wei et al. (2018). This is probably because of the competition between them while collecting used products. But total collection rate of used products is higher in dual-collection mode. This means that the dual-collection option increases consumer surplus, and it is preferable for social welfare and environmental protection. Due to higher customer demand, profits of the manufacturer, the retailer and the whole supply chain increase. Thus, the dual-collection mode is also profitable for both individuals and the whole supply chain. It is also noted that optimal decisions in the second period are independent of the collection option of the manufacturer. As the manufacturer has to spend greening cost, he always wants the retailer to bear some cost. The greening level in CS-Model increases as cost sharing helps to reduce the cost burden due to green production. Although the customers have to pay more for higher green product, due to higher greening level and higher marketing effort, the market demand increases and as a result, profits of the manufacturer, the retailer, and the whole supply chain increase. While comparing CS-Model with the centralized model, we note that the cost sharing contract fails to coordinate the supply chain but it can help the manufacturer and the retailer to achieve the win-win situation.

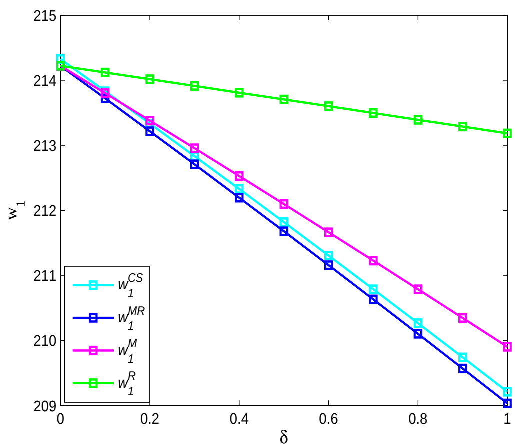
**Table 4.1.5:** Optimal results of the MR-Model.

| Optimal results | $(\theta, e)$ | $(\theta, 0)$ | $(0, e)$ | $(0, 0)$ |
|---|---|---|---|---|
| $w_1$ | 210.102 | 210.032 | 204.786 | 205.020 |
| $w_2$ | 199.585 | 199.263 | 194.091 | 194.091 |
| $p_1$ | 288.710 | 284.017 | 280.412 | 276.357 |
| $p_2$ | 268.249 | 263.894 | 259.843 | 256.136 |
| $\theta_1$ | 3.15013 | 2.96487 | - | - |
| $\theta_2$ | 3.71929 | 3.50086 | - | - |
| $e_1$ | 2.55948 | - | 2.46237 | - |
| $e_2$ | 2.70364 | - | 2.58900 | - |
| $\tau_1$ | 0.24996 | 0.23526 | 0.24048 | 0.22684 |
| $\tau_2$ | 0.03623 | 0.03410 | 0.03485 | 0.03288 |
| $\tau$ | 0.28619 | 0.26936 | 0.27533 | 0.25972 |
| $\Pi_m$ | 4015.78 | 3779.74 | 3856.73 | 3638.50 |
| $\Pi_r$ | 2117.06 | 1986.58 | 1952.76 | 1840.96 |
| $\Pi$ | 6132.84 | 5766.32 | 5809.49 | 5479.46 |

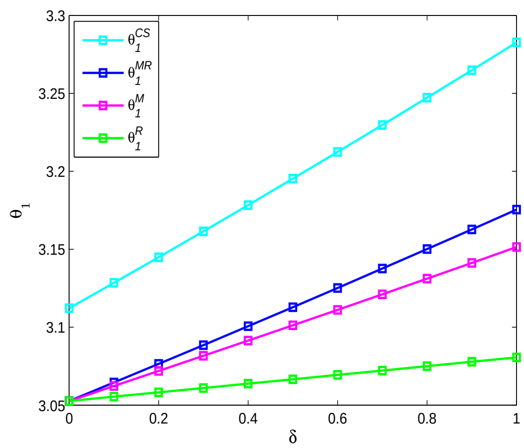
Table 4.1.5 represents the optimal results of the proposed MR-Model and the three special cases. It is noted that the wholesale price in the first period is higher in MR-Model $(\theta, e)$ followed by the wholesale prices in models $(\theta, 0)$, $(0, 0)$, and $(0, e)$. This result verifies Proposition 4.1.10. However, for the second period, it takes the same value in models $(0, e)$ and $(0, 0)$. This result verifies Proposition 4.1.13. Note that the selling price is higher in MR-Model and lower in model $(0, 0)$ for both the periods, which verifies Propositions 4.1.11 and 4.1.13. Optimal collection rate of used products in both the periods follow the similar pattern as the selling prices. Profits of the manufacturer, the retailer, and the whole supply chain also follow the pattern of the selling prices and the collection rate of used products. Thus, it appears that dual-collection option is profitable and preferable under consideration of both greening level and marketing effort.

## 4.1.5 Sensitivity analysis

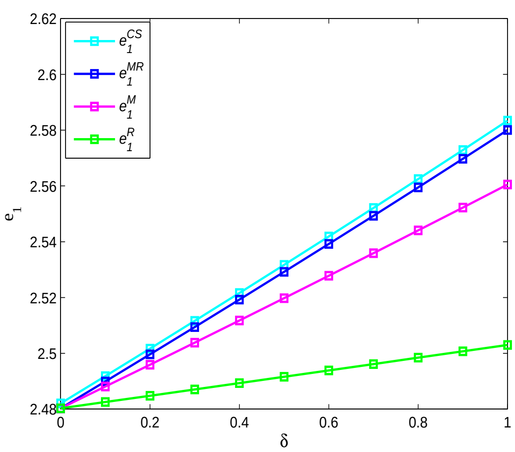
In this section, we investigate the effect of key model-parameters on the optimal results in the first period. We examine the impact of one parameter at a time on the optimal results by keeping all other parameter-values unchanged. Figs. 4.1.2-4.1.4 represent the sensitivity of the parameters $\delta$, $H$, and $\gamma_1$ and $G_1$.



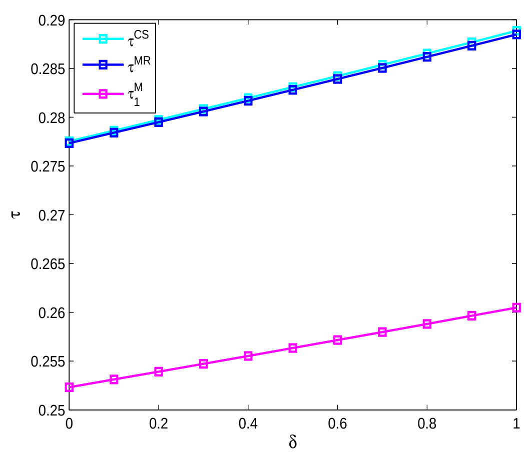

(a) $\delta$ vs wholesale price.




(b) $\delta$ vs greening level.




(c) $\delta$ vs marketing effort.




(d) $\delta$ vs collection effort.

**Fig. 4.1.2:** Change (%) in optimal results w.r.t. $\delta$.

From **Fig. 4.1.2**, we can draw the following observations:

- As the common discount factor $\delta$ in the second period increases, the wholesale price decreases and the rate of decrease is faster in MR-Model. Initially, the wholesale price in CS-Model attains the maximum value. But, as $\delta$ increases, the wholesale price in R-Model reaches the maximum value and the rate of decrease becomes slower. When $\delta$ crosses the value 0.1, the wholesale price in M-Model becomes higher than that in CS-Model. The selling price being proportional to the wholesale price, it also follows the similar pattern. We omit the graphs of selling prices in this study (see Fig. 4.1.2(a)).

- The greening level increases with $\delta$. The rate of increment is maximum in CS-Model and greening level gets the maximum value in this model. For lower value of $\delta$, the greening level attains the least value in M-Model. As $\delta$ increases, the greening level becomes lower in R-Model (see Fig. 4.1.2(b)). The marketing effort follows the similar pattern as the greening level (see Fig. 4.1.2(c)).

- As $\delta$ increases, the collection rate of used products also increases. As the rate of increase is negligible in R-Model, so we omit that graph. Total collection rate of used products is higher in CS-Model and lowest in R-Model (see Fig. 4.1.2(d)).

Due to lower selling price, and higher marketing effort and greening level, the market demand increases. As a result, profits of both individuals increase. Therefore, overall profit of the supply chain also increases in all the models.

The following observations can be made from **Fig. 4.1.3**:

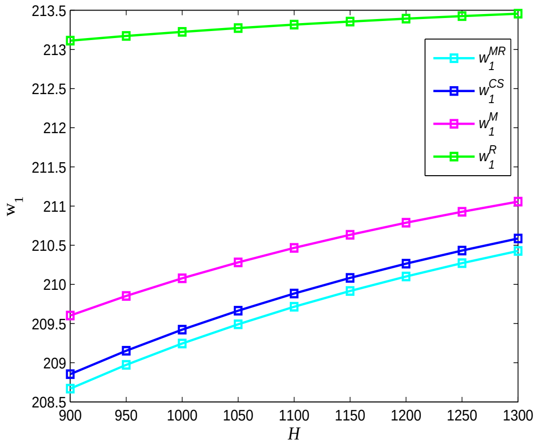
- As the investment coefficient $H$ for collecting used product increases, the wholesale price increases in all models. It attains the maximum value in R-Model and the minimum value in MR-Model (see Fig. 4.1.3(a)).

- The greening level decreases with $H$. The rate of decrease is higher in CS-Model than the other models. It attains the maximum value in CS-Model and the minimum value in R-Model (see Fig. 4.1.3(b)). The marketing effort follows the similar pattern as the greening level (see Fig. 4.1.3(c)).

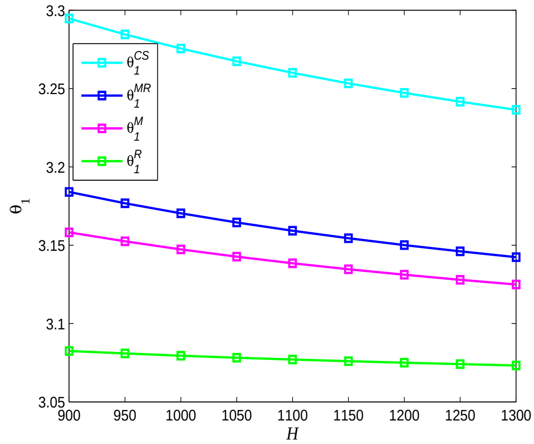
- As $H$ increases, the collection rate of used products decreases. Similar to the greening level, the rate of decrease is higher in CS-Model and MR-Model (see Fig. 4.1.3(d)).

Due to higher selling price, and lower marketing effort and greening level, the market demand decreases. As a result, profits of both individuals decrease. Thus, the total profit of the whole supply chain also decreases.

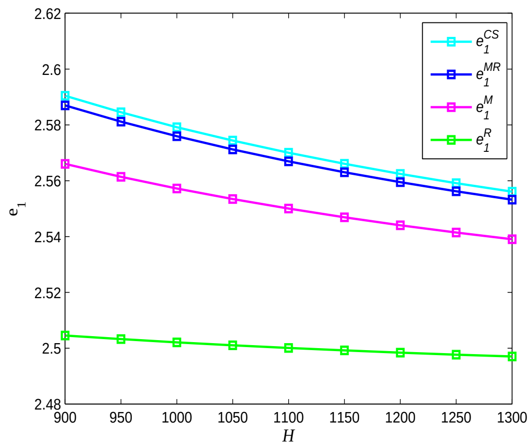
The following conclusions can be drawn from **Fig. 4.1.4**:



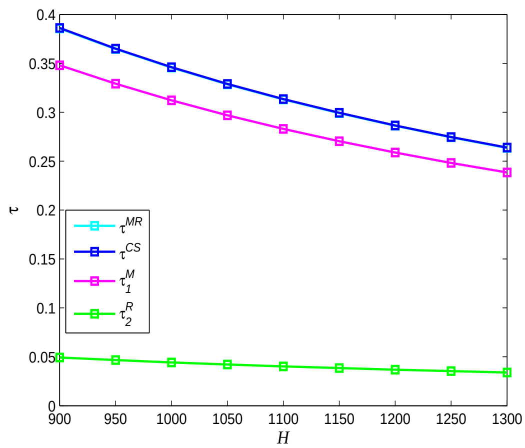

(a) $H$ vs wholesale price.




(b) $H$ vs greening level.




(c) $H$ vs marketing effort.



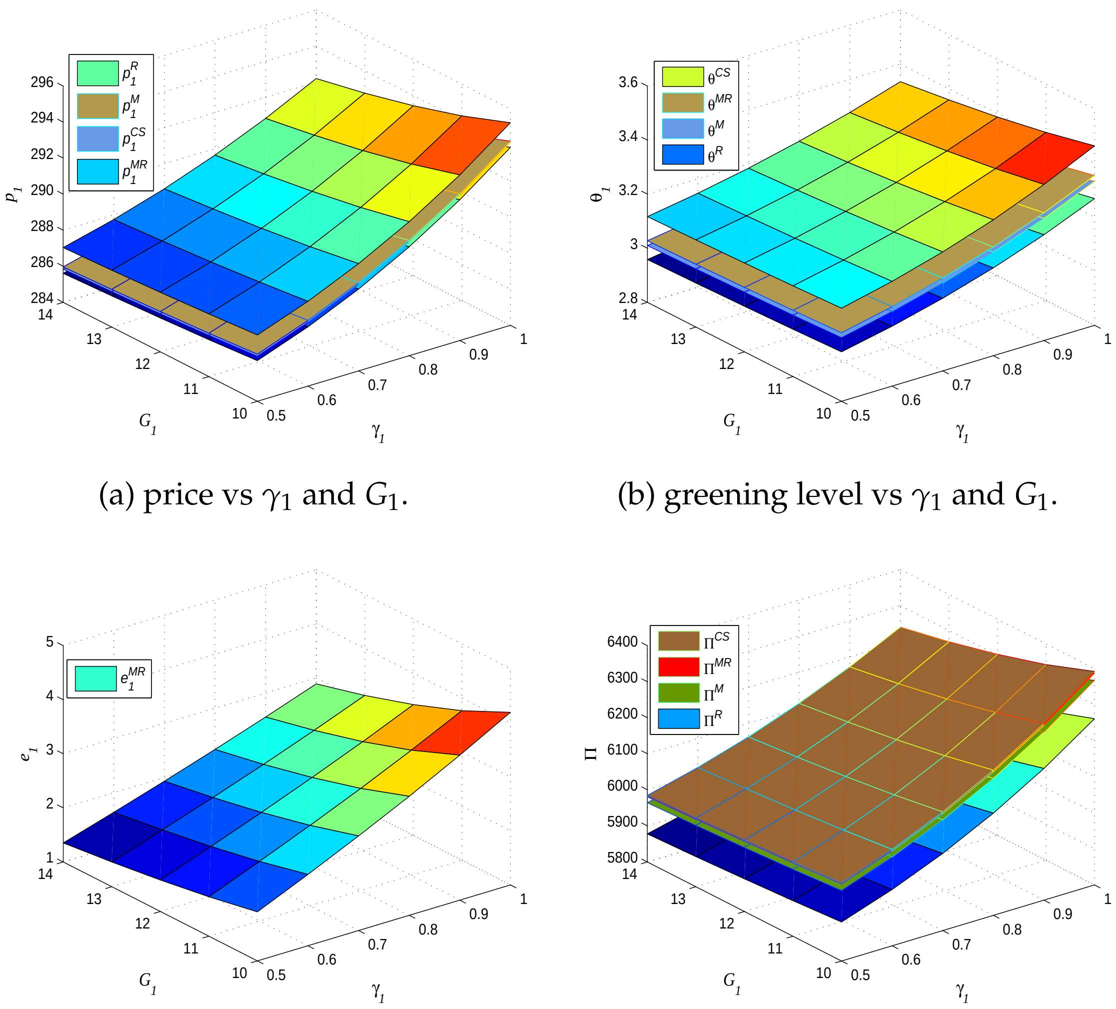

(d) $H$ vs collection effort.

**Fig. 4.1.3:** Change (%) in optimal results w.r.t. $H$.

- As the marketing effort sensitivity coefficient $\gamma_1$ in the first period increases, the selling price in all models increases. But the selling price decreases with the investment coefficient for marketing effort $G_1$, although we cannot observe it in open eyes from the graph (see Fig. 4.1.4(a)).

- The greening level of the product also increases with $\gamma_1$. Similar to other cases, it has the maximum value in CS-Model and the minimum value in R-Model. However, the greening level decreases with $G_1$ although the rate of decrease is negligible (see Fig. 4.1.4(b)).

- The marketing effort increases rapidly with $\gamma_1$ and decreases with $G_1$. As the marketing effort takes similar values in all the models, for clear representation




(a) price vs $\gamma_1$ and $G_1$.

(b) greening level vs $\gamma_1$ and $G_1$.

(c) marketing effort vs $\gamma_1$ and $G_1$.

(d) profit vs $\gamma_1$ and $G_1$.

**Fig. 4.1.4:** Change (%) in optimal results w.r.t. $\gamma_1$ and $G_1$.

here we present the graph of MR-Model only (see Fig. 4.1.4(c)).

- Although the selling price increases, due to higher marketing effort and greening level, the market demand increases with $\gamma_1$. Therefore, profits of the manufacturer, the retailer, and the whole supply chain increase. However, profits of the manufacturer, the retailer, and the whole supply chain decrease with $G_1$ (see Fig. 4.1.4(d)).

# 4.2

# *Strategies in a green closed-loop supply chain under retailer's fairness behavior*

This study considers a two-tier supply chain, where the manufacturer puts effort into product greening and the retailer exerts effort into marketing those products, under product recycling and retailer's fairness concern. Depending on the retailer's fairness behavior, two decentralized models are developed, each of which is again subdivided into three models under consideration of different options of used product collection. As an extension of the previous work in this chapter, here we consider the effects of collecting used products through the third-party collector. The centralized model is presented as a benchmark case. Finally, a restitution-based wholesale price contract is proposed for channel coordination. The main goal of this study is to find the answer to the following research questions:

- Which is the best reverse channel from the manufacturer, the retailer, and the customers' perspective?
- What are the effects of the retailer's fairness concern on the optimal decisions and profitability of the channel members?
- Is the proposed contract able to coordinate the supply chain perfectly?

## 4.2.1 Assumptions and notations

In addition to the common assumptions, the following assumptions are made for developing the proposed models:

**(1)** Following the common assumptions, the market demand takes the form $D(p,\theta,e) = D_0 - \alpha p + \beta\theta + \gamma e$, where $\alpha$, $\beta$, and $\gamma$ are the price sensitivity

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factor, the greening level sensitivity factor, and the marketing effort sensitivity factor of the market demand, respectively (Chen and Akmalul'Ulya, 2019). For the rest of the study, $D(p, \theta, e)$ and $D$ will be interchangeable.

**(2)** In general, it is not always possible to collect all the used products. So, the return quantity is taken as a fraction of total demand *i.e.* $D_r = \tau D$, where $0 < \tau < 1$ (Savaskan et al., 2004).

**(3)** In order to ensure the positivity of the optimal results, the parameters $\lambda, \eta$, and $H$ are so chosen that $\lambda > \frac{\beta^2}{2\alpha}, \eta > \frac{\gamma^2}{2\alpha}, H > \frac{\alpha(X-A)^2}{2}$, and $\lambda(2\alpha\eta - \gamma^2) - \eta\beta^2 > 0$.

The required notations used for establishing the proposed models are presented in Table 4.2.1.

**Table 4.2.1:** Decision variables and parameters.

| Notations | Description |
|---|---|
| Decision variables | |
| $w$ | unit wholesale price of the manufacturer. |
| $p$ | unit selling price of the retailer. |
| $\theta$ | level of green innovation. |
| $e$ | marketing effort level of the retailer. |
| $\tau$ | collection rate of used products. |
| Parameters | |
| $D_0$ | basic market demand. |
| $D$ | market demand. |
| $D_r$ | return quantity. |
| $c_m(c_r)$ | unit manufacturing (remanufacturing) cost of the new (returned) product. |
| $\rho$ | fraction of remanufactured products available for selling in the primary market. |
| $w_R$ | unit selling price of the remanufactured product in the secondary market. |
| $\lambda$ | green investment-related cost coefficient. |
| $\eta$ | marketing effort-related cost coefficient. |
| $H$ | collection cost coefficient. |
| $A$ | unit price paid to the customer for used products. |
| $B$ | unit transfer price of the used products ($B > A$). |
| $\Pi_i^j$ | profit function where superscript $j$ denotes the supply chain models ($j = C, MN, RN, TN, MF, RF, TF, CO$) while the subscript $i$ denotes the supply chain members and the entire supply chain, respectively ($i = m, r, t, w$). |
| $(.)^j$ | optimal decisions under model $j$. |

## 4.2.2 Model development and analysis

In this section, we develop the centralized model as the benchmark case and three decentralized models with different options for collecting used products. Before discussing our main models *i.e.* models under fairness behavior (see Fig. 4.2.1), we first discuss models without retailer's fairness behavior. The availability of used product in the primary market is depicted in Fig. 4.2.2. In all the proposed models, the manufacturer as the Stackelberg leader first decides his decisions. After that, the retailer and/or the third-party simultaneously decide their decisions.

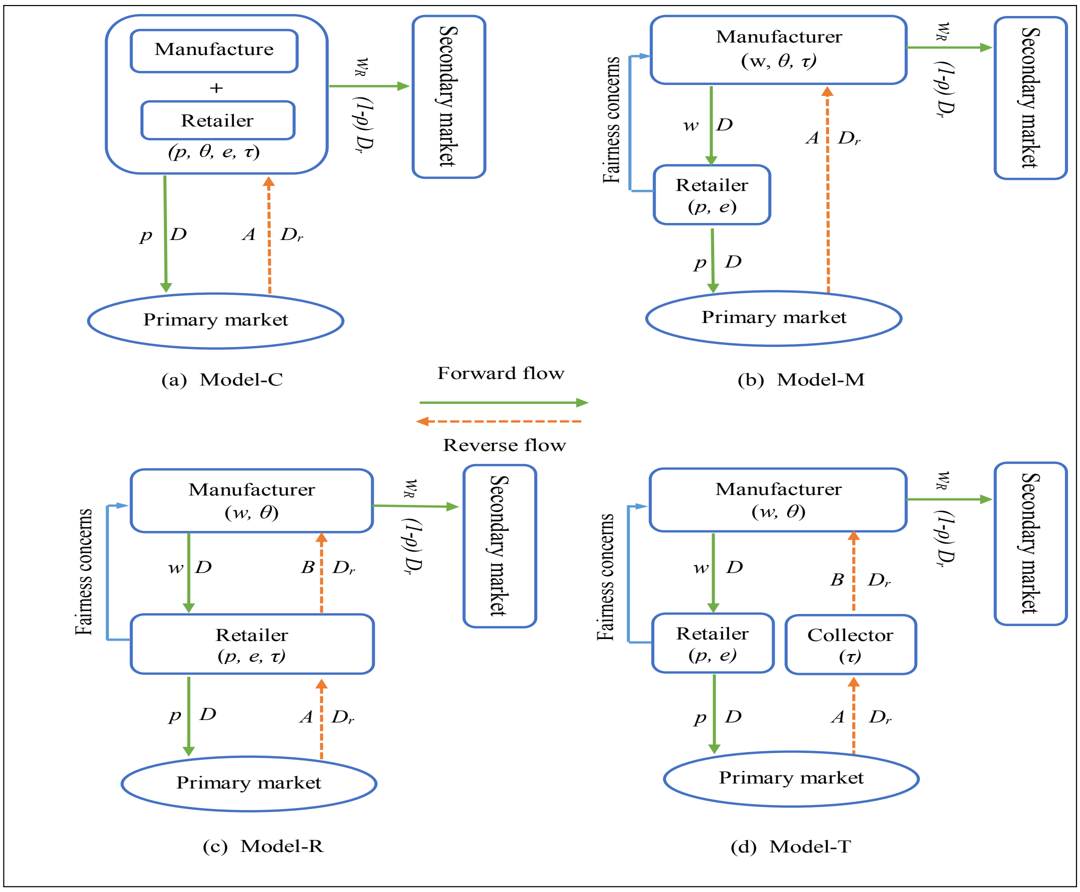



**Fig. 4.2.1:** Proposed closed-loop supply chain models.

### 4.2.2.1 *The centralized model (Model-C)*

In the centralized model, all the supply chain members work as a single decision-making entity whose goal is to elevate the entire supply chain's profit with respect to all the decisions viz. selling price $p$, greening level $\theta$, marketing effort $e$, and collection rate of used products $\tau$. As the single decision-making entity is handling

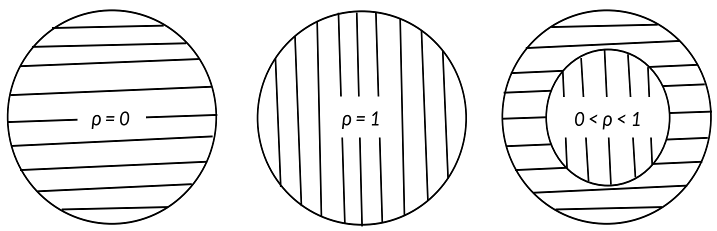



**Fig. 4.2.2:** Availability of remanufactured products in the primary market.

all decisions, the internal transfer prices $w$ and $B$ have no role in this model (see Fig. 4.2.1(a)). Hence, the objective function of Model-C is given by

$$\max_{(p,\theta,e,\tau)} \Pi_w^C = pD - c_m(D-\rho D_r) - (c_r+A)D_r + w_R(1-\rho)D_r - \lambda\theta^2 - \eta e^2 - H\tau^2 \tag{4.2.1}$$

Here, the first term is the sales revenue obtained from selling the green product in the primary market. The second and third terms are respectively the manufacturing and the remanufacturing (including acquisition price) costs. The revenue obtained from selling low standard remanufactured products in the secondary market is represented by the fourth term and the remaining terms are respectively green investment cost, marketing effort-related cost, and collection-related cost.

**Lemma 4.2.1.** *The profit function $\Pi_w^C$ of Model-C is jointly concave in $p$, $\theta$, $e$ and $\tau$.*

**Proof.** $\frac{\partial \Pi_w^C}{\partial p} = D_0 - 2\alpha p + \beta\theta + \gamma e + \alpha[c_m - \tau(X-A)]$; $\frac{\partial^2 \Pi_w^C}{\partial p^2} = -2\alpha < 0$,
$\frac{\partial \Pi_w^C}{\partial \theta} = \beta[p - c_m + \tau(X-A)] - 2\lambda\theta$; $\frac{\partial^2 \Pi_w^C}{\partial \theta^2} = -2\lambda < 0$,
$\frac{\partial \Pi_w^C}{\partial e} = \gamma[p - c_m + \tau(X-A)] - 2\eta e$; $\frac{\partial^2 \Pi_w^C}{\partial e^2} = -2\eta < 0$,
$\frac{\partial \Pi_w^C}{\partial \tau} = (X-A)(D_0 - \alpha p + \beta\theta + \gamma e) - 2H\tau$; $\frac{\partial^2 \Pi_w^C}{\partial \tau^2} = -2H < 0$,
$\frac{\partial^2 \Pi_w^C}{\partial p \partial \theta} = \beta$; $\frac{\partial^2 \Pi_w^C}{\partial p \partial e} = \gamma$; $\frac{\partial^2 \Pi_w^C}{\partial p \partial \tau} = -\alpha(X-A)$; $\frac{\partial^2 \Pi_w^C}{\partial e \partial \theta} = 0$; $\frac{\partial^2 \Pi_w^C}{\partial \tau \partial \theta} = \beta(X-A)$; $\frac{\partial^2 \Pi_w^C}{\partial \tau \partial e} = \gamma(X-A)$.

The corresponding Hessian matrix associated with $\Pi_w^C$ is given by

$$H^C = \begin{pmatrix} \frac{\partial^2 \Pi_w^C}{\partial p^2} & \frac{\partial^2 \Pi_w^C}{\partial p \partial \theta} & \frac{\partial^2 \Pi_w^C}{\partial p \partial e} & \frac{\partial^2 \Pi_w^C}{\partial p \partial \tau} \\ \frac{\partial^2 \Pi_w^C}{\partial \theta \partial p} & \frac{\partial^2 \Pi_w^C}{\partial \theta^2} & \frac{\partial^2 \Pi_w^C}{\partial \theta \partial e} & \frac{\partial^2 \Pi_w^C}{\partial \theta \partial \tau} \\ \frac{\partial^2 \Pi_w^C}{\partial e \partial p} & \frac{\partial^2 \Pi_w^C}{\partial e \partial \theta} & \frac{\partial^2 \Pi_w^C}{\partial e^2} & \frac{\partial^2 \Pi_w^C}{\partial e \partial \tau} \\ \frac{\partial^2 \Pi_w^C}{\partial \tau \partial p} & \frac{\partial^2 \Pi_w^C}{\partial \tau \partial \theta} & \frac{\partial^2 \Pi_w^C}{\partial \tau \partial e} & \frac{\partial^2 \Pi_w^C}{\partial \tau^2} \end{pmatrix}$$

$$= \begin{pmatrix} -2\alpha & \beta & \gamma & -\alpha(X-A) \\ \beta & -2\lambda & 0 & \beta(X-A) \\ \gamma & 0 & -2\eta & \gamma(X-A) \\ -\alpha(X-A) & \beta(X-A) & \gamma(X-A) & -2H \end{pmatrix}$$

The principal minors are: $|M_1| = -2\alpha < 0$, $|M_2| = 4\alpha\lambda - \beta^2 > 0$, as $\lambda > \frac{\beta^2}{2\alpha}$, $|M_3| = -2[4\alpha\lambda\eta - (\lambda\gamma^2 + \eta\beta^2)] < 0$, as $2\alpha\lambda\eta - (\lambda\gamma^2 + \eta\beta^2) > 0$ and $|H^C| = 4\big[H\big(\lambda(4\alpha\eta - \gamma^2) - \eta\beta^2\big) - \alpha^2\eta\lambda(X-A)^2\big] > 0$, as $H\big(\lambda(4\alpha\eta - \gamma^2) - \eta\beta^2\big) - \alpha^2\eta\lambda(X-A)^2 = \alpha\lambda\eta[2H - \alpha(X-A)^2] + H[2\alpha\lambda\eta - (\lambda\gamma^2 + \eta\beta^2)] > 0$. Therefore, the Hessian matrix $H^C$ is negative definite *i.e.* the profit function $\Pi_w^C$ is jointly concave with respect to $p$, $\theta$, $e$ and $\tau$, which proves Lemma 4.2.1. ■

Since the profit function is jointly concave, optimal decisions of Model-C (which can be obtained through utilizing the first order necessary conditions for optimality of the objective function (4.2.1)) are given as follows:

$$\begin{aligned} p^C &= \frac{D_0\eta\lambda\big(2H - \alpha(X-A)^2\big) + Hc_m\big(\lambda(2\alpha\eta - \gamma^2) - \eta\beta^2\big)}{H\big(\lambda(4\alpha\eta - \gamma^2) - \eta\beta^2\big) - \alpha^2\eta\lambda(X-A)^2}, \\ \theta^C &= \frac{\beta\eta H(D_0 - c_m\alpha)}{H\big(\lambda(4\alpha\eta - \gamma^2) - \eta\beta^2\big) - \alpha^2\eta\lambda(X-A)^2}, \\ e^C &= \frac{\gamma\lambda H(D_0 - c_m\alpha)}{H\big(\lambda(4\alpha\eta - \gamma^2) - \eta\beta^2\big) - \alpha^2\eta\lambda(X-A)^2}, \\ \tau^C &= \frac{\alpha\eta\lambda X(D_0 - c_m\alpha)}{H\big(\lambda(4\alpha\eta - \gamma^2) - \eta\beta^2\big) - \alpha^2\eta\lambda(X-A)^2}. \end{aligned}$$

With these values of optimal decisions, the optimal market demand, return quantity, and the profit of the entire supply chain are given by
$D^C = \frac{2\alpha\lambda\eta H(D_0 - c_m\alpha)}{H\big(\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-\alpha^2\eta\lambda(X-A)^2}$, $D_r^C = \frac{2\alpha^2\lambda^2\eta^2 H(X-A)(D_0-c_m\alpha)^2}{[H\big(\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-\alpha^2\eta\lambda(X-A)^2]^2}$,
$\Pi_w^C = \frac{\lambda\eta H(D_0-c_m\alpha)^2}{H\big(\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-\alpha^2\eta\lambda(X-A)^2}$.

**Corollary 4.2.1.** *The assumption 3 ensures the positivity of the optimal results but it does not guarantee that $\tau < 1$. In order to satisfy the condition $\tau^C < 1$, the collection cost coefficient should be large enough such that $H > \frac{\alpha\eta\lambda(X-A)\big((D_0-c_m\alpha)+\alpha(X-A)\big)}{\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2}$.*

**Corollary 4.2.2.** *The optimal decisions of Model-C follow the following properties:*

1. $\frac{\partial\theta^C}{\partial\beta} > 0$; $\frac{\partial p^C}{\partial\beta} > 0$; $\frac{\partial e^C}{\partial\beta} > 0$; $\frac{\partial\tau^C}{\partial\beta} > 0$.
2. $\frac{\partial\theta^C}{\partial\gamma} > 0$; $\frac{\partial p^C}{\partial\gamma} > 0$; $\frac{\partial e^C}{\partial\gamma} > 0$; $\frac{\partial\tau^C}{\partial\gamma} > 0$.
3. $\frac{\partial\theta^C}{\partial\lambda} < 0$; $\frac{\partial p^C}{\partial\lambda} < 0$; $\frac{\partial e^C}{\partial\lambda} < 0$; $\frac{\partial\tau^C}{\partial\lambda} < 0$.

4. $\frac{\partial \theta^C}{\partial \eta} < 0$; $\frac{\partial p^C}{\partial \eta} < 0$; $\frac{\partial e^C}{\partial \eta} < 0$; $\frac{\partial \tau^C}{\partial \eta} < 0$.

5. $\frac{\partial \theta^C}{\partial H} < 0$; $\frac{\partial p^C}{\partial H} > 0$; $\frac{\partial e^C}{\partial H} < 0$; $\frac{\partial \tau^C}{\partial H} < 0$.

Corollary 4.2.2 shows that the greening level and the marketing effort sensitivity coefficients have a positive effect on optimal decisions of Model-C. It is conspicuous that if the customers are more sensitive towards the greening level of the product and the marketing effort of the retailer, they abdicate the product with a lower greening level from the retailer who applies less effort in marketing that product. So, the greening level of the product and the marketing effort of the retailer increase. Higher greening level and marketing effort demand higher selling price. It is also observed that the collection rate of used products enhances with these coefficients. If the channel members invest more for improving their respective efforts then they require to put less efforts. So, when green innovation and marketing effort-related costs increase, optimal decisions of the channel members tend to decrease. Similar to the green innovation and marketing effort-related costs, if the used products collection cost increases, the collection rate of used products also decreases. At the same time, the greening level and the marketing effort also drop. Due to the higher collection price, in this case, the centralized decision-maker charges a higher selling price to maintain the profitability of the entire supply chain.

### 4.2.2.2 Decentralized models

In the decentralized scenario, members of the supply chain work independently and optimize their decisions by maximizing their individual profits. In the following, we develop two models – 'A. The retailer is not concerned about fairness behavior' and 'B. The retailer is concerned about fairness behavior'. Each of these two models again contains three models depending on used products collection strategy.

#### A. The retailer is not concerned about fairness behavior

*I. Used products collection through the manufacturer (Model-MN)*

In Model-MN, besides producing and selling the green product to the retailer in the forward channel, the manufacturer directly collects used products from the end-customers through the reverse channel. The retailer delivers those products in the primary market (see Fig. 4.2.1(b)). Hence, the objective functions of the manufacturer and the retailer in Model-MN are given by

$$\max_{(w,\theta,\tau)} \Pi_m^{MN} = (w - c_m)D + (X - A)D_r - \lambda\theta^2 - H\tau^2, \quad (4.2.2)$$

$$\max_{(p,e)} \Pi_r^{MN} = (p - w)D - \eta e^2 \quad (4.2.3)$$

**Lemma 4.2.2.** *For given $w$, $\theta$, and $\tau$, the profit function $\Pi_r^{MN}$ of the retailer in Model-MN is jointly concave in $p$ and $e$.*

**Proof.** $\frac{\partial \Pi_r^{MN}}{\partial p} = D_0 - 2\alpha p + \beta\theta + \gamma e + \alpha w$; $\frac{\partial^2 \Pi_r^{MN}}{\partial p^2} = -2\alpha < 0$,
$\frac{\partial \Pi_r^{MN}}{\partial e} = \gamma(p - w) - 2\eta e$; $\frac{\partial^2 \Pi_r^{MN}}{\partial e^2} = -2\eta < 0$; $\frac{\partial^2 \Pi_r^{MN}}{\partial e \partial p} = \gamma < 0$.
The Hessian matrix associated with $\Pi_r^{MN}$ is given by

$$H_R^{MN} = \begin{pmatrix} \frac{\partial^2 \Pi_r^{MN}}{\partial p^2} & \frac{\partial^2 \Pi_r^{MN}}{\partial p \partial e} \\ \frac{\partial^2 \Pi_r^{MN}}{\partial e \partial p} & \frac{\partial^2 \Pi_r^{MN}}{\partial e^2} \end{pmatrix} = \begin{pmatrix} -2\alpha & \gamma \\ \gamma & -2\eta \end{pmatrix}$$

The principal minors are: $|M_1| = -2\alpha < 0$ and $|H_R^{MN}| = 4\alpha\eta - \gamma^2 > 0$, as $\eta > \frac{\gamma^2}{2\alpha}$. Therefore, the Hessian matrix $H_R^{MN}$ is negative definite *i.e.* the profit function $\Pi_r^{MN}$ is jointly concave in $p$ and $e$, which proves Lemma 4.2.2. ■

There exist unique values of $p$ and $e$, which can be obtained from utilizing first order necessary conditions for optimality. So, optimal decisions of the retailer are

$$p(w,\theta) = \frac{2\eta(D_0 + \alpha w + \beta\theta) - w\gamma^2}{4\alpha\eta - \gamma^2}, \quad e(w,\theta) = \frac{\gamma(D_0 - \alpha w + \beta\theta)}{4\alpha\eta - \gamma^2}.$$

**Corollary 4.2.3.** *The optimal selling price and the marketing effort obey the following properties:*

1. $\frac{\partial p}{\partial w} > 0$; $\frac{\partial p}{\partial \theta} > 0$.

2. $\frac{\partial e}{\partial w} < 0$; $\frac{\partial e}{\partial \theta} > 0$.

Corollary 4.2.3 indicates that an increase in both the wholesale price and the greening level of the product increases the selling price, which is quite obvious. An increase in the greening level implies that the manufacturer has to invest more in green innovation. In order to maintain profitability, he has to enhance the wholesale price of the product. A higher wholesale price of the product forces the retailer to set a higher selling price. As the manufacturer exerts more effort in green innovation, the retailer also promotes the marketing effort. Again, if the retailer has to buy the product by paying a higher wholesale price, she shows less interest in enhancing the marketing effort. The increasing (decreasing) rate of the marketing effort depends on the greening level (selling price) sensitivity coefficient of the market demand.

With these reactions of the retailer, the manufacturer determines his decisions by optimizing the objective function (4.2.2) and it leads to the following lemma:

**Lemma 4.2.3.** *The profit function $\Pi_m^{MN}$ of the manufacturer in Model-MN is jointly concave in $w$, $\theta$, and $\tau$.*

**Proof.** With the optimal decisions of the retailer, the manufacturer's profit function becomes

$$\Pi_m^{MN} = \frac{2\alpha\eta(D_0 - \alpha w + \beta\theta)[w - c_m + \tau(X - A)]}{4\alpha\eta - \gamma^2} - \lambda\theta^2 - H\tau^2$$

Now,

$\frac{\partial^2\Pi_m^{MN}}{\partial w^2} = -\frac{4\alpha^2\eta}{4\alpha\eta-\gamma^2} < 0;\ \frac{\partial^2\Pi_m^{MN}}{\partial\theta^2} = -2\lambda < 0;\ \frac{\partial^2\Pi_m^{MN}}{\partial\tau^2} = -2H < 0,$

$\frac{\partial^2\Pi_m^{MN}}{\partial w\partial\theta} = \frac{2\alpha\beta\eta}{4\alpha\eta-\gamma^2};\ \frac{\partial^2\Pi_m^{MN}}{\partial w\partial\tau} = -\frac{2\alpha^2\eta(X-A)}{4\alpha\eta-\gamma^2};\ \frac{\partial^2\Pi_m^{MN}}{\partial\tau\partial\theta} = \frac{2\alpha\beta\eta(X-A)}{4\alpha\eta-\gamma^2}.$

The Hessian matrix associated with $\Pi_m^{MN}$ is given by

$$H_M^{MN} = \begin{pmatrix} -\frac{4\alpha^2\eta}{4\alpha\eta-\gamma^2} & \frac{2\alpha\beta\eta}{4\alpha\eta-\gamma^2} & -\frac{2\alpha^2\eta(X-A)}{4\alpha\eta-\gamma^2} \\ \frac{2\alpha\beta\eta}{4\alpha\eta-\gamma^2} & -2\lambda & \frac{2\alpha\beta\eta(X-A)}{4\alpha\eta-\gamma^2} \\ -\frac{2\alpha^2\eta(X-A)}{4\alpha\eta-\gamma^2} & \frac{2\alpha\beta\eta(X-A)}{4\alpha\eta-\gamma^2} & -2H \end{pmatrix}$$

The principal minors are: $|M_1| = -\frac{4\alpha^2\eta}{4\alpha\eta-\gamma^2} < 0$; $|M_2| = \frac{4\alpha^2\eta[2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2]}{(4\alpha\eta-\gamma^2)^2} > 0$ and $|H_M^{MN}| = \frac{-8\alpha^2\eta\left[H\left(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right)-\alpha^2\lambda\eta(X-A)^2\right]}{(4\alpha\eta-\gamma^2)^2} < 0$ (due to the condition of Corollary 4.2.1). Thus, the Hessian matrix $H_M^{MN}$ is negative definite *i.e.* the profit function $\Pi_m^{MN}$ is jointly concave in $w$, $\theta$, and $\tau$, which proves Lemma 4.2.3. ■

The optimal values of the manufacturer's decision variables can be obtained by utilizing the first order necessary conditions for optimality of the manufacturer's objective function. The optimal decisions of the manufacturer and the retailer are summarized as follows:

$$\begin{aligned}
w^{MN} &= \frac{D_0\lambda\left[H(4\alpha\eta-\gamma^2)-\alpha^2\eta(X-A)^2\right]+Hc_m\alpha\left[\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right]}{\alpha\left[H\left(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]}, \\
\theta^{MN} &= \frac{\beta\eta H(D_0-c_m\alpha)}{H\left(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2}, \\
\tau^{MN} &= \frac{\alpha\eta\lambda(X-A)(D_0-c_m\alpha)}{H\left(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2}, \\
p^{MN} &= \frac{D_0\lambda\left[H(6\alpha\eta-\gamma^2)-\alpha^2\eta(X-A)^2\right]+Hc_m\alpha\left[\lambda(2\alpha\eta-\gamma^2)-\eta\beta^2\right]}{\alpha\left[H\left(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]}, \\
e^{MN} &= \frac{\alpha\eta\lambda(D_0-c_m\alpha)}{H\left(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2}.
\end{aligned}$$

With these optimal decisions, the optimal market demand, return quantity and profits of the manufacturer, the retailer, and the entire supply chain for Model-MN are given by

$D^{MN} = \frac{2\alpha\lambda\eta H(D_0 - c_m\alpha)}{H\left(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2}$, $D_r^{MN} = \frac{2\alpha^2\lambda^2\eta^2 H(X-A)(D_0-c_m\alpha)^2}{\left[H\left(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]^2}$,

$\Pi_m^{MN} = \frac{\lambda\eta H(D_0-c_m\alpha)^2}{H\left(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2}$, $\Pi_r^{MN} = \frac{\lambda^2\eta H^2(4\alpha\eta-\gamma^2)(D_0-c_m\alpha)^2}{\left[H\left(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]^2}$,

$\Pi_w^{MN} = \frac{\lambda\eta H(D_0-c_m\alpha)^2\left[H\left(3\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]}{\left[H\left(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]^2}$.

**Corollary 4.2.4.** *The optimal wholesale price, profits of the manufacturer and the retailer in Model-MN obey the following properties:*

1. $\frac{\partial w^{MN}}{\partial \beta} > 0$; $\frac{\partial \Pi_m^{MN}}{\partial \beta} > 0$; $\frac{\partial \Pi_r^{MN}}{\partial \beta} > 0$.
2. $\frac{\partial w^{MN}}{\partial \gamma} > 0$; $\frac{\partial \Pi_m^{MN}}{\partial \gamma} > 0$; $\frac{\partial \Pi_r^{MN}}{\partial \gamma} > 0$.
3. $\frac{\partial w^{MN}}{\partial \lambda} < 0$; $\frac{\partial \Pi_m^{MN}}{\partial \lambda} < 0$; $\frac{\partial \Pi_r^{MN}}{\partial \lambda} < 0$.
4. $\frac{\partial w^{MN}}{\partial \eta} < 0$; $\frac{\partial \Pi_m^{MN}}{\partial \eta} < 0$; $\frac{\partial \Pi_r^{MN}}{\partial \eta} < 0$.
5. $\frac{\partial w^{MN}}{\partial H} > 0$; $\frac{\partial \Pi_m^{MN}}{\partial H} < 0$; $\frac{\partial \Pi_r^{MN}}{\partial H} < 0$.

Different model-parameters have a similar effect on the optimal decisions of Model-MN as described in Model-C. So, in this case, we omit those results. We know that when customers are more sensitive towards the greening level and the marketing effort, the greening level and the marketing effort increase. As green innovation needs more investment, the manufacturer has to increase the wholesale price of the product. A higher wholesale price improves the manufacturer's earning, and a higher greening level and a higher marketing effort promote the market demand. As a result, profits of the manufacturer and the retailer increase. But higher green investment costs, marketing effort, and collection effort costs pull the profits of the channel members.

*II. Used products collection through the retailer (Model-RN)*

In Model-RN, the retailer has a dual job, one in the forward logistics and another in the reverse logistics. In the forward logistics, the retailer purchases the green product from the manufacturer and sells it in the primary market. In the reverse logistics, she collects used products from end-customers at $A$ per unit and transfers them to the manufacturer in return for transfer price $B$ per unit (see Fig. 4.2.1(c)). The objective functions of the manufacturer and the retailer for Model-RN are given by

$$\begin{aligned}\max_{(w,\theta)} \Pi_m^{RN} &= (w-c_m)D + (X-B)D_r - \lambda\theta^2, && (4.2.4)\\ \max_{(p,e,\tau)} \Pi_r^{RN} &= (p-w)D + (B-A)D_r - \eta e^2 - H\tau^2 && (4.2.5)\end{aligned}$$

**Lemma 4.2.4.** *For given $w$ and $\theta$, the profit function $\Pi_r^{RN}$ of the retailer in Model-RN is jointly concave in $p$, $e$, and $\tau$.*

**Proof.** The proof is similar to the case of Model-MN. ■

There exist unique values of $p$, $e$, and $\tau$, which can be obtained from the first order necessary conditions for optimality. The optimal decisions of the retailer are

$$\begin{aligned}p(w,\theta) &= \frac{\eta(D_0+\beta\theta)[2H-\alpha(B-A)^2] + Hw(2\alpha\eta-\gamma^2)}{H(4\alpha\eta-\gamma^2)-\alpha^2\eta(B-A)^2},\\ e(w,\theta) &= \frac{\gamma H(D_0-\alpha w+\beta\theta)}{H(4\alpha\eta-\gamma^2)-\alpha^2\eta(B-A)^2},\quad \tau(w,\theta) = \frac{\alpha\eta(B-A)(D_0-\alpha w+\beta\theta)}{H(4\alpha\eta-\gamma^2)-\alpha^2\eta(B-A)^2}.\end{aligned}$$

After getting the retailer's reactions, the manufacturer determines his decisions through optimizing the objective function (4.2.4) and it leads to the following lemma:

**Lemma 4.2.5.** *The profit function $\Pi_m^{RN}$ of the manufacturer in Model-RN is jointly concave in $w$ and $\theta$ .*

**Proof.** The proof is similar to the case of Model-MN. ■

The optimal decisions of the manufacturer and the retailer are summarized as follows:

$$\begin{aligned}w^{RN} &= \frac{\begin{pmatrix} D_0\lambda\left[H(4\alpha\eta-\gamma^2)-\alpha^2\eta(B-A)(C_1+C_2)\right] \\ +c_m\alpha\left[H\big(\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-\alpha^2\eta\lambda(B-A)^2\right]\end{pmatrix}}{\alpha\left[H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-A)(B-A)\right]},\\ \theta^{RN} &= \frac{\beta\eta H(D_0-c_m\alpha)}{H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-A)(B-A)},\\ p^{RN} &= \frac{D_0\lambda\left[H(6\alpha\eta-\gamma^2)-2\alpha^2\eta(B-A)(X-A)\right]+c_m\alpha H\left[\big(\lambda(2\alpha\eta-\gamma^2)-\eta\beta^2\big)\right]}{\alpha\left[H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-A)(B-A)\right]},\\ e^{RN} &= \frac{\gamma\lambda H(D_0-c_m\alpha)}{H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-A)(B-A)},\\ \tau^{RN} &= \frac{\alpha\eta\lambda(B-A)(D_0-c_m\alpha)}{H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-A)(B-A)}.\end{aligned}$$

With these decision variables, the optimal demand, return quantity and profits of the manufacturer, the retailer, and the entire supply chain for Model-RN are given by

$$\begin{aligned}
D^{RN} &= \frac{2\alpha\lambda\eta H(D_0 - c_m\alpha)}{H\big(2\lambda(4\alpha\eta - \gamma^2) - \eta\beta^2\big) - 2\alpha^2\eta\lambda(X-A)(B-A)},\\
D_r^{RN} &= \frac{2\alpha^2\lambda^2\eta^2 H(B-A)(D_0 - c_m\alpha)^2}{\big[H\big(2\lambda(4\alpha\eta - \gamma^2) - \eta\beta^2\big) - 2\alpha^2\eta\lambda(X-A)(B-A)\big]^2},\\
\Pi_m^{RN} &= \frac{\lambda\eta H(D_0 - c_m\alpha)^2}{H\big(2\lambda(4\alpha\eta - \gamma^2) - \eta\beta^2\big) - 2\alpha^2\eta\lambda(X-A)(B-A)},\\
\Pi_r^{RN} &= \frac{\lambda^2\eta H\big(H(4\alpha\eta - \gamma^2) - \alpha^2\eta(B-A)^2\big)(D_0 - c_m\alpha)^2}{\big[H\big(2\lambda(4\alpha\eta - \gamma^2) - \eta\beta^2\big) - 2\alpha^2\eta\lambda(X-A)(B-A)\big]^2},\\
\Pi_w^{RN} &= \frac{\lambda\eta H(D_0 - c_m\alpha)^2\big[H\big(3\lambda(4\alpha\eta - \gamma^2) - \eta\beta^2\big) - \alpha^2\eta\lambda(B-A)(2X+B-A)\big]}{\big[H\big(2\lambda(4\alpha\eta - \gamma^2) - \eta\beta^2\big) - 2\alpha^2\eta\lambda(X-A)(B-A)\big]^2}.
\end{aligned}$$

### *III. Used products collection through the third-party (Model-TN)*

In Model-TN, the manufacturer outsources the collection activity to an independent third-party, who collects used products from end-customers by paying a price of $A$ per unit and transfers it to the manufacturer at a transfer price of $B$ per unit (see Fig. 4.2.1(d)). This type of collection activity is common in metal, plastic, paper, and glass industries. The objective functions of the manufacturer, the retailer, and the third-party for Model-TN are given by

$$\max_{(w,\theta)} \Pi_m^{TN} = (w - c_m)D + (X-B)D_r - \lambda\theta^2, \tag{4.2.6}$$

$$\max_{(p,e)} \Pi_r^{TN} = (p - w)D - \eta e^2, \text{ and} \tag{4.2.7}$$

$$\max_{(\tau)} \Pi_t^{TN} = (B-A)D_r - H\tau^2 \tag{4.2.8}$$

Similar to Model-MN, in this case also the retailer determines her optimal decisions (selling price and marketing effort) through maximizing her own profit. Based on this, the third-party ascertains the optimal collection effort. The optimal values of $p$ and $e$ can be obtained from the first order necessary conditions for optimality of Eq. (4.2.7) and that of $\tau$ (since $\frac{\partial^2\Pi_t^{TN}}{\partial\tau^2} = -2H < 0$) can be obtained from the first order necessary conditions for optimality of Eq. (4.2.8). The optimal decisions of the retailer and the third-party are given by

$$\begin{aligned}
p(w,\theta) &= \frac{2\eta(D_0 + \alpha w + \beta\theta) - w\gamma^2}{4\alpha\eta - \gamma^2}, \quad e(w,\theta) = \frac{\gamma(D_0 - \alpha w + \beta\theta)}{4\alpha\eta - \gamma^2},\\
\tau(w,\theta) &= \frac{\alpha\eta(B-A)(D_0 - \alpha w + \beta\theta)}{4\alpha\eta - \gamma^2}.
\end{aligned}$$

After getting these reactions of the retailer and the third-party, the manufacturer determines his optimal decisions by optimizing the objective function (4.2.6). The optimal decisions of the manufacturer, the retailer, and the third-party are summarized as follows:

$$
\begin{aligned}
w^{TN} &= \frac{D_0\lambda\left[H(4\alpha\eta-\gamma^2)-2\alpha^2\eta(B-A)(X-B)\right]+c_m\alpha H\left[\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\right]}{\alpha\left[H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-B)(B-A)\right]},\\
\theta^{TN} &= \frac{\beta\eta H(D_0-c_m\alpha)}{H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-B)(B-A)},\\
p^{TN} &= \frac{D_0\lambda\left[H(6\alpha\eta-\gamma^2)-2\alpha^2\eta(B-A)(X-B)\right]+c_m\alpha H\left[\big(\lambda(2\alpha\eta-\gamma^2)-\eta\beta^2\big)\right]}{\alpha\left[H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-B)(B-A)\right]},\\
e^{TN} &= \frac{\gamma\lambda H(D_0-c_m\alpha)}{H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-B)(B-A)},\\
\tau^{TN} &= \frac{\alpha\eta\lambda(B-A)(D_0-c_m\alpha)}{H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-B)(B-A)}.
\end{aligned}
$$

Then the optimal market demand, return quantity and profits of the manufacturer, the retailer, and the entire supply chain for Model-TN are given by

$$
\begin{aligned}
D^{TN} &= \frac{2\alpha\lambda\eta H(D_0-c_m\alpha)}{H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-B)(B-A)},\\
D_r^{TN} &= \frac{2\alpha^2\lambda^2\eta^2 H(B-A)(D_0-c_m\alpha)^2}{\left[H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-B)(B-A)\right]^2},\\
\Pi_m^{TN} &= \frac{\lambda\eta H(D_0-c_m\alpha)^2}{H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-B)(B-A)},\\
\Pi_r^{TN} &= \frac{\lambda^2\eta H^2\big(H(4\alpha\eta-\gamma^2)-\alpha^2\eta(B-A)^2\big)(D_0-c_m\alpha)^2}{\left[H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-B)(B-A)\right]^2},\\
\Pi_t^{TN} &= \frac{\alpha^2\lambda^2\eta^2 H(B-A)^2(D_0-c_m\alpha)^2}{\left[H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-B)(B-A)\right]^2},\\
\Pi_w^{TN} &= \frac{\lambda\eta H(D_0-c_m\alpha)^2\left[H\big(3\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-\alpha^2\eta\lambda(B-A)(2X-3B+A)\right]}{\left[H\big(2\lambda(4\alpha\eta-\gamma^2)-\eta\beta^2\big)-2\alpha^2\eta\lambda(X-B)(B-A)\right]^2}.
\end{aligned}
$$

### B. The retailer is concerned about fairness behavior

Here, we consider the situation when the retailer is concerned about the fairness of the business *i.e.* she does not prefer any decision which produces either higher or lower profit than her desired equitable reference point. We assume that $\epsilon\Pi_m$ is the equitable reference point of the retailer, where $\epsilon > 0$ is the equitable payoff parameter. If $\epsilon\Pi_m > \Pi_r$, it will be disadvantageous inequality while $\epsilon\Pi_m < \Pi_r$ will be an advantageous inequality for the retailer. In our model, as the manufacturer is the leader, we consider only disadvantageous inequality. Therefore, following

Wang et al. (2019b), the utility function of the fairness concerned retailer is taken as $\hat{U}_r = \Pi_r - \xi_1(\epsilon\Pi_m - \Pi_r) = (1+\xi_1)\Pi_r - \xi_1\epsilon\Pi_m$, where $\xi_1 > 0$ is the fairness concern parameter. A large value of $\xi_1$ implies that the retailer is more concerned about fairness behavior. In order to avoid complexity in calculation, following Qian et al. (2020), we consider $\xi = \frac{\xi_1\epsilon}{1+\xi_1}$. Then the utility function of the retailer will take the form $U_r = \frac{\hat{U}_r}{1+\xi_1} = \Pi_r - \xi\Pi_m$, where $0 \le \xi \le 1$. The optimal results for different models under retailer's fairness concern *i.e.* Model-MF, Model-RF, and Model-TF are presented in Table 4.2.2.

## 4.2.3 Comparative analysis

This section compares optimal outcomes of the proposed models to get some insights. Comparing optimal results, we get the following propositions.

**Proposition 4.2.1.** *If the condition* $B \ge \frac{HX\left(2\lambda\Psi_1-\eta\beta^2\right)+\alpha^2\eta\lambda A(X-A)^2}{H\left(2\lambda\Psi_1-\eta\beta^2\right)+\alpha^2\eta\lambda(X-A)^2}$ *holds, then the optimal collection rate of used products follows the pattern* $\tau^C > \tau^{RN} \ge \tau^{MN} > \tau^{TN}$*; otherwise,* $\tau^C > \tau^{MN} > \tau^{RN} > \tau^{TN}$.

**Proof.** On simplification,

$$\tau^C - \tau^{RN} = \frac{\alpha\eta\lambda(D_0-c_m\alpha)\left[H\left(\lambda\Psi_1(2X-B-A)-(X-B)\eta\beta^2\right)-\alpha^2\eta\lambda(B-A)(X-A)^2\right]}{\left[H\left(\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0.$$

$$\tau^{RN} - \tau^{MN} = \frac{\alpha\eta\lambda(D_0-c_m\alpha)\left[H(X-B)\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(B-A)(X-A)^2\right]}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0,$$

if $B > \frac{HX\left(2\lambda\Psi_1-\eta\beta^2\right)+\alpha^2\eta\lambda A(X-A)^2}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)+\alpha^2\eta\lambda(X-A)^2\right]}$.

$$\tau^{MN} - \tau^{TN} = \frac{\alpha\eta\lambda(D_0-c_m\alpha)\left[H(X-B)\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(B-A)(X-A)(2B-X-A)\right]}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0. \qquad \blacksquare$$

From Proposition 4.2.1, it is observed that the collection rate is higher in the centralized model. Due to the fact of joint decision-making, the collector can exert more effort into collecting used products. Among the decentralized models, Model-TN has the lowest collection rate of used products, as the marginal benefit of the third-party from collecting used products in Model-TN is lower than that of the manufacturer in Model-MN (*i.e.* $B - A < X - A$). Which one of Model-MN and Model-RN can collect a higher amount of used products that depends on how much transfer price the manufacturer pays to the retailer. If the manufacturer pays a lower amount of transfer price, then the manufacturer should manipulate the collection activity himself rather than transferring it to the retailer. But a higher amount of

**Table 4.2.2:** Optimal results under retailer's fairness concern.

| | Model-MF | Model-RF | Model-TF |
|---|---|---|---|
| $w^*$ | $\frac{D_0\lambda\left[H\Psi_1-\alpha^2\eta(X-A)^2\right]+Hc_m\alpha\left[\lambda(1+2\xi)\Psi_1-\eta\beta^2\right]}{\alpha\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]}$ | $\frac{D_0\lambda\left[H\Psi_1-\alpha^2\eta\Psi_2\left(\Psi_2+2(1+\xi)(X-B)\right)\right]+c_m\alpha\left[H\left(\lambda\Psi_1(1+2\xi)-\eta\beta^2\right)-\alpha^2\eta\lambda\Psi_2\left(\Psi_2+2\xi(B-A)\right)\right]}{\alpha\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1+\xi)(X-A)\Psi_2\right]}$ | $\frac{D_0\lambda\left[H\Psi_1-2\alpha^2\eta\Psi_3\right]+c_m\alpha\left[H\left(\lambda(1+2\xi)\Psi_1-\eta\beta^2\right)+2\alpha^2\eta\lambda\xi^2\Psi_3\right]}{\alpha\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1-\xi^2)\Psi_3\right]}$ |
| $p^*$ | $\frac{D_0\lambda\left[H(6\alpha\eta-\gamma^2)(1+\xi)-\alpha^2\eta(X-A)^2\right]+Hc_m\alpha\left[\lambda(1+\xi)(2\alpha\eta-\gamma^2)-\eta\beta^2\right]}{\alpha\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]}$ | $\frac{D_0\lambda(1+\xi)\left[H(6\alpha\eta-\gamma^2)+2\alpha^2\eta(X-A)\Psi_2\right]+c_m\alpha H\left[\lambda(2\alpha\eta-\gamma^2)(1+\xi)-\eta\beta^2\right]}{\alpha\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1+\xi)(X-A)\Psi_2\right]}$ | $\frac{D_0\lambda\left[H(6\alpha\eta-\gamma^2)(1+\xi)-2\alpha^2\eta(1-\xi^2)\Psi_3\right]+c_m\alpha H\left[\lambda(2\alpha\eta-\gamma^2)(1+\xi)-\eta\beta^2\right]}{\alpha\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1-\xi^2)\Psi_3\right]}$ |
| $\theta^*$ | $\frac{\beta\eta H\Psi_4}{H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2}$ | $\frac{\beta\eta H\Psi_4}{\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1+\xi)(X-A)\Psi_2\right]}$ | $\frac{\beta\eta H\Psi_4}{\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1-\xi^2)\Psi_3\right]}$ |
| $e^*$ | $\frac{\alpha\eta\lambda(1+\xi)\Psi_4}{H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2}$ | $\frac{\gamma\lambda H(1+\xi)\Psi_4}{\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1+\xi)(X-A)\Psi_2\right]}$ | $\frac{\gamma\lambda H(1+\xi)\Psi_4}{\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1-\xi^2)\Psi_3\right]}$ |
| $\tau^*$ | $\frac{\alpha\eta\lambda(X-A)\Psi_4}{H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2}$ | $\frac{\alpha\eta\lambda(1+\xi)\Psi_2\Psi_4}{\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1+\xi)(X-A)\Psi_2\right]}$ | $\frac{\alpha\lambda\eta(B-A)(1+\xi)\Psi_4}{\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1-\xi^2)\Psi_3\right]}$ |
| $\Pi_m^*$ | $\frac{\lambda\eta H\Psi_4^2}{H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2}$ | $\frac{\lambda\eta H\Psi_4^2}{\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1+\xi)(X-A)\Psi_2\right]}$ | $\frac{D\eta\lambda H(1+\xi)\Psi_4^2}{\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1-\xi^2)\Psi_3\right]}$ |
| $\Pi_r^*$ | $\frac{\lambda^2\eta H^2\Psi_1\Psi_4^2(1+\xi)(1+3\xi)}{[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2]^2}$ | $\frac{\lambda^2\eta H(1+\xi)\Psi_4^2\left[H\Psi_1(1+3\xi)+\alpha^2\eta\Psi_2\left((B-A)(1+3\xi)+(X-B)\xi(1-\xi)\right)\right]}{\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1+\xi)(X-A)\Psi_2\right]^2}$ | $\frac{\lambda^2\eta H(1+\xi)\left(H\Psi_1(1+3\xi)+4\alpha^2\eta\xi^2\Psi_3\right)\Psi_4^2}{\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1-\xi^2)\Psi_3\right]^2}$ |
| $\Pi_t^*$ | — | — | $\frac{\alpha^2\lambda^2\eta^2H(1+\xi)^2(B-A)^2\Psi_4^2}{\left[H\left(2\lambda\Psi_1(1+\xi)-\eta\beta^2\right)-2\alpha^2\eta\lambda(1-\xi^2)\Psi_3\right]^2}$ |

Note: $\Psi_1=(4\alpha\eta-\gamma^2)$; $\Psi_2=(B-A)-(X-B)\xi$; $\Psi_3=(B-A)(X-B)$; $\Psi_4=D_0-c_m\alpha$.

transfer price encourages the retailer in collecting used products as it can improve her profitability. As a result, the collection rate becomes higher in Model-RN than that in Model-MN when the transfer price is greater than a threshold value.

**Proposition 4.2.2.** *If the condition* $\beta \geq \sqrt{\frac{2\alpha^2\lambda(B-A)(X-A)}{H}}$ *holds, then the optimal wholesale price of the brand new product follows the pattern* $w^{RN} \geq w^{TN} > w^{MN}$*; otherwise,* $w^{TN} > w^{RN} > w^{MN}$.

**Proof.** On simplification,

$$w^{RN} - w^{TN} = \frac{\alpha\eta^2\lambda(B-A)^2(D_0-c_m\alpha)\left[\beta^2 H-2\alpha^2\lambda(B-A)(X-B)\right]}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0,$$

if $\beta > \sqrt{\frac{2\alpha^2\lambda(B-A)(X-B)}{H}}$.

$$w^{TN} - w^{MN} = \frac{\alpha\eta\lambda H(D_0-c_m\alpha)\left[\lambda\Psi_1-\eta\beta^2\right]\left[(X-B)^2+(B-A)^2\right]}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0. \quad \blacksquare$$

Proposition 4.2.2 demonstrates that among three decentralized models, the manufacturer sets a lower wholesale price in Model-MN. The reason behind this outcome is that the manufacturer wants to boost the market demand by setting a relatively lower wholesale price. According to our assumption, when consumers are more sensitive towards the green product, market demand increases (*i.e.* $\frac{\partial D}{\partial \beta} > 0$). The more the market demand, the more the return will be. In Model-RN, the retailer can earn from both selling the new product (*i.e.* $(p-w)D$) and collecting used products (*i.e.* $(B-A)D_r$). But in Model-TN, the retailer can earn only from selling the new product. So, the retailer gains more profit in Model-RN. Hence, in an environmental-conscious market, the manufacturer sets a higher wholesale price in Model-RN than Model-TN. When consumers are less sensitive towards the green product, the manufacturer charges a higher wholesale price in Model-TN. This is because, in the case of Model-TN, the manufacturer has to deal with two different persons: one for selling a new product and another for collecting used products.

**Proposition 4.2.3.** *If the condition* $B \geq \frac{(X+A)}{2}$ *holds, then*
*(i) the optimal greening level of the product follows the pattern* $\theta^C > \theta^{RN} \geq \theta^{MN} > \theta^{TN}$*; otherwise,* $\theta^C > \theta^{MN} > \theta^{RN} > \theta^{TN}$.
*(ii) the optimal marketing effort of the retailer follows the pattern* $e^C > e^{RN} \geq e^{MN} > e^{TN}$*; otherwise,* $e^C > e^{MN} > e^{RN} > e^{TN}$.
*(iii) the optimal selling price of the product follows the pattern* $p^{TN} > p^{MN} \geq p^{RN} > p^C$*; otherwise,* $p^{TN} > p^{RN} > p^{MN} > p^C$.

**Proof.** (i) For the greening level,

$$\theta^C - \theta^{RN} = \frac{\beta\eta\lambda H(D_0-c_m\alpha)\left[H\Psi_1-\alpha^2\eta(2B-X-A)(X-A)\right]}{\left[H\left(\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0.$$

$$\theta^{RN} - \theta^{MN} = \frac{\beta\eta\lambda H(D_0-c_m\alpha)\left[\alpha^2\eta(2B-X-A)(X-A)\right]}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0, \text{ if } B > \frac{X+A}{2}.$$

$$\theta^{MN} - \theta^{TN} = \frac{\alpha^2\beta\eta^2\lambda H(D_0-c_m\alpha)\left[(B-A)^2+(X-B)^2\right]}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0.$$

(ii) For the marketing effort,

$$e^C - e^{RN} = \frac{\gamma\lambda^2 H(D_0-c_m\alpha)\left[H\Psi_1-\alpha^2\eta(2B-X-A)(X-A)\right]}{\left[H\left(\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0.$$

$$e^{RN} - e^{MN} = \frac{\alpha^2\gamma\eta\lambda^2 H(D_0-c_m\alpha)(2B-X-A)(X-A)}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0, \text{ if } B > \frac{X+A}{2}.$$

$$e^{MN} - e^{TN} = \frac{\alpha^2\gamma\eta\lambda^2 H(D_0-c_m\alpha)\left[(B-A)^2+(X-B)^2\right]}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0.$$

(iii) For the selling price,

$$p^{TN} - p^{MN} = \frac{\alpha\eta\lambda H(D_0-c_m\alpha)\left[\lambda(2\alpha\eta-\gamma^2)-\eta\beta^2\right]\left[(B-A)^2+(X-B)^2\right]}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0.$$

$$p^{MN} - p^{RN} = \frac{\alpha\eta\lambda H(D_0-c_m\alpha)(2B-X-A)(X-A)\left[\lambda(2\alpha\eta-\gamma^2)-\eta\beta^2\right]}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0, \text{ if } B > \frac{X+A}{2}.$$

$$p^{RN} - p^C = \frac{\lambda H(D_0-c_m\alpha)\left[\lambda(2\alpha\eta-\gamma^2)-\eta\beta^2\right]\left[H\Psi_1-\alpha^2\eta(2B-X-A)(X-A)\right]}{\left[H\left(\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0. \quad \blacksquare$$

Proposition 4.2.3 shows that the greening level and the marketing effort are higher in Model-C. This is due to the joint decision-making. Since Model-C is free from the double-marginalization effect, the selling price is lower than decentralized models. As the collection rate is lower in Model-TN, the manufacturer reduces the greening level of the product. Due to the lower greening level, the retailer also decreases the marketing effort. The higher wholesale price in Model-TN forces the retailer to set a higher selling price. In Model-MN, the manufacturer can promote market demand by only setting a lower wholesale price, but in Model-RN, the transfer price also plays as a stimulant for enhancing market demand indirectly. So, in Model-RN, if the manufacturer has to pay a higher transfer price, due to the fact of higher market demand, he increases the greening level of the product. Higher greening level and higher transfer price help the retailer in selling the product with lower selling price and higher marketing effort. The opposite situation holds when the manufacturer pays a lower transfer price. Therefore, under a higher transfer price, Model-RN is beneficial from consumers' perspective.

**Proposition 4.2.4.** *The optimal profits of the manufacturer and the retailer have the following relationships.*
*(i) If the condition* $B \geq \frac{(X+A)}{2}$ *holds, then the optimal profit of the manufacturer follows the pattern* $\Pi_m^{RN} \geq \Pi_m^{MN} > \Pi_m^{TN}$*; otherwise,* $\Pi_m^{MN} > \Pi_m^{RN} > \Pi_m^{TN}$*.*
*(ii) If the condition* $B \geq A + \sqrt{\frac{\lambda H \Psi_1 \left[2H(X-B)^2\left(2\lambda\Psi_1-\beta^2\eta\right)-\alpha^2\eta\lambda(X-A)^4\right]}{\eta\left[\beta^2H^2\left(2\lambda\Psi_1-\beta^2\eta\right)-\alpha^2\eta\lambda(X-A)^2\left(2\beta^2H+\alpha^2\lambda(X-A)^2\right)\right]}}$ *holds, then the optimal profit of the retailer follows the pattern* $\Pi_r^{RN} \geq \Pi_r^{MN} > \Pi_r^{TN}$*; otherwise,* $\Pi_r^{MN} > \Pi_r^{RN} > \Pi_r^{TN}$*.*

**Proof.** (i) For the manufacturer's profit,
$\Pi_m^{RN} - \Pi_m^{MN} = \frac{\alpha^2\eta^2\lambda^2H(D_0-c_m\alpha)^2(2B-X-A)(X-A)}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0$, if $B > \frac{X+A}{2}$.
$\Pi_m^{MN} - \Pi_m^{TN} = \frac{\alpha^2\eta^2\lambda^2H(D_0-c_m\alpha)^2\left[(B-A)^2+(X-B)^2\right]}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]} > 0.$
(ii) For the retailer's profit,
$\Pi_r^{RN} - \Pi_r^{MN} = \frac{\alpha^2\eta^2\lambda^2H(D_0-c_m\alpha)^2\left[(B-A)^2\eta Y_1-\lambda H\Psi_1 Y_2\right]}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]^2\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]^2} > 0$,
if $B > A + \sqrt{\frac{\lambda H\Psi_1 Y_2}{\eta Y_1}}$.
where $Y_1 = \left[\beta^2H^2\left(2\lambda\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda\left(2\beta^2H + \alpha^2\lambda(X-A)^2\right)\right]$,
$Y_2 = \left[2H(X-B)^2\left(2\lambda\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^4\right]$.
$\Pi_r^{MN} - \Pi_r^{TN} = \frac{\alpha^2\eta^2\lambda^3H^2(D_0-c_m\alpha)^2\left[(B-A)^2+(X-B)^2\right]\left[2H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda\left((X-A)^2+2\Psi_3\right)\right]}{\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-\alpha^2\eta\lambda(X-A)^2\right]^2\left[H\left(2\lambda\Psi_1-\eta\beta^2\right)-2\alpha^2\eta\lambda(X-A)(B-A)\right]^2} > 0.$ ■

A higher selling price, and lower greening level and marketing effort diminish the market demand in Model-TN. The collection rate of used products is also lower in Model-TN. Lower market demand and collection rate remit the profit of the manufacturer, which is shown in Proposition 4.2.4. In Model-RN, a higher transfer price can encourage the retailer to collect more used products. The more the used products, the less the production cost will be. So, in that situation the manufacturer's profit is higher in Model-RN; otherwise, it will be higher in Model-MN.

In Model-TN, the retailer can earn only from selling a new product, but she has to pay a higher wholesale price, which makes her profit less. As we have mentioned before, the transfer price plays a provoking role in rising market demand. A higher amount of transfer price in Model-RN can promote market demand as well as the earning of the retailer from collecting used products, thereby increasing her profit.

From the above discussion, we learn that if the manufacturer agrees to pay a higher transfer price then Model-RN is beneficial to all the channel members including customers. Otherwise, Model-MN will give the best possible outcome. In the following, we'll investigate how the fairness behavior of the retailer affects the optimal decisions and profitability of the channel members.

**Proposition 4.2.5.** *A comparison between the optimal results of fairness model and without fairness model gives the following relationships.*
*(i)* $w^{iN} > w^{iF}$; $p^{iN} > p^{iF}$; $\theta^{iN} > \theta^{iF}$; $e^{iN} > e^{iF}$; $\tau^{iN} > \tau^{iF}$.
*(ii)* $\Pi_m^{iN} > \Pi_m^{iF}$; $\Pi_r^{iN} < \Pi_r^{iF}$; $\Pi_w^{iN} > \Pi_w^{iF}$, $\quad i = M, R, T$.

**Proof.** On simplification,

$$w^{MN} - w^{MF} = \frac{2\lambda^2 H\Psi_1(D_0 - c_m\alpha)\left[H\Psi_1 - \alpha^2\eta(X-A)^2\right]}{\left[H\left(2\lambda\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda(1+\xi)\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]} > 0.$$

$$p^{MN} - p^{MF} = \frac{\eta\lambda H\xi(D_0 - c_m\alpha)\left[H\beta^2(6\alpha\eta - \gamma^2) - \alpha^2\lambda(2\alpha\eta - \gamma^2)(X-A)^2\right]}{\left[H\left(2\lambda\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda(1+\xi)\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]} > 0.$$

$$\theta^{MN} - \theta^{MF} = \frac{2\beta\eta\lambda H^2\xi(D_0 - c_m\alpha)\Psi_1}{\left[H\left(2\lambda\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda(1+\xi)\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]} > 0.$$

$$e^{MN} - e^{MF} = \frac{\gamma\eta\lambda H\xi(D_0 - c_m\alpha)\left(\beta^2 H + \alpha^2\lambda(X-A)^2\right)}{\left[H\left(2\lambda\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda(1+\xi)\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]} > 0.$$

$$\tau^{MN} - \tau^{MF} = \frac{2\alpha\eta\lambda^2 H\xi(X-A)(D_0 - c_m\alpha)\Psi_1}{\left[H\left(2\lambda\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda(1+\xi)\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]} > 0.$$

$$\Pi_m^{MN} - \Pi_m^{MF} = \frac{2\eta\lambda^2 H^2\xi(D_0 - c_m\alpha)^2\Psi_1}{\left[H\left(2\lambda\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]\left[H\left(2\lambda(1+\xi)\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]} > 0.$$

$$\Pi_r^{MF} - \Pi_r^{MN} = \frac{\eta\lambda^2 H^2\xi(D_0 - c_m\alpha)^2\Psi_1\left[Z^2\xi(4+3\xi) - 4\lambda H\xi\Psi_1 Z - 4\lambda^2 H^2\xi^2\Psi_1\right]}{\left[H\left(2\lambda\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]^2\left[H\left(2\lambda(1+\xi)\Psi_1 - \eta\beta^2\right) - \alpha^2\eta\lambda(X-A)^2\right]^2}.$$

where $Z = H(2\lambda\Psi_1 - \eta\beta^2) - \alpha^2\eta\lambda(X-A)^2$.

Let $F(Z) = Z^2\xi(4+3\xi) - 4\lambda H\xi\Psi_1 Z - 4\lambda^2 H^2\xi^2\Psi_1$. The discriminant of $F(Z)$ is $16\lambda^2 H^2\xi^2\Psi_1^2[1+\xi(4+3\xi)] > 0$. Hence, the roots of $F(Z)$ are real and are given by $Z_{+,-} = \frac{2\lambda H\Psi_1[1\pm\sqrt{1+\xi(4+3\xi)}]}{4+3\xi}$. Now, $Z > Z_{+,-}$. Therefore, $\Pi_r^{MF} > \Pi_r^{MN}$ is proved. Proofs for the retailer-led collection and third-party-led collection being similar, for brevity, we omitted those proofs. ■

Proposition 4.2.5 reveals that the fairness behavior of the retailer harms green innovation, marketing effort, and product recycling. As the retailer takes care of the utility in addition to thinking about her profit, in this case, the manufacturer does not take any risk to improve the greening level of the product. Due to the lower greening level, he also charges a lower wholesale price. Lower wholesale price and greening level force the retailer to sell the product with lower selling price and marketing effort. The collector also shows less interest in collecting used products. Although the selling price decreases, due to lower greening level and marketing effort, the market demand becomes worse, which lessens the profit of the manufacturer and the entire supply chain. Since the retailer thinks about her utility, the fairness behavior can only elevate the profit of the retailer.

**Proposition 4.2.6.** *If the condition* $B \geq \frac{(\sqrt{\xi}X+A)}{1+\sqrt{\xi}}$ *holds, then*
*(i)* $p^{TF} \geq p^{RF}$; $\theta^{RF} \geq \theta^{TF}$; $e^{RF} \geq e^{TF}$*; otherwise the pattern will be reversed.*
*(ii)* $\Pi_m^{RF} \geq \Pi_m^{TF}$*; otherwise, the pattern will be reversed.*

**Proof.** On simplification, the numerator of $p^{RF} - p^{TF}$ becomes $2\alpha\eta\lambda H(1+\xi)(D_0 - c_m\alpha)[\xi(X-B)^2 - (B-A)^2][\lambda(2\alpha\eta - \gamma^2)(1+\xi) - \eta\beta^2]$ which is greater than 0 if $B < \frac{(\sqrt{\xi}X+A)}{1+\sqrt{\xi}}$. Hence, $p^{RF} > p^{TF}$ if $B < \frac{(\sqrt{\xi}X+A)}{1+\sqrt{\xi}}$.
The other results of Proposition 4.2.6 can be proved similarly. ∎

Propositions 4.2.3 and 4.2.4 suggest that the transfer price ($B$) does not affect optimal decisions and profitability of channel members in Model-TN under a fair-neutral retailer. However, Proposition 4.2.6 shows that under fair-minded retailer, the transfer price influences optimal decisions and profitability of channel members. If the retailer is concerned about the fairness of the business, the manufacturer prefers to transfer the collection activity to the third-party, since in this case, he has to pay less transfer price. A less transfer price helps him to exert more effort in green innovation, which can promote his profitability through improving market demand.

#### 4.2.3.1 Restitution-based wholesale price contract (Model-CO)

The above comparative analysis shows that if the transfer price exceeds a threshold value, then the collection rate of used products by the retailer is more profitable for all channel members, including customers. Again, the fairness behavior of the retailer improves the profit of the retailer but it lessens the profit of the manufacturer. So, we consider a restitution-based wholesale price contract under used products collection through the retailer. In this contract, the manufacturer and the retailer are willing to engage in integrated planning and adopt the central decision-making framework. The manufacturer sets a new wholesale price $w^{CO}$ depending on whether his profit is lower or higher than that of Model-RN. If his profit in the coordinated structure is lower than that of Model-RN, then he will charge higher wholesale price from the retailer to restitute his profit loss, while in the opposite situation, he will reduce the wholesale price to restitute the profit loss of the retailer. So, the demand and return function of Model-RN under coordinated structure will convert from $D^{RN}$ to $D^C$ and from $D_r^{RN}$ to $D_r^C$, respectively. Therefore, profits of the manufacturer and the retailer under this contract become

$$\Pi_m^{CO} = (w^{CO} - c_m)D^C + (X - B)D_r^C - \lambda(\theta^C)^2 \tag{4.2.9}$$

$$\Pi_r^{CO} = (p^C - w^{CO})D^C - \eta(e^C)^2 + (B - A)D_r^C - H(\tau^C)^2 \tag{4.2.10}$$

The manufacturer will participate in the contract if his profit becomes greater than or equal to that of Model-RN, and the retailer will participate in the contract if her profit becomes greater than or equal to that of Model-RF. From the manufacturer's condition, we get

$$\Pi_m^{CO} \geq \Pi_m^{RN} \Rightarrow w^{CO} \geq \frac{\Pi_m^{RN} + c_m D^C + \lambda(\theta^C)^2 - (X - B)D_r^C}{D^C} (= w_{min})$$

From the retailer's condition, we get

$$\Pi_r^{CO} \geq \Pi_r^{RF} \Rightarrow w^{CO} \leq \frac{p^C D^C + (B - A)D_r^C - \eta(e^C)^2 - H(\tau^C)^2 - \Pi_r^{RF}}{D^C} (= w_{max})$$

Under these conditions, the profit of the entire supply chain becomes $\Pi_w^{CO} = \Pi_m^{CO} + \Pi_r^{CO} = \Pi_w^C$. Thus we have the following proposition.

**Proposition 4.2.7.** *If the manufacturer sets the wholesale price $w^{CO} \in [w_{min}, w_{max}]$, then the proposed restitution-based wholesale price contract can coordinate the supply chain.*

If the proposed contract coordinates the supply chain then there will be some surplus profit $\Delta = \Pi_w^C - \Pi_m^{RN} - \Pi_r^{RF}$ which can be divided between the channel members according to their bargaining powers. Without any loss of generality, we assume that the manufacturer and the retailer have the same bargaining power (*i.e.* symmetric bargaining power). So, their profits under the contract are given by

$$\Pi_m^{CO} = \Pi_m^{RN} + \frac{1}{2}\Delta \text{ and } \Pi_r^{CO} = \Pi_r^{RF} + \frac{1}{2}\Delta.$$

Also, under symmetric bargaining, the optimal wholesale price is

$$w^{CO} = \frac{(p^C + c_m)D^C + (2B - X - A)D_r^C - \eta(e^C)^2 - H(\tau^C)^2 + \lambda(\theta^C)^2 + \Pi_m^{RN} - \Pi_r^{RF}}{2D^C}$$

### 4.2.4 Numerical analysis

This section deals with numerical analysis of the optimal results for the developed models and presents some meaningful managerial insights. We take the following hypothetical parameter values in accordance with the assumptions of our study: $D_0 = 100; \alpha = 0.11; \beta = 0.85; \gamma = 0.3; c_m = 150; c_r = 55; A = 40; B = 70; \lambda = 100; \eta = 90; H = 1500; w_R = 100; \rho = 0.8; \xi = 0.12$ in appropriate units.

**Table 4.2.3:** Optimal results of the proposed models.

| Optimal | Without fairness | | | With fairness | | | | |
|---|---|---|---|---|---|---|---|---|
| results | Model-MN | Model-RN | Model-TN | Model-MF | Model-RF | Model-TF | Model-C | Model-CO |
| $w$ | 525.499 | 529.530 | 529.530 | 484.279 | 488.405 | 488.222 | - | 372.201 |
| $p$ | 720.948 | 719.742 | 722.926 | 720.817 | 719.514 | 722.601 | 522.136 | 522.136 |
| $\theta$ | 0.83066 | 0.83599 | 0.82193 | 0.73948 | 0.74459 | 0.73247 | 1.70843 | 1.70843 |
| $e$ | 0.32575 | 0.32784 | 0.32233 | 0.32479 | 0.32704 | 0.32171 | 0.66997 | 0.66997 |
| $\tau$ | 0.32249 | 0.21637 | 0.21274 | 0.28709 | 0.20289 | 0.21233 | 0.66327 | 0.66327 |
| $\Pi_m$ | 8160.02 | 8212.36 | 8074.27 | 7264.27 | 7314.53 | 7195.46 | - | 9973.38 |
| $\Pi_r$ | 4192.51 | 4176.24 | 4104.85 | 5060.96 | 5048.37 | 4967.26 | - | 6809.43 |
| $\Pi_t$ | - | - | 67.8844 | - | - | 67.6264 | - | - |
| $\Pi_w$ | 12352.5 | 12388.6 | 12247.0 | 12325.2 | 12362.9 | 12230.3 | 16782.8 | 16782.8 |

Table 4.2.3 displays that the numerical example verifies all the theoretical results. The collection rate of used products is higher in Model-MN, which contradicts the result of Ma et al. (2017) who showed that the collection rate of used products is higher in Model-RN. The manufacturer prefers the collection through the retailer while the retailer prefers the collection through the manufacturer. The entire channel profit is higher in Model-RN and lower in Model-TN, which negates the outcome of Chen et al. (2018) who suggested that the total profit will be higher in Model-MN. While comparing these results with those of the models with the retailer's fairness concern, one can notice that the fairness behavior only improves the profit of the retailer. But it decreases the values of other decision variables, profits of the manufacturer and the entire supply chain. It is also observed that the trends of optimal results follow a similar pattern that of without the retailer's fairness concern. Thus, from the comparison of decentralized models, we conclude that the collection through the third-party provides the worst performance while the collection through the manufacturer is preferable to the retailer and the collection through the retailer is beneficial to the manufacturer and the entire supply chain.

Although the retailer's fairness concern promotes the retailer's profit or Model-

RN gives higher profit to the manufacturer, all these decentralized models fail to compete with Model-C. It is noted that the selling price in Model-C is lower than those of the decentralized models, but the greening level, the marketing effort, and the collection rate of used product are more than two times. The entire channel profit is 35.5% higher than that of Model-RN, which illustrates the significance of channel coordination. The proposed restitution-based wholesale price contract can perfectly coordinate the supply chain and both the channel members can achieve a win-win situation (see Fig. 4.2.3).

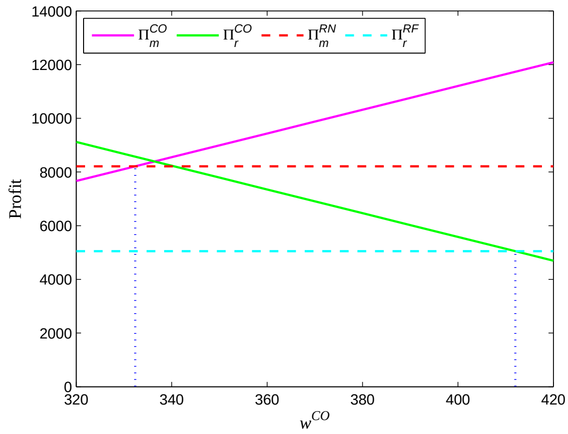



**Fig. 4.2.3:** Win-win situation for both members.

**Table 4.2.4:** Optimal results of the proposed models when $\rho = 0$.

| Optimal results | Without fairness | | | With fairness | | | | |
|---|---|---|---|---|---|---|---|---|
| | Model-MN | Model-RN | Model-TN | Model-MF | Model-RF | Model-TF | Model-C | Model-CO |
| $w$ | 532.607 | 537.992 | 537.853 | 491.302 | 497.210 | 496.564 | - | 385.372 |
| $p$ | 724.435 | 723.963 | 727.008 | 723.929 | 723.400 | 726.202 | 536.602 | 536.602 |
| $\theta$ | 0.81527 | 0.81735 | 0.80391 | 0.72725 | 0.72933 | 0.71833 | 1.64456 | 1.64456 |
| $e$ | 0.31971 | 0.32053 | 0.31525 | 0.31942 | 0.32033 | 0.31550 | 0.64493 | 0.64493 |
| $\tau$ | 0.03517 | 0.21155 | 0.20807 | 0.03137 | 0.23256 | 0.20823 | 0.07094 | 0.07094 |
| $\Pi_m$ | 8008.80 | 8029.26 | 7897.21 | 7144.19 | 7164.59 | 7056.50 | - | 9672.70 |
| $\Pi_r$ | 4038.56 | 3992.09 | 3926.80 | 4895.02 | 4839.26 | 4772.80 | - | 6482.72 |
| $\Pi_t$ | - | - | 64.9398 | - | - | 65.0397 | - | - |
| $\Pi_w$ | 12047.4 | 12021.4 | 11889.0 | 12039.2 | 12003.9 | 11894.3 | 16155.4 | 16155.4 |

Table 4.2.4 represents optimal results of proposed models when $\rho = 0$ *i.e.* none of the remanufactured products are like-new and are sold in the secondary market. In this situation, the wholesale price and the selling price increase for maintaining the profitability while the other decision variables and profits of the channel members and the entire supply chain decrease compared to the results shown in Table 4.2.3. The collection rates of used products under the manufacturer-led collection and Model-C are highly affected and those are decreased by almost 89%.

Table 4.2.5 illustrates the optimal results of different models when $\rho = 1$ *i.e.*, all the remanufactured products are like-new product and are sold in the primary market. This situation has a positive effect on all the optimal results *i.e.* the wholesale price and the selling price decrease while other decision variables and profits of the

**Table 4.2.5:** Optimal results of the proposed models when $\rho = 1$.

| Optimal results | Without fairness | | | With fairness | | | | |
|---|---|---|---|---|---|---|---|---|
| | Model-MN | Model-RN | Model-TN | Model-MF | Model-RF | Model-TF | Model-C | Model-CO |
| $w$ | 521.843 | 527.354 | 527.391 | 480.679 | 486.583 | 486.085 | - | 360.962 |
| $p$ | 719.155 | 718.656 | 721.876 | 719.221 | 718.735 | 721.678 | 514.474 | 514.474 |
| $\theta$ | 0.83858 | 0.84078 | 0.82656 | 0.74574 | 0.74766 | 0.73610 | 1.74226 | 1.74226 |
| $e$ | 0.32885 | 0.32972 | 0.32414 | 0.32754 | 0.32838 | 0.32331 | 0.68324 | 0.68324 |
| $\tau$ | 0.39791 | 0.21761 | 0.21393 | 0.35386 | 0.19506 | 0.21338 | 0.82672 | 0.82672 |
| $\Pi_m$ | 8237.79 | 8259.44 | 8119.78 | 7325.84 | 7344.61 | 7231.05 | - | 10141.5 |
| $\Pi_r$ | 4272.81 | 4224.26 | 4151.26 | 5147.11 | 5091.53 | 5017.71 | - | 6973.61 |
| $\Pi_t$ | - | - | 68.6518 | - | - | 68.2972 | - | - |
| $\Pi_w$ | 12510.6 | 12483.7 | 12339.7 | 12473.0 | 12436.1 | 12317.1 | 17115.1 | 17115.1 |

channel members and the entire supply chain enhance. Similar to the previous case, in this situation also, the collection rates of used products under the manufacturer-led collection and Model-C are highly affected compared to the other models.

**Table 4.2.6:** Optimal results of the proposed models when $w_R = 0$.

| Optimal results | Without fairness | | | With fairness | | | | |
|---|---|---|---|---|---|---|---|---|
| | Model-MN | Model-RN | Model-TN | Model-MF | Model-RF | Model-TF | Model-C | Model-CO |
| $w$ | 530.503 | 533.809 | 533.738 | 489.220 | 492.515 | 492.433 | - | 384.801 |
| $p$ | 723.403 | 721.876 | 724.989 | 723.006 | 721.308 | 724.419 | 532.377 | 532.377 |
| $\theta$ | 0.81982 | 0.82656 | 0.81282 | 0.73088 | 0.73755 | 0.72533 | 1.66322 | 1.66322 |
| $e$ | 0.32150 | 0.32414 | 0.31875 | 0.32101 | 0.32394 | 0.31858 | 0.65224 | 0.65224 |
| $\tau$ | 0.17682 | 0.21393 | 0.21038 | 0.15764 | 0.21808 | 0.21026 | 0.35873 | 0.35873 |
| $\Pi_m$ | 8053.58 | 8119.78 | 7984.76 | 7179.79 | 7245.31 | 7125.30 | - | 9753.86 |
| $\Pi_r$ | 4083.84 | 4082.61 | 4014.35 | 4943.93 | 4950.75 | 4868.60 | - | 6584.80 |
| $\Pi_t$ | - | - | 66.3876 | - | - | 66.3141 | - | - |
| $\Pi_w$ | 12137.4 | 12202.4 | 12065.5 | 12123.7 | 12196.1 | 12060.2 | 16338.7 | 16338.7 |

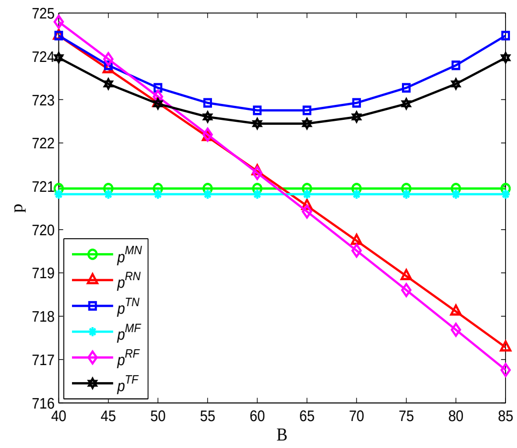
Table 4.2.6 demonstrates the situation when the low standard remanufactured products have no value in the secondary market. So, those products are abandoned. The optimal results of different models follow the same pattern of the case $\rho = 0$ but are less affected than those of the case $\rho = 0$.

Analytical comparison reveals that the transfer price $B$ has very important impact in optimal decision-making. So, in the following, we'll visualize the effect of $B$ on optimal decisions and profit of the channel members.

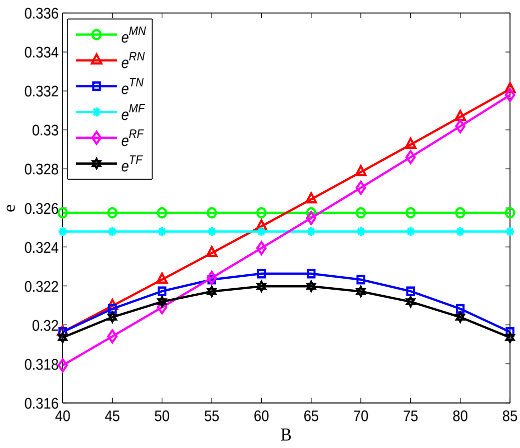
#### 4.2.4.1 Effect of the transfer price $B$

Fig. 4.2.4 exposes the following insights:

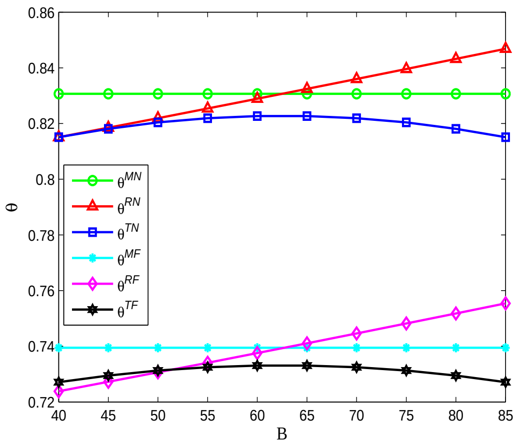
(i) An increase in $B$ decreases the selling price under the retailer-led collection. The rate of decrement is higher under the fairness behavior of the retailer. In case of



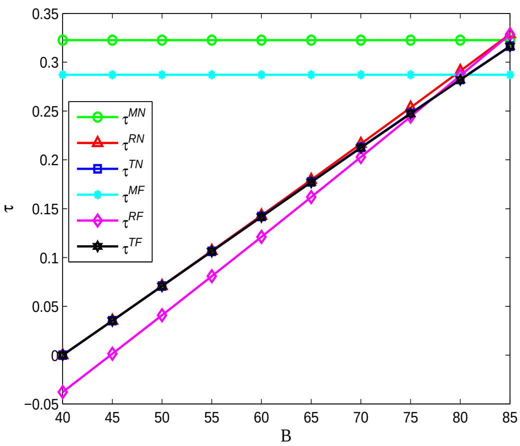

(a) $B$ vs selling price.



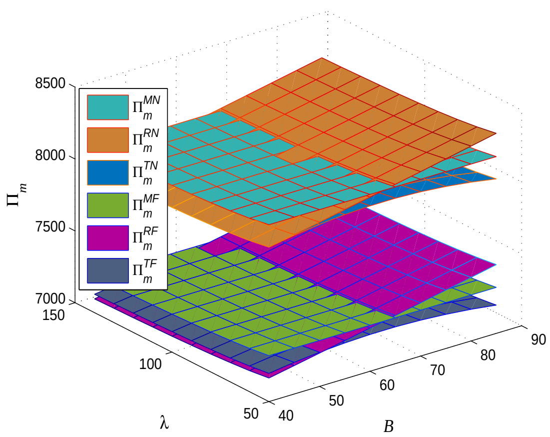

(b) $B$ vs marketing effort.



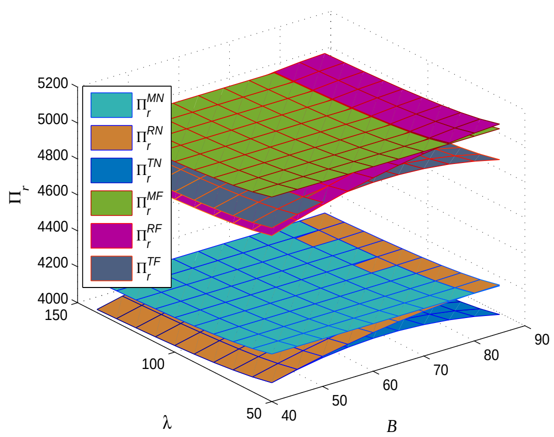

(c) $B$ vs greening level.




(d) $B$ vs collection rate.




(e) $B$ vs manufacturer's profit.



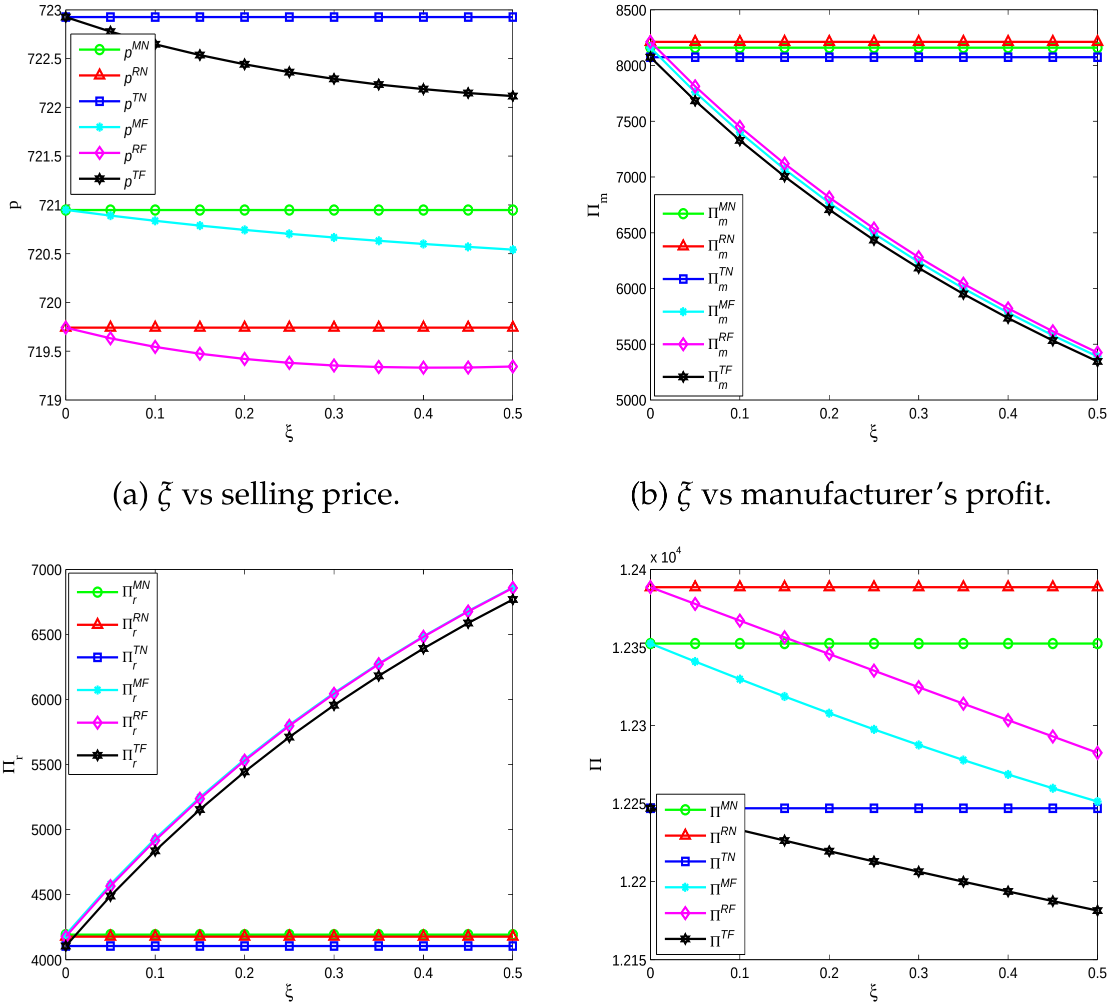

(f) $B$ vs retailer's profit.

**Fig. 4.2.4:** Sensitivity of optimal results w.r.t. $B$.

collection through third-party, the selling price decreases up to a certain value of $B$. After that, it tends to increase. It is noticed from Fig. 4.2.4(a) that, for lower values of $B$, the fair-minded retailer charges a higher selling price under its own collection process than that of the third-party, which validates the result of Proposition 4.2.6.
(ii) In case of retailer-led collection, the retailer can earn from both selling the new product and collecting used products. So, when $B$ increases, she promotes her effort in marketing the product. But in the case of collection through the third-party, the retailer earns only from selling the new product. So, she diminishes her effort for a higher value of $B$. It is also noted from Fig. 4.2.4(b) that, for lower $B$, the fair-minded retailer puts less effort in Model-RF than Model-TF. Similar to the marketing effort, the greening level of the product also increases with $B$ (see Fig. 4.2.4(c)).
(iii) The more the transfer price, the more the collection rate of used products will be. Similar to other decision variables, for lower $B$, the collection rate of used products is higher in Model-TF than that of Model-RF under fair-minded retailer. The fairness concerned retailer exerts more effort in collecting used products only when $B$ is greater than some threshold value; otherwise, she shows no interest in collecting used products (see Fig. 4.2.4(d)).
(iv) On one hand, a lower selling price, and higher greening level and marketing effort increase market demand. On the other hand, a higher collection rate collects more used products. The more the used products, the less the production cost will be. As a result, the profit of the manufacturer is increased by $B$. For a lower value of $B$, the profit of the manufacturer follows the sequence $\Pi_m^{MF} > \Pi_m^{TF} > \Pi_m^{RF}$. After some threshold value of $B$, the sequence changes to $\Pi_m^{MF} > \Pi_m^{RF} > \Pi_m^{TF}$. Finally, for higher value of $B$, the sequence becomes $\Pi_m^{RF} > \Pi_m^{MF} > \Pi_m^{TF}$ (see Fig. 4.2.4(e)).
(v) Fig. 4.2.4(f) illustrates that fairness behavior and $B$ can improve the profit of the retailer. For a lower value of $B$, the third-party puts more effort into collecting used products than the retailer. The fair-minded retailer also prefers the collection through the third-party for lower $B$. When $B$ exceeds a threshold value, the profit of the retailer in Model-RF becomes higher than that in Model-MF.

#### 4.2.4.2 *Effect of the fairness concern parameter $\xi$*

Fig. 4.2.5 discloses the following insights:
(i) $\xi$ is the parameter that measures how much the retailer is concerned about the fairness of the business *i.e.* the fairness of the profit distribution. For a higher value




(a) $\xi$ vs selling price.

(b) $\xi$ vs manufacturer's profit.

(c) $\xi$ vs retailer's profit.

(d) $\xi$ vs total channel's profit.

**Fig. 4.2.5:** Sensitivity of optimal results w.r.t. $\xi$.

of $\xi$, the retailer is more concerned about the fairness of the profit distribution. Fig. 4.2.5(a) depicts the decreasing trend of the selling price with $\xi$. The reason is that the retailer wants to increase the market demand by decreasing the selling price.

(ii) Fig. 4.2.5(b) displays that the profit of the manufacturer decreases with $\xi$. This is because, under the retailer's strong fairness behavior, the manufacturer takes no risk in improving the greening level. At the same time, he decreases the wholesale price. A lower wholesale price generates a lower profit for the manufacturer.

(iii) Although the retailer decreases the selling price, the rate of decrement is lower than that of the wholesale price. A lower wholesale price assists the retailer to improve her profit (see Fig. 4.2.5(c)). Although the profit of the retailer increases, the rate of increment is lower than the rate of decrement of the manufacturer's profit. As a result, the profit of the entire supply chain decreases (see Fig. 4.2.5(d)).

## 4.3
## *Conclusions*

Some valuable managerial insights obtained from the comparison and discussion of optimal results of Section 4.1 are given below: First, for a manufacturing or a retailing firm, two major issues are risks and costs. Every member of the supply chain always wants to maximize his own profit without taking any risk and not investing much. So, they adopt a wait-and-see approach which leads them to work cooperatively. Second, discount factor in the second period has a significant impact on the optimal results and the profit of the supply chain. A higher estimation of discount factor decreases the selling price and increases the greening level, marketing effort, collection rate of used products in the first period and overall profit of the supply chain. It has no effect on second period's decisions. Third, the performance of the supply chain can be improved by implementing either the greening effort or the marketing effort or both. Fourth, the manufacturer's collection option of used products has no impact on the optimal results of the second period but it has significant effect on the optimal results of the first period. Fifth, dual-collection option of the manufacturer helps the manufacturer to sell the higher green product with a lower price. So, it helps to increase consumer surplus. Sixth, in the current technological age, customers can get sufficient information easily about any product through internet before purchasing. If the manufacturer and the retailer exert effort in green innovation and marketing, respectively then the environment-friendly customers can spend higher money while purchasing green product without worrying about the brand. So, branded company should apply innovative green practices while producing product and relatively non-branded company should apply effort in marketing their product besides greening their product. Lastly, business managers should increase the awareness about coordination to improve their profits. As the manufacturer produces green product and bears all the extra costs to produce green product, in order to encourage the manufacturer in green manufacturing, the retailer should bear some cost. Although cost sharing contract increases the wholesale prices and the selling prices, due to higher marketing effort and greening level, market demand increases. The more the market demand, the more the return quantity will be. So, profits of the supply chain members and the whole supply chain become higher than those in other decentralized models.

From the comparison and discussion of optimal results of Section 4.2, various managerial insights are derived. Firstly, in the case of a fair-neutral retailer, the used products collection through the third-party results in lower greening level, marketing effort, the collection rate of used products and profits of the channel members. So, under a fair-neutral retailer, used products collection through the third-party seems to be disadvantageous for all the channel members. Secondly, the unit transfer price plays a provoking role in determining whether the manufacturer or the retailer performs the used products collection activity. If the manufacturer denies to pay much transfer price then collection through the manufacturer is profitable; otherwise, the collection through the retailer is preferable under a fair-neutral retailer. Thirdly, the retailer's fairness behavior only improves its profit while decreases the optimal values of the decision variables, and profits of the manufacturer and the entire supply chain. Fourthly, when all the remanufactured products become like-new products, it is profitable for all the channel members including consumers. It is also beneficial to the environment, since it encourages the collector to collect more used products. Fifthly, when transferring the collection activity becomes a preferred strategy and the manufacturer refuses to spend too much transfer price, the collection through the third-party will be favorable for the manufacturer under the retailer's fairness concern. Even the fair-minded retailer also prefers the third-party-led collection when the manufacturer refuses to pay much transfer price. Finally, the proposed contract helps in creating an operating environment built on trust, commitment and mutual benefits (social). Furthermore, it can improve the collection rate of used products which help in rising environmental sustainability. Moreover, it enhances profits of channel members and the entire supply chain. Hence, it is beneficial from an economic perspective. In this manner, the proposed restitution-based wholesale price contract elevates all three dimensions of sustainability.

# 5

# Strategies for a dual-channel green closed-loop supply chain

## 5.0 Introduction

In this chapter, we consider a two-echelon dual-channel CLSC model with a single manufacturer and a single retailer. The manufacturer produces new products from the fresh raw materials and at the same time, s/he also remanufactures the returned products. We propose two models. In the first model, there is no return while in the second model, there is dual return. Both the models are developed under various market powers viz. the centralized policy, the manufacturer-led decentralized policy, the retailer-led decentralized policy, and the Nash game. With the help of game-theoretic approaches, we will try to answer the following questions:

- Which one of the two models gives the best optimal decisions of the CLSC?
- How does dual-channel affect the supply chain members and whole supply chain?
- How do the degree of customer loyalty to the retail channel, green investment cost and retailer loyalty to the returned items influence the pricing and the greening policies and profit allocation in the dual-channel green supply chain?

This chapter is based on the work published in *Flexible Services and Manufacturing Journal*, 2020, 32(3), 724-761.

## 5.1 Notations and assumptions

The following notations are used for developing the proposed model:

| | |
|---|---|
| $w$ | unit wholesale price of the manufacturer in the retail channel. |
| $p_0$ | unit selling price of the manufacturer in the direct channel. |
| $p$ | unit selling price of the retailer in the retail channel. |
| $\theta$ | level of green innovation. |
| $D_0$ | demand in the direct channel. |
| $D_1$ | demand in the retail channel. |
| $D(= D_0 + D_1)$ | total demand quantity. |
| $D_R$ | collection quantity. |
| $c_m$ | unit manufacturing cost of the end product from the raw materials. |
| $c_r(< c_m)$ | unit manufacturing cost of the end product from the used product. |
| $a$ | basic market demand. |
| $d_0$ | basic return quantity. |
| $\tau$ | degree of manufacturer's loyalty to the return quantity, $0 \leq \tau \leq 1$. |
| $\lambda$ | green innovation investment efficiency coefficient. |
| $A_0$ | price paid by the manufacturer to the customer to collect the used product through direct channel. |
| $A_1$ | price paid by the retailer to the customer to collect the used product through retail channel. |
| $A_2$ | price paid by the manufacturer to the retailer to collect the used product through retail channel. |
| $\Pi_m$ | profit of the manufacturer. |
| $\Pi_r$ | profit of the retailer. |
| $\Pi$ | profit of the whole system. |
| $(\ )^{Ij}$ | optimal results in Model I. |
| $(\ )^{IIj}$ | optimal results in Model II. |
| $j$ | = C,M,R,D |

C = Centralized policy; M = Manufacturer-led decentralized policy; R = Retailer-led decentralized policy; D = Decentralized policy (Nash game).

The following assumptions are made to establish the proposed model:

**(1)** Market demands for the traditional retail channel and the direct channel are deterministic and linearly dependent on the greening level and the selling price of the green product. Demand functions in the direct and the retail channels are assumed as $D_0 = (1-\rho)a - \alpha_0 p_0 + \beta_0 p + \gamma_0\theta$ and $D_1 = \rho a - \alpha_1 p + \beta_1 p_0 + \gamma_1\theta$, respectively (Li et al., 2016). So, the total demand is $D = D_0 + D_1 = a - (\alpha_0 - \beta_1)p_0 - (\alpha_1 - \beta_0)p + (\gamma_0 + \gamma_1)\theta$. The parameters $\alpha_i$ and $\beta_i$ $(i = 0, 1)$ represent the self-price sensitivity and the cross-price sensitivity parameters, respectively. We assume $\alpha_i > \beta_i$ $(i = 0, 1)$, which indicates that the self-price effect is greater than the cross-price effect (Hanssens et al., 2003; Kurata et al., 2007); $\gamma_0$ and $\gamma_1$ are the sensitivity of greening level in the direct channel and the retail channel, respectively; $\rho$ $(0 \leq \rho \leq 1)$ is the market share (customer loyalty) to the retail channel and $(1 - \rho)$ is the market share to the direct channel. In order to make the model tractable, we assume that the cross-price effects are symmetric (Huang and Swaminathan, 2009) *i.e.* $\beta_0 = \beta_1 = \beta$.

**(2)** The collection quantity depends on the greening level $\theta$. As the greening level decreases, the collection quantity increases. We take, $D_R = d_0 - d_1\theta$, where $d_0$ is independent of greening level, $d_1$ is the green level sensitivity parameter for the collection quantity, and $\theta < d_0/d_1$ such that the collection quantity is non-negative (Li et al., 2013; Giri et al., 2019). The manufacturer collects $\tau$ portion of this quantity directly through the direct channel and the retailer collects the remaining portion $(1 - \tau)$ through the retail channel.

**(3)** Both the retail channel and the direct channel have their own customers. We assume $\gamma_1 > \gamma_0$, which indicates that the effect of green product in the retail channel is greater than that in the direct channel. This is because, customers can check products thoroughly while purchasing through the retail channel (Li et al., 2016).

**(4)** The quality of the remanufactured product is "like-new" (Savaskan et al., 2004; Giri and Sharma, 2014). Customers are attracted by the remanufactured products as well as new ones. Here we assume $c_m > c_r$ which implies that remanufacturing a used product is more profitable than manufacturing a new product. In the real business scenario, there are many evidences that new products can be replaced by remanufactured products completely *e.g.* used cameras, used printer cartridges, etc. For these products, it is difficult for consumers to distinguish between new and remanufactured products. Consequently, the same price can be set.

**(5)** In order to ensure that all players of the supply chain are profitable in the business, we assume that $c_m - c_r > A_2 > A_1 > 0$, $c_m - c_r > A_0 > 0$ and $p > w > 0$. Also, in order to ensure that the retailer cannot buy the green product from the direct channel, we assume $p_0 > w$. For ease of presentation of the chapter, we consider $C_0 = c_m - c_r - A_0 > 0$, $C_1 = c_m - c_r - A_1 > 0$, and $C_2 = c_m - c_r - A_2 > 0$.

## 5.2 Model formulation and analysis

We consider a dual-channel two-echelon closed-loop green supply chain consisting of a manufacturer (re-manufacturer) and a retailer, where the manufacturer produces and sells based on their choices. The finished products are sold to the customers through the forward dual-channel while used products are collected from the customers through the reverse dual-channel (see Fig. 5.1). We assume that the manufacturer produces the green product with the greening level $\theta$ at a price of $c_m$ and sells it to the retailer at the wholesale price $w$. Then the retailer sells the products to potential customers through the traditional retail channel at a

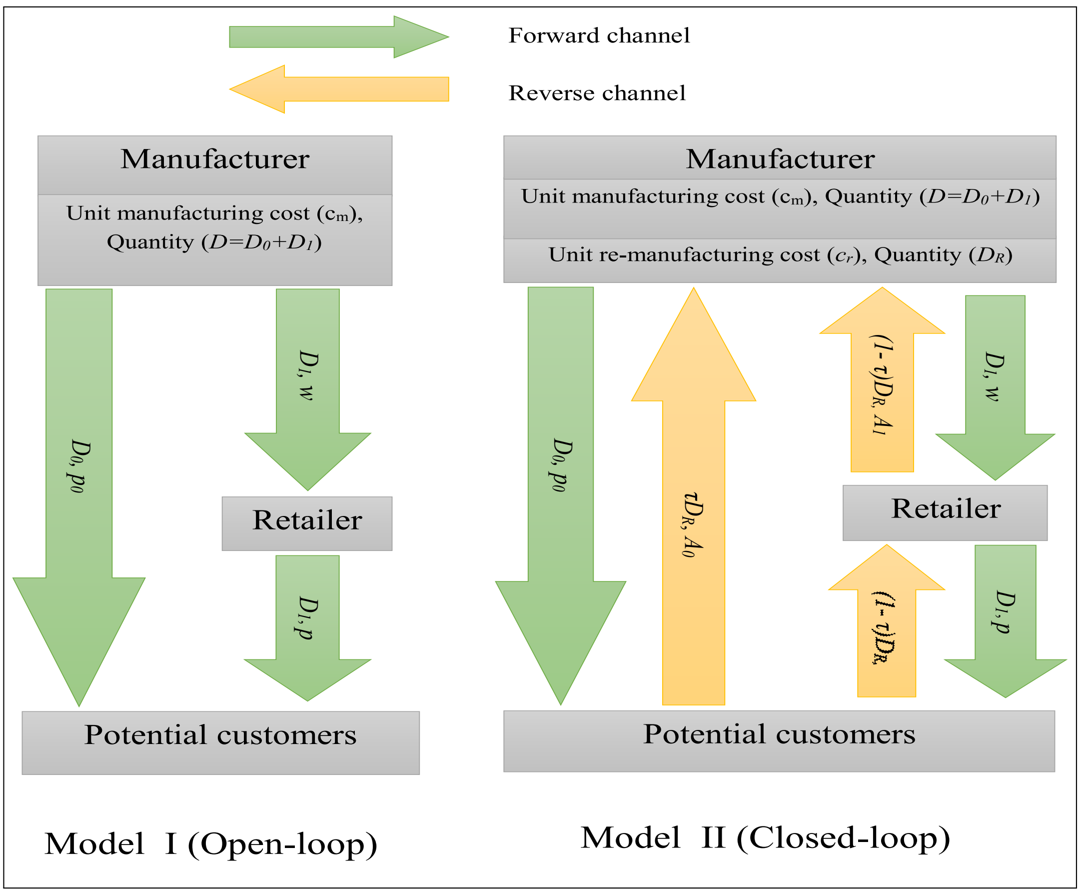



**Fig. 5.1:** Dual-channel supply chain.

selling price of $p$. The manufacturer may also consider the direct channel to sell the product to customers at the price $p_0$ (In India, Homeshop18 (https://www.homeshop18.in), Naaptol (https://www.naaptol.com), etc. display different items of different companies through their own TV channel and attract customers). In the reverse channel, the retailer collects used products at the price $A_1$ and sells it to the manufacturer for remanufacturing at the price $A_2$. The manufacturer also collects used products directly at the price $A_0$. Now-a-days many companies collect used products by advertising. For example, OLX (https://www.olx.in) and Quikr (https://www.quikr.com) collect used cars, bikes and scooters, electronic instruments, home and kitchen instruments, furniture through the internet. The manufacturer has to invest some extra money to achieve the green innovation, which is assumed as an increasing and convex cost component $\lambda\theta^2$ to characterize the diminishing investment with respect to $\theta$ (Ghosh and Shah, 2015). The profit function for the manufacturer is given by

$$\begin{aligned}\Pi_m(w, p_0, \theta) &= p_0 D_0 + w D_1 - c_m(D - D_R) - (c_r + A_0)(1-\tau)D_R \\ &\quad -(c_r + A_2)\tau D_R - \lambda\theta^2 \end{aligned} \quad (5.1)$$

Here the first two terms indicate the revenues of products sold through the direct channel and the traditional retail channel, respectively. The third term denotes production cost of the product produced from the raw materials. The fourth and fifth terms represent recycling (remanufacturing) cost of the returned products through the direct channel and the retail channel, respectively. The last term denotes the extra cost for producing green product.

The profit function of the retailer is given by

$$\Pi_r(p) = (p - w)D_1 + (A_2 - A_1)\tau D_R \quad (5.2)$$

So, the total profit of the whole supply chain is given by

$$\begin{aligned}\Pi(p, p_0, \theta) &= p_0 D_0 + p D_1 - c_m(D - D_R) - (c_r + A_0)(1-\tau)D_R \\ &\quad -(c_r + A_1)\tau D_R - \lambda\theta^2 \end{aligned} \quad (5.3)$$

Before we discuss the main model *i.e.* the closed-loop green supply chain model, we first discuss the open-loop supply chain model in the following subsection.

### 5.2.1 Model I : No return policy

Here only the forward dual-channel exists *i.e.* the manufacturer and the retailer do not entertain any return policy. The manufacturer produces the green product and sells it to the potential customers through the retail channel as well as the direct channel. The profit functions of the manufacturer and the retailer are given respectively by

$$\Pi_m(w, p_0, \theta) = p_0 D_0 + w D_1 - c_m D - \lambda\theta^2 \quad (5.4)$$

$$\Pi_r(p) = (p - w) D_1 \quad (5.5)$$

With these profit functions, we discuss four different policies which are described as follows.

#### 5.2.1.1 Centralized policy

In the centralized scenario, the manufacturer and the retailer are considered as an integrated business unit. They cooperatively decide the retail prices of the product in the dual-channel as well as the greening level to maximize the profit of the whole system. Since there is a single decision-maker, the internal credit transfer parameter (wholesale price $w$) does not play any role. Small companies usually benefit from centralized structure because in that case, owners often stand at the leading position of the business operations. Among the large companies, Apple computer utilizes centralized policy, where most of the decisions are highly decorated at the top, which the lower level of employees execute very tightly.

The profit function ($\Pi^{IC}$) of the centralized dual-channel green supply chain is given by

$$\Pi^{IC}(p^{IC}, p_0^{IC}, \theta^{IC}) = p_0^{IC} D_0^{IC} + p^{IC} D_1^{IC} - c_m D^{IC} - \lambda(\theta^{IC})^2 \quad (5.6)$$

**Proposition 5.1.** *If* $\lambda > \max\left\{\frac{\gamma_0^2}{4\alpha_0}, \frac{\alpha_1\gamma_0^2 + 2\beta\gamma_0\gamma_1 + \alpha_0\gamma_1^2}{4(\alpha_0\alpha_1 - \beta^2)}\right\}$ *then unique optimal decisions in the centralized policy are given by*

$$\begin{aligned}
p_0^{IC} &= \frac{1}{2\Psi_1}\Big[a[(4\alpha_1\lambda - \gamma_1^2)(1-\rho) + \rho(\gamma_0\gamma_1 + 4\beta\lambda)] \\
&\quad + c_m[\Psi_1 - (\alpha_1\gamma_0^2 + (\alpha_1+\beta)\gamma_0\gamma_1 + \beta\gamma_1^2)]\Big], \\
\theta^{IC} &= \frac{1}{\Psi_1}\Big[a[(\alpha_1\gamma_0 + \beta\gamma_1)(1-\rho) + \rho(\alpha_0\gamma_1 + \beta\gamma_0)] \\
&\quad - c_m[(\alpha_0\alpha_1 - \beta^2)(\gamma_0 + \gamma_1)]\Big], \\
p^{IC} &= \frac{1}{2\Psi_1}\Big[a[(\gamma_0\gamma_1 + 4\beta\lambda)(1-\rho) + \rho(4\alpha_0\lambda - \gamma_0^2)] \\
&\quad + c_m[\Psi_1 - (\beta\gamma_0^2 + (\alpha_0+\beta)\gamma_0\gamma_1 + \alpha_0\gamma_1^2)]\Big], \\
\textit{where } \Psi_1 &= 4\lambda(\alpha_0\alpha_1 - \beta^2) - (\alpha_1\gamma_0^2 + 2\beta\gamma_0\gamma_1 + \alpha_0\gamma_1^2)
\end{aligned}$$

**Proof.** From Eq. (5.6), we have
$\frac{\partial \Pi^{IC}}{\partial p_0} = -2p_0\alpha_0 + 2p\beta + c_m(\alpha_0 - \beta) + \gamma_0\theta + a(1-\rho)$; $\frac{\partial^2 \Pi^{IC}}{\partial p_0^2} = -2\alpha_0$;
$\frac{\partial \Pi^{IC}}{\partial \theta} = p_0\gamma_0 + p\gamma_1 - c_m(\gamma_0 + \gamma_1) - 2\theta\lambda$; $\frac{\partial^2 \Pi^{IC}}{\partial \theta^2} = -2\lambda$;
$\frac{\partial \Pi^{IC}}{\partial p} = -2p\alpha_1 + 2p_0\beta + c_m(\alpha_1 - \beta) + \gamma_1\theta + a\rho$; $\frac{\partial^2 \Pi^{IC}}{\partial p^2} = -2\alpha_1$;
$\frac{\partial^2 \Pi^{IC}}{\partial p_0 \partial \theta} = \gamma_0$; $\frac{\partial^2 \Pi^{IC}}{\partial p_0 \partial p} = 2\beta$; $\frac{\partial^2 \Pi^{IC}}{\partial \theta \partial p} = \gamma_1$.
The Hessian matrix associated with the profit function $\Pi^{IC}$ is given by

$$H^{IC} = \begin{pmatrix} \frac{\partial^2 \Pi^{IC}}{\partial p_0^2} & \frac{\partial^2 \Pi^{IC}}{\partial p_0 \partial \theta} & \frac{\partial^2 \Pi^{IC}}{\partial p_0 \partial p} \\ \frac{\partial^2 \Pi^{IC}}{\partial \theta \partial p_0} & \frac{\partial^2 \Pi^{IC}}{\partial \theta^2} & \frac{\partial^2 \Pi^{IC}}{\partial \theta \partial p} \\ \frac{\partial^2 \Pi^{IC}}{\partial p \partial p_0} & \frac{\partial^2 \Pi^{IC}}{\partial p \partial \theta} & \frac{\partial^2 \Pi^{IC}}{\partial p^2} \end{pmatrix} = \begin{pmatrix} -2\alpha_0 & \gamma_0 & 2\beta \\ \gamma_0 & -2\lambda & \gamma_1 \\ 2\beta & \gamma_1 & -2\alpha_1 \end{pmatrix}$$

Now, $|H_1^{IC}| = -2\alpha_0 < 0$, $|H_2^{IC}| = 4\alpha_0\lambda - \gamma_0^2 > 0, \text{if } \lambda > \frac{\gamma_0^2}{4\alpha_0}$.
Again, $|H^{IC}| = 2[\alpha_1\gamma_0^2 + 2\beta\gamma_0\gamma_1 + \alpha_0\gamma_1^2 - 4\lambda(\alpha_0\alpha_1 - \beta^2)]$.
$< 0, \text{if } \lambda > \frac{\alpha_1\gamma_0^2 + 2\beta\gamma_0\gamma_1 + \alpha_0\gamma_1^2}{4(\alpha_0\alpha_1 - \beta^2)}$.
Therefore, $H^{IC}$ is negative definite if and only if $\lambda > \max\left\{\frac{\gamma_0^2}{4\alpha_0}, \frac{\alpha_1\gamma_0^2 + 2\beta\gamma_0\gamma_1 + \alpha_0\gamma_1^2}{4(\alpha_0\alpha_1 - \beta^2)}\right\}$.
If the Hessian matrix is negative definite then there exists a unique optimal solution which can be obtained by solving $\frac{\partial \Pi^{IC}}{\partial p_0} = 0$, $\frac{\partial \Pi^{IC}}{\partial \theta} = 0$, and $\frac{\partial \Pi^{IC}}{\partial p} = 0$ simultaneously, as given in Proposition 5.1. ■

From the existence and uniqueness condition for optimal decisions given in Proposition 5.1, it is clear that the manufacturer should invest a minimum amount always for product greening.

As there is only a single decision-maker in the centralized scenario, the market share has valuable impact on the price of the product in direct channel and retail channel. It can be shown by simple calculation that when

$$\rho > \frac{\begin{pmatrix} a[4\lambda(\alpha_1 - \beta) - \gamma_1(\gamma_0 + \gamma_1)] - c_m[(\alpha_1 - \beta)\gamma_0^2 + (\alpha_1 - \alpha_0)\gamma_0\gamma_1 - (\alpha_0 - \beta)\gamma_1^2] \\ -2d_1[(\alpha_1 - \beta)\gamma_0 - (\alpha_0 - \beta)\gamma_1][C_0 + \tau(A_0 - A_1)] \end{pmatrix}}{a[4\lambda(\alpha_0 + \alpha_1 - 2\beta) - (\gamma_0 + \gamma_1)^2]},$$

the selling price in the retail channel is higher than that in the direct channel. This is because, for smaller value of $\rho$, the market demand in the direct channel increases. As a result, the manufacturer can easily increase the selling price of the product in the direct channel without any hesitation. So, it depends on the market share whether the retail selling price will be greater than the direct selling price or not.

#### 5.2.1.2 *Manufacturer-led decentralized policy*

Here we consider a Stackelberg game where the manufacturer is the Stackelberg leader and the retailer is the follower. GM, Toyota, Canon, Xerox, LG, Videocon, Sony, Samsung, and HP are some companies where the manufacturers have more power than the retailers. In India, Surya group produces energy saving LED lights and they are the leader in their market.

In this policy, the retailer first gives the best response to the manufacturer and then the manufacturer decides the optimal decisions to maximize his/her profit. Our objective is to

$$\begin{aligned}
\max_{(p_0^{IM}, w^{IM}, \theta^{IM})} \Pi_m^{IM}(p_0^{IM}, w^{IM}, \theta^{IM}) &= \max_{(p_0^{IM}, w^{IM}, \theta^{IM})} \left[p_0^{IM} D_0^{IM} + w^{IM} D_1^{IM} - c_m D^{IM} - \lambda(\theta^{IM})^2\right] \\
\text{such that } (p^{IM}) &= \arg\max_{p^{IM}} \Pi_r^{IM}(p^{IM}) \\
&= \max_{p^{IM}} (p^{IM} - w^{IM}) D_1^{IM}.
\end{aligned}$$

**Proposition 5.2.** *If* $\lambda > \frac{2\alpha_1^2\gamma_0^2 + 4\alpha_1\beta\gamma_0\gamma_1 + (\beta^2 + \alpha_0\alpha_1)\gamma_1^2}{8\alpha_1(\alpha_0\alpha_1 - \beta^2)}$*, then the manufacturer-led decentralized policy provides unique optimal decisions of the manufacturer as*

$$\begin{aligned}
w^{IM} &= \frac{1}{2\Psi_2}\Big[c_m[\Psi_2 - \big(2\alpha_1\beta\gamma_0^2 + (2\alpha_0\alpha_1 + \alpha_1\beta + \beta^2)\gamma_0\gamma_1 + \alpha_0(\alpha_1 + \beta)\gamma_1^2\big)] \\
&\quad + a[\big(\gamma_1(2\alpha_1\gamma_0 + \beta\gamma_1) + 8\alpha_1\beta\lambda\big)(1 - \rho) - \rho\big(\gamma_0(2\alpha_1\gamma_0 + \beta\gamma_1) - 8\lambda\alpha_0\alpha_1\big)]\Big], \\
p_0^{IM} &= \frac{1}{2\Psi_2}\Big[c_m[\Psi_2 - \big(2\alpha_1^2\gamma_0^2 + \alpha_1(3\beta + \alpha_1)\gamma_0\gamma_1 + \beta(\alpha_1 + \beta)\gamma_1^2\big)] \\
&\quad + a\alpha_1[(8\alpha_1\lambda - \gamma_1^2)(1 - \rho) + \rho(\gamma_0\gamma_1 + 8\beta\lambda)]\Big], \\
\theta^{IM} &= \frac{1}{\Psi_2}\Big[a[2\alpha_1(\alpha_1\gamma_0 + \beta\gamma_1)(1 - \rho) + \rho\big(2\alpha_1\beta\gamma_0 + (\beta^2 + \alpha_0\alpha_1)\gamma_1\big)] \\
&\quad - c_m[\big(2\alpha_1\gamma_0 + (\alpha_1 + \beta)\gamma_1\big)(\alpha_0\alpha_1 - \beta^2)]\Big]
\end{aligned}$$

*and the corresponding optimal decision of the retailer as*

$$\begin{aligned}
p^{IM} &= \frac{1}{2\Psi_2}\Big[c_m[\alpha_1^2(4\alpha_0\lambda - \gamma_0^2) - 2\beta(\beta\gamma_0\gamma_1 + \alpha_0\gamma_1^2 + 2\beta^2\lambda) \\
&\quad - \alpha_1\big(3\beta\gamma_0^2 + 3(\alpha_0 + \beta)\gamma_0\gamma_1 + 2\alpha_0\gamma_1^2 - 4\beta(\alpha_0 - \beta)\lambda\big)] + a[\big(\gamma_1(3\alpha_1\gamma_0 + 2\beta\gamma_1) \\
&\quad + 8\alpha_1\beta\lambda\big)(1 - \rho) - \rho\big(\gamma_0(3\alpha_1\gamma_0 + 2\beta\gamma_1) - 4\lambda(3\alpha_0\alpha_1 - \beta^2)\big)]\Big]. \\
\textit{where } \Psi_2 &= 8\alpha_1\lambda(\alpha_0\alpha_1 - \beta^2) - (2\alpha_1^2\gamma_0^2 + 4\alpha_1\beta\gamma_0\gamma_1 + (\beta^2 + \alpha_0\alpha_1)\gamma_1^2).
\end{aligned}$$

**Proof.** *The retailer's reaction*

From Eq. (5.5), we have the second order sufficient condition $\frac{\partial^2 \Pi_r^{IM}}{\partial p^2} = -2\alpha_1 < 0$, which ensures that unique optimal solution exists. From the first order optimality condition $\frac{\partial \Pi_r^{IM}}{\partial p} = 0$, we get the optimal reaction as $p^{IM} = \frac{\rho a + \beta p_0 + \gamma_1\theta + \alpha_1 w}{2\alpha_1}$.

*The manufacturer's reaction*

After getting the reaction of the retailer, the manufacturer maximizes his profit and determines the optimal decisions. The Hessian matrix associated with the profit function $\Pi_m^{IM}$ is given by

$$H^{IM} = \begin{pmatrix} -\alpha_1 & \beta & \frac{\gamma_1}{2} \\ \beta & -2\alpha_0 + \frac{\beta^2}{\alpha_1} & \frac{\beta\gamma_1}{2\alpha_1} + \gamma_0 \\ \frac{\gamma_1}{2} & \frac{\beta\gamma_1}{2\alpha_1} + \gamma_0 & -2\lambda \end{pmatrix}$$

Now, $|H_2^{IM}| = 2(\alpha_0\alpha_1 - \beta^2) > 0$, as $\alpha_i > \beta$ $(i = 0, 1)$.

Again, $|H^{IM}| = \frac{(2\alpha_1^2\gamma_0^2 + 4\alpha_1\beta\gamma_0\gamma_1 + (\beta^2+\alpha_0\alpha_1)\gamma_1^2) - 8\alpha_1\lambda(\alpha_0\alpha_1-\beta^2)}{2\alpha_1}$

$< 0, \text{if } \lambda > \frac{(2\alpha_1^2\gamma_0^2 + 4\alpha_1\beta\gamma_0\gamma_1 + (\beta^2+\alpha_0\alpha_1)\gamma_1^2)}{8\alpha_1(\alpha_0\alpha_1-\beta^2)}$.

Therefore, $H^{IM}$ is negative definite if and only if $\lambda > \frac{(2\alpha_1^2\gamma_0^2 + 4\alpha_1\beta\gamma_0\gamma_1 + (\beta^2+\alpha_0\alpha_1)\gamma_1^2)}{8\alpha_1(\alpha_0\alpha_1-\beta^2)}$. Under this condition, the unique optimal solution can be obtained from the first order optimality conditions as given in Proposition 5.2. ■

#### 5.2.1.3 Retailer-led decentralized policy

In the retailer-led decentralized policy, the retailer is the Stackelberg leader and the manufacturer is the follower. Giant retailer like Wal-Mart can influence the sales by lowering selling price. European retailers such as Carrefour and Casino have created their personal brands to compete with the renowned manufacturing brand.

In the retailer-led policy, the manufacturer gives the best response first and then the retailer determines the optimal decisions. The manufacturer's profit function is increasing in $w$. Since $p > w$, therefore, $w$ cannot be equal to $p$. To tackle this problem, we apply the similar approach as proposed by Xie and Neyret (2009); SeyedEsfahani et al. (2011), and Giri and Sharma (2014), which considered that the manufacturer's unit profit margin is equal to the retailer's unit profit margin. In this policy as well as Nash game, the manufacturer has to give a reaction of wholesale price optimizing his profit function which linearly increases with the wholesale price. So, if the manufacturer optimizes his profit function with respect to the wholesale price, then we have $w = p$. This leads the profit of the retailer equal to zero, which is unacceptable in any decentralized policy. Hence, we take unit wholesale price of the manufacturer as $w = (p + c_m)/2$. Then the optimal decisions of the retailer are to be obtained from the following:

$$\begin{aligned} \max_{p^{IR}} \Pi_r^{IR}(p^{IR}) &= \max_{p^{IR}} [(p^{IR} - w^{IR})D_1^{IR}] \\ \text{such that } (p_0^{IR}, \theta^{IR}) &= \arg \max_{(p_0^{IR}, \theta^{IR})} \Pi_m^{IR}(p_0^{IR}, \theta^{IR}) \\ &= \max_{(p_0^{IR}, \theta^{IR})} \left[ p_0^{IR} D_0^{IR} + w^{IR} D_1^{IR} - c_m D^{IR} - \lambda(\theta^{IR})^2 \right] \\ w^{IR} &= (p^{IR} + c_m)/2. \end{aligned}$$

**Proposition 5.3.** *If* $\lambda > \max\left\{\frac{\gamma_0^2}{4\alpha_0}, \frac{\alpha_1\gamma_0^2+2\beta\gamma_0\gamma_1+\alpha_0\gamma_1^2}{4\alpha_0\alpha_1-3\beta^2}\right\}$ *then the retailer-led decentralized policy provides the unique optimal decision of the retailer as*

$$\begin{aligned} p^{IR} &= \frac{1}{2\Psi_3}\Big[c_m[\Psi_3+\beta\lambda(2\alpha_0-\beta)-(\beta\gamma_0^2+(\alpha_0+\beta)\gamma_0\gamma_1+\alpha_0\gamma_1^2)] \\ &\quad +a[(\gamma_0\gamma_1+2\beta\lambda)(1-\rho)+\rho(4\alpha_0\lambda-\gamma_0^2)]\Big] \end{aligned}$$

*and the corresponding optimal decisions of the manufacturer as*

$$\begin{aligned} p_0^{IR} &= \frac{4a\lambda(1-\rho)+c_m[4\alpha_0\lambda-2\beta\lambda-\gamma_0(2\gamma_0+\gamma_1)]+(\gamma_0\gamma_1+6\beta\lambda)p^{IR}}{2(4\alpha_0\lambda-\gamma_0^2)}, \\ \theta^{IR} &= \frac{2a\gamma_0(1-\rho)-c_m[(2\alpha_0+\beta)\gamma_0+2\alpha_0\gamma_1]+(3\beta\gamma_0+2\alpha_0\gamma_1)p^{IR}}{2(4\alpha_0\lambda-\gamma_0^2)}, \\ w^{IR} &= (p^{IR}+c_m)/2. \\ \textit{where } \Psi_3 &= \lambda(4\alpha_0\alpha_1-3\beta^2)-(\alpha_1\gamma_0^2+2\beta\gamma_0\gamma_1+\alpha_0\gamma_1^2). \end{aligned}$$

**Proof.** *The manufacturer's reaction*

The Hessian matrix associated with the profit function $\Pi_m^{IR}$ is given by
$H^{IR} = \begin{pmatrix} -2\alpha_0 & \gamma_0 \\ \gamma_0 & -2\lambda \end{pmatrix}$

It is clear that $|H_1^{IR}| < 0$ and $|H^{IR}| = 4\alpha_0\lambda - \gamma_0^2 > 0$, if $\lambda > \frac{\gamma_0^2}{4\alpha_0}$. Therefore, $H^{IR}$ is negative definite if and only if $\lambda > \frac{\gamma_0^2}{4\alpha_0}$ and the unique optimal decisions of the manufacturer is then given by Proposition 5.3.

*The retailer's reaction*

After getting the reaction of the manufacturer, the retailer optimizes its profit and determines optimal decision. Now, $\frac{\partial^2\Pi_r^{IR}}{\partial p^2} = \frac{\left(\alpha_1\gamma_0^2+2\beta\gamma_0\gamma_1+\alpha_0\gamma_1^2\right)-\lambda\left(4\alpha_0\alpha_1-3\beta^2\right)}{(4\alpha_0\lambda-\gamma_0^2)} < 0$, if $\lambda > \frac{\left(\alpha_1\gamma_0^2+2\beta\gamma_0\gamma_1+\alpha_0\gamma_1^2\right)}{(4\alpha_0\alpha_1-3\beta^2)}$. With this restriction on $\lambda$, the unique optimal decision of the retailer is obtained as given in Proposition 5.3. ∎

#### 5.2.1.4 Decentralized policy (Nash Game)

In the decentralized scenario, the manufacturer and the retailer take their decisions simultaneously and non-cooperatively. Nash game can be seen in the market of small-to-medium sized manufacturer and retailer. In this market, the manufacturer and the retailer have the same power and so they work non-cooperatively.

In this case, our objective is to

$$\max_{(p_0^{ID},\theta^{ID})} \Pi_m^{ID}(p_0^{ID},\theta^{ID}) = \max_{(p_0^{ID},\theta^{ID})} \left[p_0^{ID}D_0^{ID} + w^{ID}D_1^{ID} - c_m D^{ID} - \lambda(\theta^{ID})^2\right]$$

$$\begin{aligned}\text{such that } w^{ID} &= (p^{ID}+c_m)/2\\ \max_{p^{ID}} \Pi_r^{ID}(p^{ID}) &= \max_{p^{ID}} [(p^{ID}-w^{ID})D_1^{ID}].\end{aligned}$$

For the above model, we derive the following proposition:

**Proposition 5.4.** *If $\lambda > \frac{\gamma_0^2}{4\alpha_0}$ then the decentralized (Nash Game) policy provides the following unique optimal decisions:*

$$\begin{aligned}
p_0^{ID} &= \frac{1}{2\Psi_4}\Big[c_m[\Psi_4 - \big(2\alpha_1\gamma_0^2 + (\alpha_1+\beta)\gamma_0\gamma_1 + \beta\gamma_1^2\big) + \lambda(3\beta^2 + 2\alpha_1\beta)]\\
&\quad + a[(8\alpha_1\lambda - \gamma_1^2)(1-\rho) + \rho(\gamma_0\gamma_1 + 6\beta\lambda)]\Big],\\
\theta^{ID} &= \frac{1}{2\Psi_4}\Big[c_m[\gamma_0(\alpha_1\beta + 3\beta^2 - 4\alpha_0\alpha_1) + \gamma_1\big(\beta(\alpha_0+\beta) - 2\alpha_0\alpha_1\big)]\\
&\quad + a[(4\alpha_1\gamma_0 + \beta\gamma_1)(1-\rho) + \rho(3\beta\gamma_0 + 2\alpha_0\gamma_1)]\Big],\\
p^{ID} &= \frac{1}{\Psi_4}\Big[c_m[\lambda(4\alpha_0\alpha_1 - \beta(2\alpha_0+\beta)) - \big((\alpha_1+\beta)\gamma_0^2 + (\alpha_0+\beta)\gamma_0\gamma_1 + \alpha_0\gamma_1^2\big)]\\
&\quad + a[(\gamma_0\gamma_1 + 2\beta\lambda)(1-\rho) + \rho(4\alpha_0\lambda - \gamma_0^2)]\Big],\\
w^{ID} &= (p^{ID}+c_m)/2.\\
\textit{where } \Psi_4 &= \lambda(8\alpha_0\alpha_1 - 3\beta^2) - (2\alpha_1\gamma_0^2 + 2\beta\gamma_0\gamma_1 + \alpha_0\gamma_1^2).
\end{aligned}$$

**Proof.** It is easy to see that $\frac{\partial^2\Pi_r^{ID}}{\partial p^2} = -\alpha_1 < 0$, $\frac{\partial^2\Pi_m^{ID}}{\partial p_0^2} = -2\alpha_0 < 0$, and $\frac{\partial^2\Pi_m^{ID}}{\partial\theta^2} = -2\lambda < 0$. The associated Hessian matrix is given by

$$H^{ID} = \begin{pmatrix} -2\alpha_0 & \gamma_0 \\ \gamma_0 & -2\lambda \end{pmatrix}$$

which is negative definite if $\lambda > \frac{\gamma_0^2}{4\alpha_0}$. Then, from the first order condition of optimality, the optimal decisions $(p_0^{ID}, \theta^{ID}, p^{ID}, w^{ID})$ of the decentralized policy can be obtained as given in Proposition 5.4. ■

### 5.2.2 Model II : Dual-channel return policy

In this policy, dual activities exist in both the forward and the reverse channels. The manufacturer produces the green product and sells to the potential customers through the retail channel as well as the direct channel. In the reverse channel, the manufacturer collects the used products from the customers through the direct channel as well as the retailer. For instance, IBM and Compaq encourage customers to use their recovery services for easy renewal of their end-of-use products. Again, Xerox collects the used products from the customers directly by providing prepaid mailboxes.

Similar to Model I, here also we discuss four different policies depending on the manufacturer's and the retailer's dominance power. As the optimal results can be derived in a manner similar to those of Model I, we list the results in Table 5.1.

**Table 5.1:** Optimal results under Model II.

| Decisions | Optimal decisions |
|---|---|
| $p_0^{IIC}$ | $p_0^{IC} - \frac{d_1\left(\alpha_1\gamma_0+\beta\gamma_1\right)\left(C_0+\tau(A_0-A_1)\right)}{\Psi_1}$ |
| $\theta^{IIC}$ | $\theta^{IC} - \frac{2d_1\left(\alpha_0\alpha_1-\beta^2\right)\left(C_0+\tau(A_0-A_1)\right)}{\Psi_1}$ |
| $p^{IIC}$ | $p^{IC} - \frac{d_1\left(\beta\gamma_0+\alpha_0\gamma_1\right)\left(C_0+\tau(A_0-A_1)\right)}{\Psi_1}$ |
| $w^{IIM}$ | $w^{IM} - \frac{2d_1\alpha_1(\beta\gamma_0+\alpha_0\gamma_1)\left(C_0-\tau(A_2-A_0)\right)}{\Psi_2}$ |
| $p_0^{IIM}$ | $p_0^{IM} - \frac{2d_1\alpha_1\left(\alpha_1\gamma_0+\beta\gamma_1\right)\left(C_0-\tau(A_2-A_0)\right)}{\Psi_2}$ |
| $\theta^{IIM}$ | $\theta^{IM} - \frac{4d_1\alpha_1(\alpha_0\alpha_1-\beta^2)\left(C_0-\tau(A_2-A_0)\right)}{\Psi_2}$ |
| $p^{IIM}$ | $p^{IM} - \frac{d_1\left(2\alpha_1(\beta\gamma_0+3\alpha_0\gamma_1)-\beta^2\gamma_1\right)\left(C_0-\tau(A_2-A_0)\right)}{\Psi_2}$ |
| $p^{IIR}$ | $p^{IR} - \frac{d_1[(\beta\gamma_0+2\alpha_0\gamma_1)\left(C_0+\tau(A_0-A_1)\right)+2\tau\beta\gamma_0(A_2-A_1)]}{2\Psi_3}$ |
| $p_0^{IIR}$ | $\frac{4a\lambda(1-\rho)+c_m[4\alpha_0\lambda-2\beta\lambda-\gamma_0(2\gamma_0+\gamma_1)]+(\gamma_0\gamma_1+6\beta\lambda)p^{IIR}-d_1\gamma_0\left(C_0-\tau(A_2-A_0)\right)}{2(4\alpha_0\lambda-\gamma_0^2)}$ |
| $\theta^{IIR}$ | $\frac{2a\gamma_0(1-\rho)-c_m[(2\alpha_0+\beta)\gamma_0+2\alpha_0\gamma_1]+(3\beta\gamma_0+2\alpha_0\gamma_1)p^{IIR}-4d_1\alpha_0\left(C_0-\tau(A_2-A_0)\right)}{2(4\alpha_0\lambda-\gamma_0^2)}$ |
| $w^{IIR}$ | $(p^{IIR}+c_m)/2$ |
| $p_0^{IID}$ | $p_0^{ID} - \frac{d_1\left(4\alpha_1\gamma_0+3\beta\gamma_1\right)\left(C_0-\tau(A_2-A_0)\right)}{2\Psi_4}$ |
| $\theta^{IID}$ | $\theta^{ID} - \frac{d_1(8\alpha_0\alpha_1-3\beta^2)\left(C_0-\tau(A_2-A_0)\right)}{2\Psi_4}$ |
| $p^{IID}$ | $p^{ID} - \frac{d_1(\beta\gamma_0+2\alpha_0\gamma_1)\left(C_0-\tau(A_2-A_0)\right)}{\Psi_4}$ |
| $w^{IID}$ | $w^{ID} - \frac{d_1(\beta\gamma_0+2\alpha_0\gamma_1)\left(C_0-\tau(A_2-A_0)\right)}{2\Psi_4}$ |

### 5.2.3 Comparison and discussions

From Propositions 5.1-5.4 and Table 5.1, it is clear that greening level of the product in Model I is higher than that in Model II. This is because, in Model I, there is no return policy and the green product is produced from the fresh raw materials whereas in Model II, the manufacturer entertains a return policy and remanufactures the used products. As the greening level of the product is higher in Model I, the manufacturer has to invest more money for green innovation. So, the manufacturer sets higher wholesale price in the retail channel and higher selling price in the direct channel. As the selling price depends on the wholesale price, the selling price in the retail channel in Model I increases. On the other hand, for the lower green product, market demand in Model II may decrease. In order to maintain market demand, the manufacturer has to lower the direct selling price and wholesale price in retail channel. The retailer also decreases her selling price in the retail channel. In this case, the retailer follows the tactic of 'higher greening level in higher price'.

In Table 5.2, we now present the sensitivity of optimal decisions with respect to customer loyalty to the retail channel ($\rho$) and retailer's loyalty on the return quantity ($\tau$) analytically. Table 5.2 illustrates that, for all the centralized, manufacturer-led

**Table 5.2:** Sensitivity with respect to $\rho$ and $\tau$.

| Parameter | Policy | $p_0$ | $p$ | $w$ | $\theta$ |
|---|---|---|---|---|---|
| $\rho$ | centralized | $\frac{\partial p_0^C}{\partial \rho} < 0$ | $\frac{\partial p^C}{\partial \rho} > 0$ | - | $\frac{\partial \theta^C}{\partial \rho} < 0$, if $\alpha_1\gamma_0 > \alpha_0\gamma_1$ |
| | manufacturer-led | $\frac{\partial p_0^M}{\partial \rho} < 0$ | $\frac{\partial p^M}{\partial \rho} > 0$ | $\frac{\partial w^M}{\partial \rho} > 0$ | $\frac{\partial \theta^M}{\partial \rho} < 0$ |
| | Nash | $\frac{\partial p_0^D}{\partial \rho} < 0$ | $\frac{\partial p^D}{\partial \rho} > 0$ | $\frac{\partial w^D}{\partial \rho} > 0$ | $\frac{\partial \theta^D}{\partial \rho} < 0$ |
| $\tau$ | centralized | $\frac{\partial p_0^C}{\partial \tau} < 0$ | $\frac{\partial p^C}{\partial \tau} < 0$ | - | $\frac{\partial \theta^C}{\partial \tau} < 0$, provided that $A_0 > A_1$ |
| | manufacturer-led | $\frac{\partial p_0^M}{\partial \tau} > 0$ | $\frac{\partial p^M}{\partial \tau} > 0$ | $\frac{\partial w^M}{\partial \tau} > 0$ | $\frac{\partial \theta^M}{\partial \tau} > 0$, provided that $A_2 > A_0$ |
| | Nash | $\frac{\partial p_0^D}{\partial \tau} > 0$ | $\frac{\partial p^D}{\partial \tau} > 0$ | $\frac{\partial w^D}{\partial \tau} > 0$ | $\frac{\partial \theta^D}{\partial \tau} > 0$, provided that $A_2 > A_0$ |

decentralized policy, and Nash game, the selling price in the direct channel and the greening level decrease, and the wholesale price and the selling price in the retail channel increase with respect to $\rho$. This is because, for smaller value of $\rho$, the basic market in the direct channel increases. So, the market demand in the direct channel also increases. The manufacturer can acquire significant profit from dual-channel green supply chain. This influences the manufacturer to invest more money in green innovation. The price of the product is proportional to the greening level. So, the manufacturer sets a higher selling price in the direct channel. On the other hand, for higher value of $\rho$, the market demand in the retail channel increases. So, the manufacturer can set higher wholesale price without bothering the greening level of the product, which forces the retailer to set higher selling price. However, the market demand in the direct channel decreases when $\rho$ increases. In order to attract customers and maintain the profit, the manufacturer has to decrease the selling price in the direct channel.

**Insight 5.1.**

- *Market share has important impact on the optimal decisions of the supply chain. The manufacturer and the retailer can sell lower green product with higher price in the large market. However, they have to reduce selling price in comparatively smaller market.*

The last row of Table 5.2 demonstrates that, when the return quantity of used products through the retail channel increases, the manufacturer has to pay a higher price to the retailer for the returned product which obliged the manufacturer to set higher wholesale price in the retail channel and a higher selling price in the direct channel. As the manufacturer remanufactures these returned products and the cost of remanufacturing is less than manufacturing cost, the manufacturer gains more from remanufacturing which he can invest for producing more environment-friendly products. As a result, the greening level increases. In the centralized policy, when the return quantity of used products through the retail channel increases, the manufacturer has to pay lower price to the customer than the direct channel. So, the manufacturer can reduce the selling prices of the product in the retail channel and the direct channel. Due to lower selling price, the manufacturer cannot invest more to produce better green products. As a result, the greening level decreases.

**Insight 5.2.**

- *Effect of retailer's loyalty to the return quantity on the optimal decisions depends on the price paid by the manufacturer and the retailer while collecting used products through the e-tail and the retail channel.*

**Property 5.1.**

*(i) In case of centralized policy,* $\frac{\partial p^C}{\partial p_0} > 0, \frac{\partial p_0^C}{\partial p} > 0, \frac{\partial p^C}{\partial \theta} > 0$ *and* $\frac{\partial p_0^C}{\partial \theta} > 0.$

*(ii) In case of retailer-led decentralized policy,* $\frac{\partial p_0^R}{\partial p} > 0$ *and* $\frac{\partial \theta^R}{\partial p} > 0$*, whenever* $\sqrt{\alpha_0} > \frac{\gamma_0}{2}.$

**Proof.** From Eq. (5.3), using the first order optimality condition of $\Pi^C$, we get $p$ in terms of $p_0$. Now, $\frac{\partial p^C}{\partial p_0} = \frac{\gamma_0\gamma_1+4\lambda\beta}{4\alpha_1\lambda-\gamma_1^2} > 0.$
Again, from Eq. (5.3), using the first order optimality condition of $\Pi^C$, we get $p_0$ in terms of $p$. Now, $\frac{\partial p_0^C}{\partial p} = \frac{\gamma_0\gamma_1+4\lambda\beta}{4\alpha_0\lambda-\gamma_0^2} > 0$. Also, $\frac{\partial p^C}{\partial \theta} = \frac{\alpha_0\gamma_1+\beta\gamma_0}{2(\alpha_0\alpha_1-\beta^2)} > 0$ and $\frac{\partial p_0^C}{\partial \theta} = \frac{\alpha_1\gamma_0+\beta\gamma_1}{2(\alpha_0\alpha_1-\beta^2)} > 0$. From Eq. (5.1), using the first order optimality condition of $\Pi_m$, we get $p_0$ and $\theta$ in terms of $p$. Also, $\frac{\partial p_0^{IIR}}{\partial p} = \frac{\gamma_0\gamma_1+6\lambda\beta}{2(4\alpha_0-\gamma_0^2)} > 0$ and $\frac{\partial \theta^{IIR}}{\partial p} = \frac{2\alpha_0\gamma_1+3\gamma_0\beta}{2(4\alpha_0-\gamma_0^2)} > 0$. ■

Property 5.1 shows that, in order to open a dual-channel, it is necessary for the manufacturer and the retailer to maintain the relationship between the selling prices. It also implies that customers have to buy more environment-friendly products by paying extra money. Although, we have assumed that, for the same green product, customers have to pay more money in the retail channel than the direct channel, but when the retail price in the retail channel is more sensitive than the selling price in the direct channel, the direct selling price increases more than the retail price in the retail channel. This indicates that the greening level affects both the direct and the retail channel's pricing strategies and in this case, the manufacturer engages more aggressive pricing than the retail channel. Property 5.1$(ii)$ indicates that, in case of retailer-led decentralized policy, the greening level changes positively with the selling price in the retail channel whenever the price sensitivity in the direct channel is greater than the greening level sensitivity.

**Property 5.2.** *In case of manufacturer-led decentralized policy, the following results hold:*

(i) $\frac{\partial w^M}{\partial \theta} > 0,\ \frac{\partial p^M}{\partial \theta} > 0 \ and\ \frac{\partial p_0^M}{\partial \theta} > 0.$

(ii) $\frac{\partial \Pi_r^M}{\partial \theta} > 0 \ if\ w < \frac{\rho a+\beta_1 p_0+\gamma_1\theta}{\alpha_1}.$

**Proof.** From Eq. (5.2), using the first order optimality condition of $\Pi_r$, we get $p^M = \frac{\rho a+\beta p_0+\gamma_1\theta+\alpha_1 w}{2\alpha_1}$. Now $\frac{\partial p^M}{\partial \theta} = \frac{\gamma_1}{2\alpha_1} > 0$. Putting this value of $p^M$ in Eq. (5.1), and using the first order optimality condition we get, $w^M = \frac{c_m\alpha_0\alpha_1+a\beta-c_m\beta^2+\beta\gamma_0\theta+\alpha_0\gamma_1\theta+a(\alpha_0-\beta)\rho}{2\alpha_0\alpha_1-2\beta^2}$ and $p_0^M = \frac{c_m\alpha_0\alpha_1-c_m\beta^2+\alpha_1\gamma_0\theta+\beta\gamma_1\theta+a(\alpha_1-\alpha_1\rho+\beta\rho)}{2\alpha_0\alpha_1-2\beta^2}$.
Then, $\frac{\partial w^M}{\partial \theta} = \frac{\alpha_0\gamma_1+\beta\gamma_0}{2(\alpha_0\alpha_1-\beta^2)} > 0$ and $\frac{\partial p_0^M}{\partial \theta} = \frac{\alpha_1\gamma_0+\beta\gamma_1}{2(\alpha_0\alpha_1-\beta^2)} > 0$. Again, from Eq. (5.2), $\frac{\partial \Pi_r^M}{\partial \theta} = \frac{\gamma_1(\rho a+\beta p_0+\gamma_1\theta-\alpha_1 w)}{2\alpha_1} > 0$, if $w < \frac{\rho a+\beta p_0+\gamma_1\theta}{\alpha_1}$. ■

Property 5.2 implies that $w^M$ increases as $\theta$ increases and consequently, $p^M$ increases. This is because, when the greening level increases, the cost of the item also increases. So, the channel members charge higher price in both the traditional retail channel and the direct channel. Although the retail price increases, due to more environment-friendly product, customers want to buy more. As a result, the profit of the retailer increases. However, when the wholesale price exceeds the threshold, the retailer must charge a higher retail price. This time, the customers refuse to buy the products by paying more money.

## 5.3 Numerical analysis

In this section, we perform a numerical study to compare the optimal results derived in the previous section under different policies. The numerical data sets are chosen from the existing literature which are close to this chapter (e.g., Giri et al. (2017)). We consider the following three different numerical examples depending on the price paid by the manufacturer and the retailer while collecting used products from the customers through both the retail and e-tail channels.

**Example 1.** $\rho = 0.85; a = 90; \alpha_0 = 0.09; \alpha_1 = 0.16; \beta = 0.075; \gamma_0 = 0.75; \gamma_1 = 0.87; d_0 = 20; d_1 = 5; \lambda = 150; c_m = 120; c_r = 40; A_0 = 65; A_1 = 55; A_2 = 70; \tau = 0.6\ (A_2 > A_0 > A_1)$.

**Example 2.** All data are same as Example 1 except $A_0 = 60; A_1 = 65; A_2 = 70\ (A_2 > A_1 > A_0)$.

**Example 3.** All data are same as Example 1 except $A_0 = 80; A_1 = 65; A_2 = 70\ (A_0 > A_2 > A_1)$.

**Table 5.3:** Optimal results for three examples.

| Optimal decisions | Example 1 | | | | | | | | Example 2 | | | | Example 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model I | | | | Model II | | | | | | | | | | | |
| | C | D | M | R | C | D | M | R | C | D | M | R | C | D | M | R |
| $p_0$ | **533.366** | **354.54** | 529.95 | 393.449 | **529.483** | **353.133** | 527.74 | 391.114 | 530.223 | 352.898 | 527.372 | 391.389 | 531.702 | 353.837 | 528.845 | 392.414 |
| $w$ | - | 252.398 | 524.49 | 282.906 | - | 251.955 | 522.885 | 281.735 | - | 251.881 | 522.618 | 282.061 | - | 252.176 | 523.688 | 282.425 |
| $p$ | **526.971** | **384.796** | **630.653** | 445.812 | **524.151** | **383.909** | **628.764** | 443.47 | 524.688 | 383.761 | 628.449 | 444.122 | 525.762 | 384.353 | 629.708 | 444.849 |
| $\theta$ | **2.21363** | 0.970305 | 1.89002 | 1.15605 | **1.84574** | 0.7655 | 1.68067 | 0.946816 | 1.91582 | 0.73137 | 1.64578 | 0.91512 | 2.05597 | 0.86790 | 1.78535 | 1.05207 |
| $D_0$ | 6.68011 | 11.1788 | **14.521** | 12.3925 | 6.54215 | 11.0854 | **14.4211** | 12.2701 | 6.56843 | 11.0698 | 14.4045 | 12.2705 | 6.62099 | 11.1321 | 14.4711 | 12.3354 |
| $D_1$ | 34.1129 | **42.3673** | 16.9861 | 35.6846 | 33.9529 | **42.2255** | 16.9405 | 35.7021 | 33.9834 | 42.2018 | 16.9331 | 35.5908 | 34.0443 | 42.2964 | 16.9633 | 35.6705 |
| $D$ | 40.793 | **53.5461** | 31.5071 | 48.0771 | 40.4951 | **53.3108** | 31.3617 | 47.9722 | 40.5518 | 53.2716 | 31.3374 | 47.8613 | 40.6653 | 53.4285 | 31.4344 | 48.0060 |
| $D_R$ | - | - | - | - | 10.7713 | **16.1725** | 11.5966 | 15.2659 | 10.4209 | **16.3432** | 11.7711 | 15.4244 | 9.72017 | **15.6605** | 11.0733 | 14.7397 |
| $\Pi_m$ | - | 8090.0 | **12287.8** | 9001.47 | - | 8262.38 | **12420.6** | 9149.59 | - | 8292.31 | **12444.0** | 9188.28 | - | 8174.64 | **12352.6** | 9076.53 |
| $\Pi_r$ | - | 5609.35 | 1803.29 | **5813.23** | - | 5717.4 | 1898.01 | **5911.67** | - | 5614.64 | 1827.34 | **5814.16** | - | 5637.56 | 1831.68 | **5837.99** |
| $\Pi^j$ | **15909.3** | 13699.4 | 14091.0 | **14814.7** | **16116.2** | 13979.8 | 14318.6 | **15061.3** | 16073.8 | 13906.9 | 14271.3 | **15002.4** | 15993.2 | 13812.2 | 14184.3 | **14914.5** |
| CE$(=\frac{\Pi^j}{\Pi^C})$ | 1 | 0.89109 | 0.88570 | 0.93120 | 1 | 0.86743 | 0.88846 | 0.93454 | 1 | 0.86519 | 0.88786 | 0.93333 | 1 | 0.86363 | 0.88689 | 0.93225 |

Table 5.3 demonstrates the optimal results for three examples. As expected, the centralized policy is the benchmark case. The retailer-led decentralized policy gives the best performance and the Nash game gives the worst performance among the three decentralized policies for both models. The selling price in the direct channel is higher in the centralized case and lower in the Nash game but, in case of retail channel, the selling price is higher in the manufacturer-led decentralized policy followed by the centralized policy, the retailer-led decentralized policy, and the Nash game. This is because both the channel members in Nash game work independently. In order to take no risk on market demand, they decrease the selling prices. It is clear from Table 5.3 that, the selling price in the direct channel is lower

than that in the traditional retail channel in all cases except the centralized policy. The centralized policy gives more environment-friendly product and the Nash game gives less environment-friendly product. The player gains more profit when s/he is the Stackelberg leader. So each player wants to lead the supply chain. Table 5.3 also verifies the theoretical results that optimal decisions in Model II are lower than those in Model I. However, in Model II, the manufacturer collects and remanufactures the used products and the remanufacturing cost is less than the manufacturing cost. So, the profits of the manufacturer, the retailer and the whole system are higher than those of Model I. It is interesting to see that the total demand and the return quantity are higher in the Nash game, but the total profit cannot exceed that in the centralized policy. As the total channel profit is higher in the retailer-led decentralized policy, channel efficiency (CE) is higher in the retailer-led decentralized policy followed by the manufacturer-led decentralized policy and Nash game.

Compared to Example 1, the retailer in Example 2 pays a higher price in the retail channel than the manufacturer in the direct channel for collecting used products. So, in this case, return quantity increases. We note that higher return quantity produces less green product. Lower greening level forces both the manufacturer and the retailer to set lower prices. Since the remanufacturing cost is lower than the manufacturing cost, the profit of the manufacturer increases but the higher collection price causes a loss to the retailer. Decrement of the retailer's profit being higher than the increment of the manufacturer's profit, the total profit of the supply chain decreases. In case of the retailer-led decentralized policy, as the retailer spends more, she demands more selling price. This forces the manufacturer to set higher wholesale price and direct selling price.

In Example 3, the manufacturer spends higher collection price in the direct channel than the retail channel but the basic market for direct channel being lower, the returned quantity decreases. So, the greening level of the product increases. This helps the manufacturer and the retailer to increase the selling price. Higher greening level increases market demand. As the manufacturer spends more for collecting used products, his profit decreases but higher selling price increases the profit of the retailer. Decrement of the manufacturer's profit being higher than the increment of the retailer's profit, the total profit of the supply chain decreases.

**Insight 5.3.**

- *Collection prices of the manufacturer and the retailer for collecting used products from* *the end customers have significant impact on the pricing and greening strategies, and profitability of the supply chain.*

- *The centralized policy provides the best performance and the Nash game provides the worst performance; the player gains more profit when s/he is the Stackelberg leader; among the three decentralized policies, the retailer-led decentralized policy gives higher profit for the retailer and the whole supply chain.*

# 5.4 Sensitivity analysis

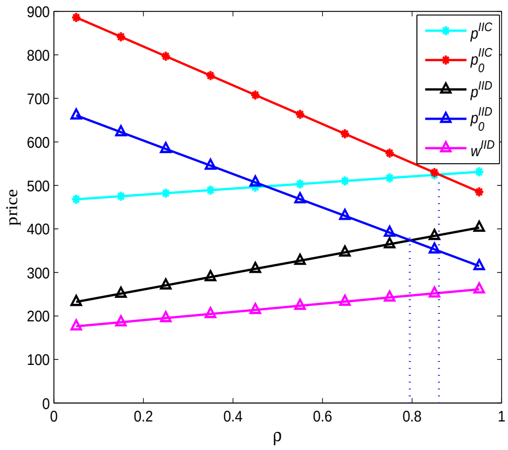
In this section, we discuss the sensitivity of some key parameters of the model. We keep all parameters fixed and change the value of one parameter at a time to investigate its impact on the optimal solution. The sensitivity of the parameters $\rho$, $\lambda$, and $\tau$ is shown in Figs. 5.2-5.4.

## *5.4.1 Effect of the degree of the customer loyalty on the retail channel*

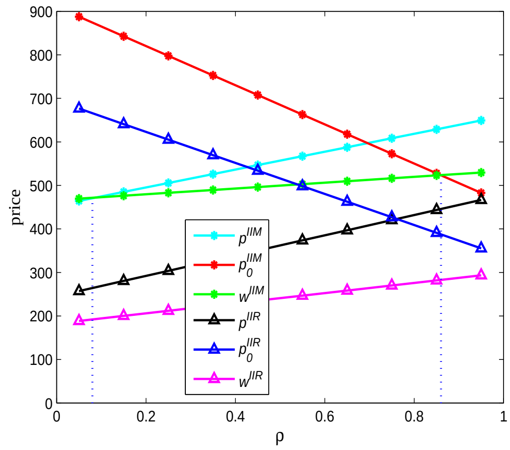
Fig. 5.2(a) shows how selling prices in the direct and the retail channels under the centralized policy and the Nash game are affected by $\rho$ in Model II (results of Model I being similar, we ignore those graphs). We see that, as $\rho$ increases, the wholesale price (for the Nash game), and the selling price in the retail channel increase and that in the direct channel decreases. The direct selling price becomes lower than the retail prices in the Nash game and the centralized policy when $\rho$ exceeds the values 0.8 and 0.86, respectively; otherwise, the direct selling price is higher than the retail price. We also note that the direct selling price and the retail price of the centralized policy are greater than those in the Nash game.

From Fig. 5.2(b), we see that, the direct selling prices for the manufacturer-led and the retailer-led decentralized policies decrease as $\rho$ increases. When $\rho$ takes the value less than 0.08, the wholesale price is greater than the retail price resulting a loss to the retailer. Also, when $\rho$ takes the value more than 0.86, the wholesale price is greater than the direct selling price. So, for dual-channel, $\rho$ must be less than 0.86. For the retailer-led decentralized policy, when $\rho$ crosses the value 0.75, the direct selling price is lower than the retail price; otherwise, the opposite situation arises.

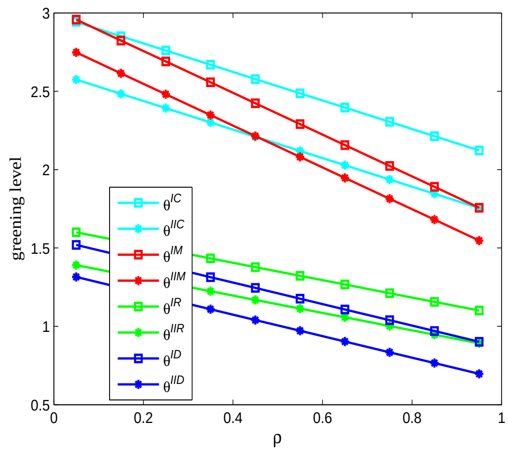
Fig. 5.2(c) illustrates changes of the greening level in the four policies for both models. We note that the greening level decreases with the increment of $\rho$. In Model



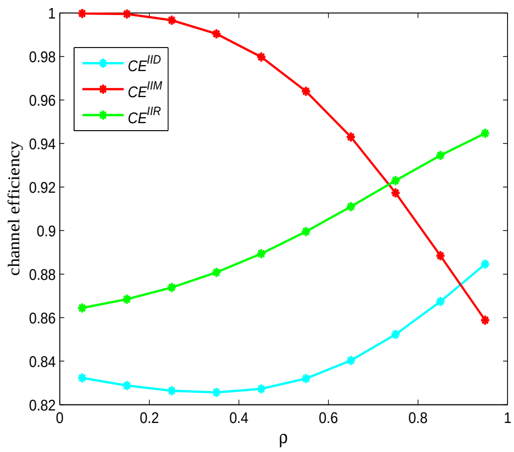

(a) $\rho$ vs price.




(b) $\rho$ vs price.




(c) $\rho$ vs greening level.




(d) $\rho$ vs channel efficiency.

**Fig. 5.2:** Effects of $\rho$ on optimal results and channel efficiency.

II, the greening level takes the least value in the decentralized policy and the highest value in the centralized policy only when $\rho$ is greater than 0.47; otherwise, it attains the maximum value in the manufacturer-led decentralized policy.

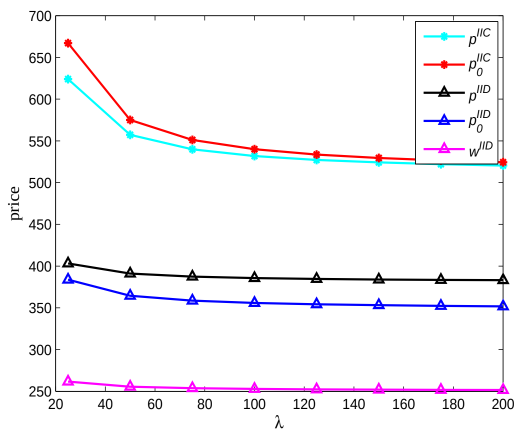
A higher retail price increases the retailer's profit but a lower direct selling price decreases the manufacturer's profit. The rate of decrease in the manufacturer's profit being higher than the rate of increase in the retailer's profit, the overall channel profit decreases. The rate of decrease in the total profit is higher in the manufacturer-led decentralized policy than other policies, which implies that the CE decreases. In case of the retailer-led decentralized policy and the Nash game, the rate of decrease in the total profit is lower than that in the centralized policy. So, in that case, the CE increases. From Fig. 5.2(d) we note that, initially the CE attains the maximum value in the manufacturer-led decentralized policy. As $\rho$ increases, it tends to decrease very fast. When $\rho$ crosses the value 0.89, it attains the least value.

**Insight 5.4.**

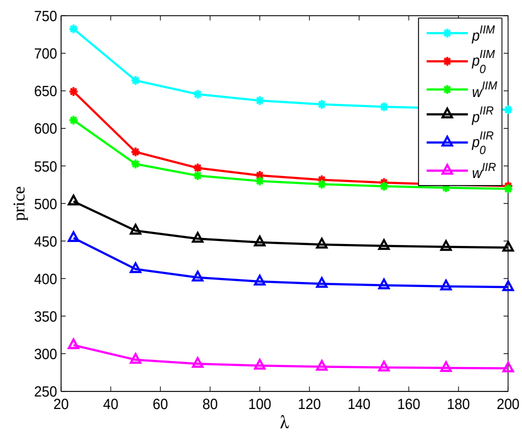
- *The volume of market share helps the manufacturer to decide whether he should sell the product through only retail channel or open dual channel.*

## 5.4.2 Effect of the green investment coefficient

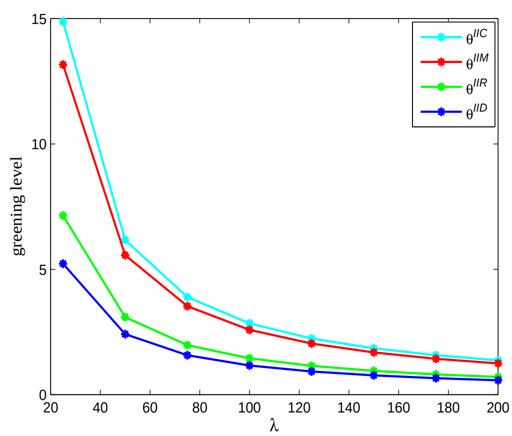
Now, we illustrate how the green investment coefficient $\lambda$ influences the optimal decisions. Figs. 5.3(a) and (b) represent the effect of $\lambda$ on the direct selling price, the wholesale price, and the retail price for various policies. As usual, these decisions are negatively related to $\lambda$. Commonly, all these decisions decrease very fast until $\lambda$ crosses a certain level, but after that, they decrease slowly for all the four policies.



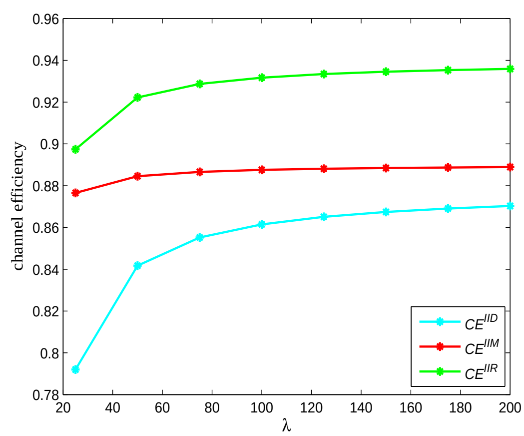

(a) $\lambda$ vs price.




(b) $\lambda$ vs price.




(c) $\lambda$ vs greening level.




(d) $\lambda$ vs channel efficiency.

**Fig. 5.3:** Effects of $\lambda$ on optimal results and channel efficiency.

From Fig. 5.3(c), we note that the greening level decreases when $\lambda$ increases. This is obvious. The higher greening cost not only discourages the manufacturer to produce the green product, but also forces them to charge a higher selling price.

Although the selling prices in both the direct and the retail channels decrease when $\lambda$ increases, the market demand decreases due to the lower green product. So, the profits of the manufacturer, the retailer, and the whole supply chain decrease. Fig. 5.3(d) shows that, as $\lambda$ increases, the CE increases fast until it crosses a certain level; after that, it remains constant. The reason behind this type of behavior of the CE is similar as discussed in the subsection 5.4.1. The CE is maximum for the retailer-led decentralized policy and minimum in the Nash game.

**Insight 5.5.**

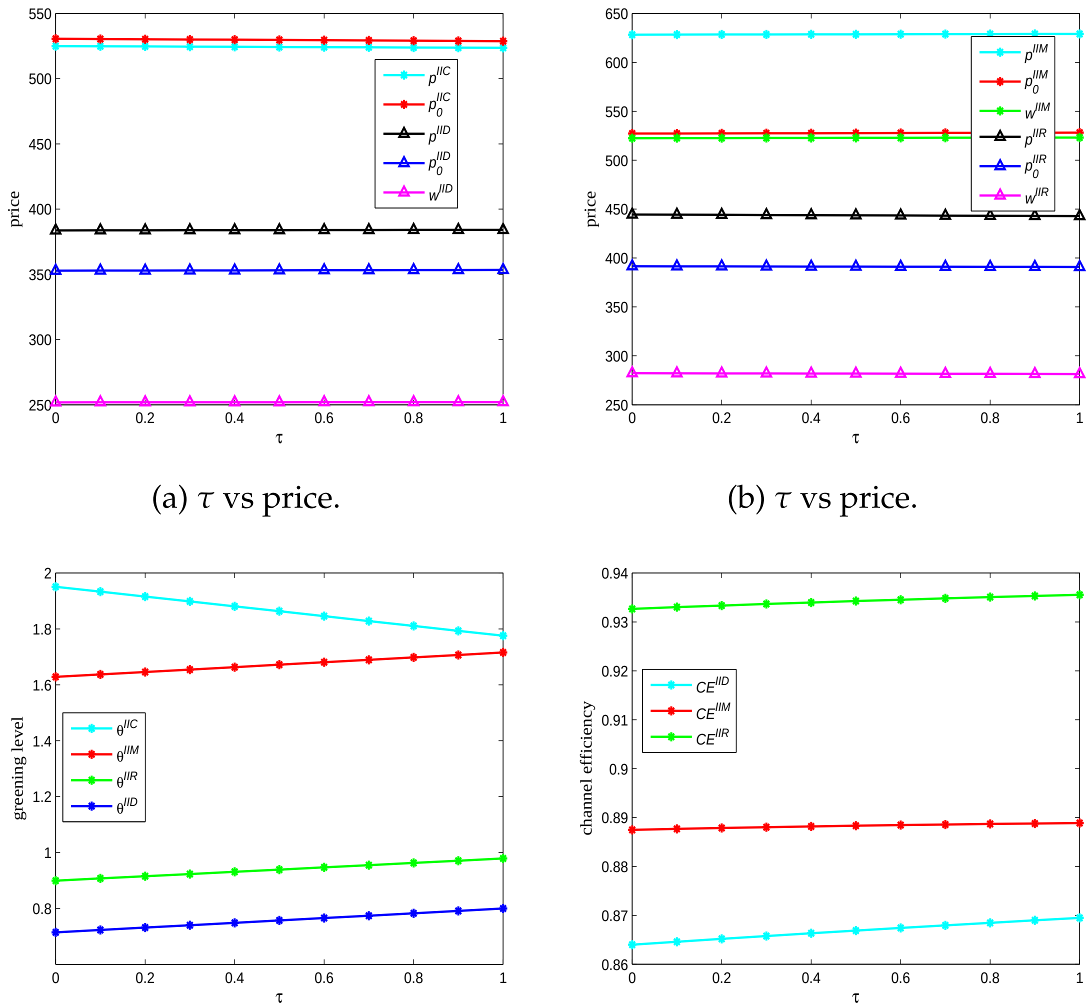
- *The manufacturer can increase the greening level and achieve higher profit by lowering the green investment cost and increasing greening sensitivity cost.*
- *As it is impossible for the manufacturer to reduce the green investment cost, higher market demand through increasing public awareness can help the manufacturer to improve greening level.*

### 5.4.3 Effect of the degree of the manufacturer's loyalty on the return quantity

In this subsection, we explore how the degree of the manufacturer's loyalty to the return quantity influences the optimal decisions. Figs. 5.4(a) and 5.4(b) depict the effect of $\tau$ on the direct selling price, the wholesale price and the retail price for the four policies. We note that, for the centralized policy, the selling prices in both the direct and retail channels decrease as $\tau$ increases. However, for the manufacturer-led decentralized policy, the retailer-led decentralized policy, and the Nash game, these variables remain unchanged as $\tau$ increases.

From Fig. 5.4(c) we observe that, as $\tau$ increases, the greening levels for the decentralized policies increase but that in the centralized policy decreases. As $\tau$ increases, although the manufacturer has to pay higher collection price, he gains more profit due to higher return. So, he can increase the greening level.

Fig. 5.4(d) demonstrates that the CE increases with $\tau$ for all the decentralized policies. When $\tau$ increases, the profit of the whole supply chain increases in all the




(a) $\tau$ vs price. (b) $\tau$ vs price.

(c) $\tau$ vs greening level. (d) $\tau$ vs channel efficiency.

**Fig. 5.4:** Effects of $\tau$ on optimal results and channel efficiency.

four policies. Profits of three decentralized policies follow the relationship: $\Pi^R > \Pi^M > \Pi^D$. So, the CE attains the maximum value for the retailer-led decentralized policy and the minimum value for the Nash game.

## 5.5 Managerial implications and conclusions

This chapter considers a dual-channel green CLSC with a manufacturer and a retailer. The manufacturer produces the green product from fresh raw materials. At the same time, he remanufactures the used products which were returned through both the direct and retail channel. The manufacturer then sells the remanufactured product together with the new product to the potential customers not only through direct channel but also through the retail channel. The market demand of the product is dependent on the direct selling price, retail price, and greening level of the product. We develop various models under different channel leaderships.

The optimal results are obtained both analytically and numerically. Numerical results show that, as usual the centralized policy provides the best result. Among the three decentralized policies, the retailer-led decentralized policy performs better in terms of the total profit of the supply chain and the profit of the retailer which is similar to the model of Choi et al. (2013). The manufacturer gains the maximum profit when s/he leads the channel. Furthermore, it is surprising to see that, the retail price of the centralized policy is greater than that in the decentralized policy. This result contradicts the result due to double marginalization and it is in the same line with the result of Li et al. (2016). In addition, we examine the sensitivity of the customer loyalty of retail channel, green investment coefficient and the manufacturer's loyalty to the return quantity on pricing and greening level. We obtain that the amount of market share plays an important role in deciding whether the manufacturer should sell the product through only retail channel or open dual channel; an increase in collection through the manufacturer directly enhances channel efficiency.

To run a business in a dual-channel, a firm manager has to take several important decisions like which channel is to be used for selling the product or when dual-channel is to be used. In this chapter, we have seen that when the market share to the retail channel is very low, the wholesale price is greater than the retail price which is not acceptable. In this case, there will be only the direct channel and no retail channel. So, the market share must be greater than some threshold value. This finding determines the situation when the retailing firm agrees to do business in the market. We have also determined that when the market share to the retail channel is very high, the direct selling price is less than the wholesale price. So, we have obtained the threshold value of market share which suggests the manufacturing enterprizes when to open a dual channel. Thus, our model will be useful to both the manufacturing firm and the retailing firm. From the sensitivity of the greening cost, we see that the direct selling price, the wholesale price, the retail price, the greening level, and the profits in all the four policies decrease as the greening cost increases. A cost sharing mechanism or government subsidy can improve the greening level of the products and the profits of the channel members and the whole supply chain.

# 6

# Cooperative and non-cooperative behavior of same level players under governmental intervention

## 6.0 Introduction

In today's business environment, the competition among manufacturers and retailers has become more responsive and an important factor of every economy in the world. Most companies focus on fulfilling value to their customers. Every company desires to provide better products and services than its competitors. That's why, several manufacturers distinguish product varieties by differentiating one or more product specifications like technology, appearance, color, etc. For instance, manufacturers like IBM, Xerox, HP, Dell, Adidas, etc. are utilizing unconventional production methods for distinguishing their businesses from competitors. Similar to manufacturers, retailers like Wal-Mart and Tesco have unmatched supply chains which focus on reducing selling prices of the products, while the other retailers try to reduce prices of the products so as to compete with big retailers. Cooperative or non-cooperative behavior among the vertical and/or horizontal players of a supply chain can play an important role in optimal decision making. In a market, multiple manufacturers and/or retailers may cooperate or compete or play the Stackelberg game while making decisions. So, there is a need to determine the best strategy for manufacturers and retailers in green supply chain.

Governments play the most prominent and strongest roles in the market, and they can influence the manufacturer in green manufacturing and consumers to purchase the green product. The green innovation needs advanced technologies, which again demands higher manufacturing costs. Government subsidy to green manufacturers assists to reduce manufacturing costs. Governments in developed countries utilize different rules, regulations, and budgetary directives to increase the knowledge of environmental pollution among the common people and green product manufacturers. For example, the German government paid €2500 subsidy to the customers for the replacement of 13-year-old vehicles (Huang et al., 2014); the Chinese government assigned ¥60000 for the purchases of new battery oriented electric vehicles (Motavalli, 2010); the government of Japan provided ¥100,00 subsidy toward tax cuts and rebates for encouraging green vehicle consumption (Li et al., 2018); Innovate the UK, a UK-based innovation agency, provided £20 million in R&D funding to improve low-carbon expansion in the automotive sector (Li et al., 2020). The Indian government is also popping up some great initiatives to encourage manufacturers, retailers, and customers to produce, sell and buy eco-friendly products. India committed to the voluntary Copenhagen Accord to reduce emissions intensity by 20-25% of 2005 by 2025 and adopted several measures including increased use of renewable energy, nuclear energy, afforestation, and solar energy for sustainable development.

This chapter is based on the following common assumption:

- In order to produce more green product, the government offers endowment to the green manufacturer for delivering every unit of green product as $s = k\theta_0(\theta - \theta_0)$, where $\theta_0$ is the minimum acceptable greening level set by the government (greening level floor) and $k$ is the adjustment factor. If $\theta \geq \theta_0$, the subsidy is $k\theta_0(\theta - \theta_0)$; otherwise, the penalty is $-k\theta_0(\theta - \theta_0)$ (Zhu and Dou, 2011; Yang et al., 2017).

The present chapter considers the effects of government intervention on the green manufacturer for producing the environment-friendly product. In addition, it develops various models considering the competing behaviors of manufacturers in Section 6.1 and those of retailers in Section 6.2 while making their best decisions.

# 6.1

# *A green closed-loop supply chain with manufacturing competition for substitutable products*

This investigation intends to focus on the horizontal cooperation and competition of the green manufacturer and the conventional non-green manufacturer who produce substitutable products. They produce and wholesale their products to a common retailer with greening level-dependent wholesale prices. Both the manufacturers collect used products directly from the consumers and remanufacture them. The government provides greening level-dependent subsidy to $M_1$ to motivate on green manufacturing. First, we develop a centralized policy (C) as the benchmark case. Next, we explore the optimal results in three manufacturer-led Stackelberg game models depending on various competing behavior of the manufacturers. Then, we develop a Nash game (N) where all channel members work simultaneously. Finally, we propose a cost sharing (CS) contract and revenue sharing under cost sharing (RCS) contract. While considering these issues simultaneously, the following queries may emerge:

- How does the government intervention to the green manufacturer influence the ideal outcomes and the profitability of the players of the CLSC?
- Which behavior of the manufacturers is favorable from the perspective of the channel individuals and consumers?
- What are the impacts of the market share, price sensitivity, green level floor on the ideal outcomes and profitability of the channel individuals?

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### 6.1.1 Notations and assumptions

The required notations for developing the proposed models are as follows:

| | |
|---|---|
| $w_i$ | unit wholesale price set by the manufacturer $i$ to the retailer ($i = 1, 2$) (decision variable). |
| $p_1$ | unit retail price of green product (decision variable). |
| $p_2$ | unit retail price of conventional non-green product (decision variable). |
| $\theta$ | level of green innovation (decision variable). |
| $D_1$ | market demand of green product. |
| $D_2$ | market demand of conventional non-green product. |
| $D_{R1}$ | return quantity to the green manufacturer. |
| $D_{R2}$ | return quantity to the non-green manufacturer. |
| $c_{m_1}$ | unit production cost of green product from the crude materials. |
| $c_{m_2}$ | unit production cost of conventional non-green product from the crude materials. |
| $A_1$ | value of used product to the green manufacturer. |
| $A_2$ | value of used product to the non-green manufacturer. |
| $a$ | basic market demand. |
| $\tau_i$ | fraction related to return quantity, $0 \leq \tau_i \leq 1$, ($i = 1, 2$). |
| $\lambda$ | green investment cost coefficient. |
| $\Pi_{m_i}$ | profit of the manufacturer $i$ ($i = 1, 2$). |
| $\Pi_r$ | profit of the retailer. |
| $\Pi$ | profit of the entire supply chain. |

The accompanying assumptions are considered for setting up the proposed models:

**(1)** Market demands of both products are deterministic and linearly reliant upon the greening level, retail prices of both products. Demand functions are assumed as $D_1 = \rho a - b_1 p_1 + b_2 p_2 + \beta_1 \theta$ and $D_2 = (1-\rho)a - b_1 p_2 + b_2 p_1 - \beta_2 \theta$, where $\rho$ is the customer loyalty to the green product, and $\beta_1$ and $\beta_2$ are green level sensitivity parameters. The parameters $b_1$ and $b_2$ address the self-price and the cross-price elasticity, respectively. We consider that $b_1 > b_2$, *i.e.* the effect of self-price is greater than that of cross-price. This takes place when the quantity of consumers leaving a market because of expansion in selling price of one product, is more prominent than the quantity of consumers shifting to this market because of expansion in the selling price of the other market. We also assume that $\beta_1 > \beta_2$, which demonstrates that the green product's impact in the green sensitive market is higher than the traditional market (Jamali and Rasti-Barzoki, 2018).

**(2)** The return quantity $D_{Ri}$ is assumed as $D_{Ri} = \tau_i D_i, i = 1, 2$. It indicates that a manufacturer only collects the product which he has sold previously. For instance, if there are two types of vehicle, namely, battery electric (Chevrolet Volt, Nissan Leaf) and diesel-powered vehicle in market, then the battery electric vehicle manufacturer only collects used battery electric vehicles.

**(3)** Unit production cost and wholesale price of the green product are dependent on the greening level and are given by $c_{m_1} = c_{m_2} + c\theta$ and $w_1 = w_2 + \alpha\theta$, where $c$ and $\alpha$ are the greening level elasticity parameter of the production cost and wholesale price of the green product, respectively.

**(4)** The manufacturers have to spend some money to collect used products and transfigure it to raw materials. Let $A_{0_i}$ be the sum of all these costs, and the value of raw materials extricated from used products to the manufacturer $M_i$ be $A_{1_i}$. Then, the benefit of the transformed raw material to the manufacturer $M_i$ is $A_i = A_{1_i} - A_{0_i}$, $i = 1, 2$.

## 6.1.2 Model development and analysis

We consider a two-echelon green CLSC consisting of two competing manufacturers,

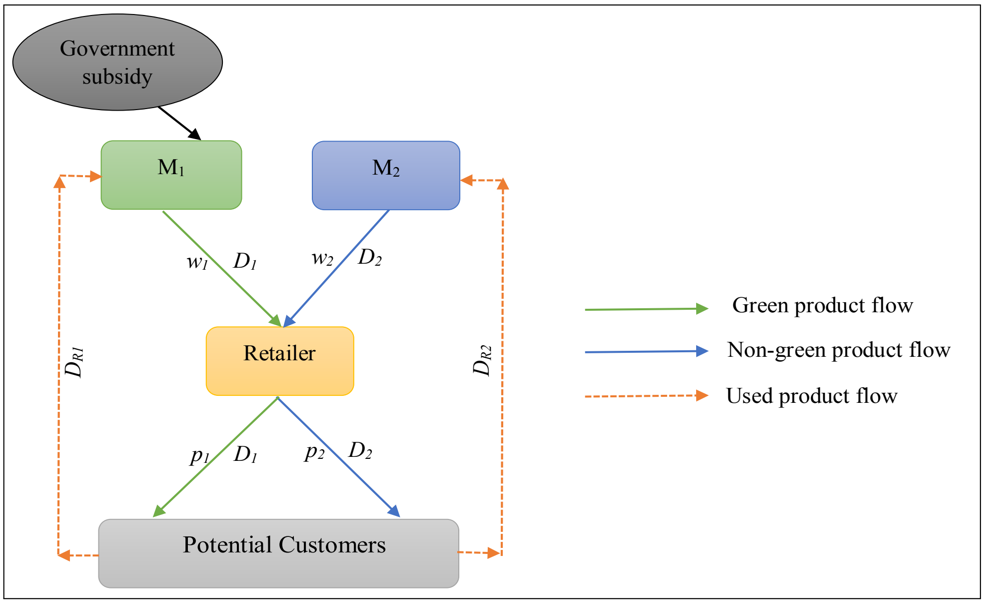



**Fig. 6.1.1:** Proposed closed-loop supply chain.

namely, green manufacturer ($M_1$) and conventional non-green manufacturer ($M_2$) and a single retailer. $M_1$ produces a green substitutable product of greening level $\theta$ at unit manufacturing cost $c_{m_1}$ by using advanced technologies and $M_2$ produces non-green product at unit manufacturing cost $c_{m_2}$ by using traditional and old-fashioned technologies. $M_i$ wholesales its product to the monopolistic retailer at unit wholesale price $w_i$, and the retailer then delivers to the potential consumers at unit retail price $p_i$, where $i = 1, 2$. Besides producing and selling new product through the forward channel, both manufacturers collect used products through the backward channel from end customers. Fig. 6.1.1 represents the graphical representation of the proposed CLSC. Under the above presumptions, the profit functions for the channel individuals are given by

$$\Pi_{m_1}(\theta) = (w_1 - c_{m_1})D_1 + sD_1 + A_1D_{R1} - \lambda\theta^2 \quad (6.1.1)$$

$$\Pi_{m_2}(w_2) = (w_2 - c_{m_2})D_2 + A_2D_{R2} \quad (6.1.2)$$

$$\Pi_r(p_1, p_2) = (p_1 - w_1)D_1 + (p_2 - w_2)D_2 \quad (6.1.3)$$

### 6.1.2.1 Centralized policy (C)

In this policy, two manufacturers and the retailer act as a single decision-making entity and they make their decisions through a cooperative game which maximizes the total profit. So, the problem of the centralized policy is given by,

$$\max_{(p_1,p_2,\theta)} \Pi^C(p_1, p_2, \theta) = \max_{(p_1,p_2,\theta)} (p_1 - c_{m_1})D_1 + (p_2 - c_{m_2})D_2 + sD_1 + A_1D_{R1} + A_2D_{R2} - \lambda\theta^2 \quad (6.1.4)$$

Utilizing the first-order optimality conditions of $\Pi^C(p_1, p_2, \theta)$, the ideal outcome for the centralized policy can be acquired as follows:

**Proposition 6.1.1.** *At the equilibrium, the centralized policy gives the accompanying unique ideal outcomes*

$$\begin{aligned} p_1^C &= \frac{1}{2\Psi_1\Xi}\Big[2(b_1\Psi_1 - b_2\Psi_2)(2[\lambda - \beta_1(k\theta_0 - c)](\Phi_1 + a\rho - \Psi_1 Y)) + \big(-\Psi_1\Psi_2 \\ &\quad +4b_2[\lambda - \beta_1(k\theta_0 - c)]\big)\big(\Psi_2(\Phi_1 + a\rho) + \Psi_1[a(1-\rho) - \Phi_2]\big)\Big], \\ p_2^C &= \frac{1}{2\Xi}\Big[M_2\Xi + [Y + \Phi_1(k\theta_0 - c)](b_1\beta_2 - b_2\beta_1) - a(1-\rho)[\beta_1 + b_1(k\theta_0 - c)]^2 \\ &\quad -a\rho[b_1b_2(k\theta_0 - c)^2 + 2b_2\beta_1(k\theta_0 - c) + (\beta_1\beta_2 - 4\lambda b_2)]\Big], \\ \theta^C &= \frac{a\rho(b_1\beta_1 - b_2\beta_2) + a(1-\rho)(\beta_1 b_2 - \beta_2 b_1) - (b_1^2 - b_2^2)[(k\theta_0 - c)(\Phi_1 + a\rho) + Y]}{\Xi}, \end{aligned}$$

*provided* $\lambda > max\left\{\beta_1(k\theta_0 - c), \frac{b_1^3(k\theta_0-c)^2 + b_1\left(\beta_1^2+\beta_2^2-b_2^2(k\theta_0-c)^2\right)+2(b_1^2-b_2^2)\beta_1(k\theta_0-c)-2b_2\beta_1\beta_2}{4(b_1^2-b_2^2)}\right\}.$

**Proof.** From Eq. (6.1.4), we get

$\frac{\partial \Pi^C}{\partial p_1} = -2b_1p_1 + 2b_2p_2 + \Psi_1\theta + a\rho + b_1M_1 - (b_1 + b_2)M_2$; $\frac{\partial^2 \Pi^C}{\partial p_1^2} = -2b_1$

$\frac{\partial \Pi^C}{\partial p_2} = 2b_2p_1 - 2b_1p_2 - \Psi_2\theta + a(1-\rho) - b_2M_1 + (b_1 + b_2)M_2$; $\frac{\partial^2 \Pi^C}{\partial p_2^2} = -2b_1$

$\frac{\partial \Pi^C}{\partial \theta} = \Psi_1 p_1 - \Psi_2 p_2 - 2[\lambda - \beta_1(k\theta_0 - c)]\theta + a\rho(k\theta_0 - c) - \beta_1 p_1 + (\beta_1 + \beta_2)M_2;$
$\frac{\partial^2 \Pi^C}{\partial \theta^2} = -2[\lambda - \beta_1(k\theta_0 - c)];\ \frac{\partial^2 \Pi^C}{\partial p_1 \partial p_2} = 2b_2;\ \frac{\partial^2 \Pi^C}{\partial p_1 \partial \theta} = \Psi_1;\ \frac{\partial^2 \Pi^C}{\partial p_2 \partial \theta} = -\Psi_2$
The Hessian matrix associated with $\Pi^C$ is given by

$$H^C = \begin{pmatrix} \frac{\partial^2 \Pi^C}{\partial p_1^2} & \frac{\partial^2 \Pi^C}{\partial p_1 \partial p_2} & \frac{\partial^2 \Pi^C}{\partial p_1 \partial \theta} \\ \frac{\partial^2 \Pi^C}{\partial p_2 \partial p_1} & \frac{\partial^2 \Pi^C}{\partial p_2^2} & \frac{\partial^2 \Pi^C}{\partial p_2 \partial \theta} \\ \frac{\partial^2 \Pi^C}{\partial \theta \partial p_1} & \frac{\partial^2 \Pi^C}{\partial \theta \partial p_2} & \frac{\partial^2 \Pi^C}{\partial \theta^2} \end{pmatrix} = \begin{pmatrix} -2b_1 & 2b_2 & \Psi_1 \\ 2b_2 & -2b_1 & -\Psi_2 \\ \Psi_1 & -\Psi_2 & -2[\lambda - \beta_1(k\theta_0 - c)] \end{pmatrix}$$

Now, $|M_1| = -2b_1 < 0$; $|M_2| = 4(b_1^2 - b_2^2) > 0$. Again $|H^C| = -2[4\lambda(b_1^2 - b_2^2) - b_1^3(k\theta_0 - c)^2 - b_1(\beta_1^2 + \beta_2^2 - b_2^2(k\theta_0 - c)^2) - 2(b_1^2 - b_2^2)\beta_1(k\theta_0 - c) + 2b_2\beta_1\beta_2] < 0$, if $\lambda > \frac{b_1^3(k\theta_0 - c)^2 + b_1\left(\beta_1^2 + \beta_2^2 - b_2^2(k\theta_0 - c)^2\right) + 2(b_1^2 - b_2^2)\beta_1(k\theta_0 - c) - 2b_2\beta_1\beta_2}{4(b_1^2 - b_2^2)}$.

Therefore, $H^C$ is negative definite if and only if
$\lambda > \max\left\{\beta_1(k\theta_0 - c), \frac{b_1^3(k\theta_0 - c)^2 + b_1\left(\beta_1^2 + \beta_2^2 - b_2^2(k\theta_0 - c)^2\right) + 2(b_1^2 - b_2^2)\beta_1(k\theta_0 - c) - 2b_2\beta_1\beta_2}{4(b_1^2 - b_2^2)}\right\}$.
Taking into account this condition, the unique ideal outcomes can be acquired from $\frac{\partial \Pi^C}{\partial p_1} = 0$, $\frac{\partial \Pi^C}{\partial p_2} = 0$, and $\frac{\partial \Pi^C}{\partial \theta} = 0$ which are given in Proposition 6.1.1. ■

### 6.1.2.2 *Decentralized policy*

In this policy, both the manufacturers and the retailer work independently for expanding their individual profits. Here, we use two types of game structures – the Stackelberg game structure and the Nash game structure. In the Stackelberg game structure, we consider manufacturer-led Stackelberg game (MS game). In MS game, the manufacturers and the retailer work noncooperatively and sequentially in a vertical direction where the manufacturers are the leader and the retailer is the follower but, in the horizontal direction, the manufacturers can work cooperatively or simultaneously or sequentially. The manufacturers decide wholesale prices and greening level and then the retailer observes these decisions of the manufacturers and determines the selling prices of the product. In this case, we utilize reverse induction to find the optimal outcomes of the manufacturers and the retailer. Depending on the manufacturers' different behaviors, we consider three sub-policies. In the Nash game structure, they work independently and simultaneously.

#### *A. Centralized intra Stackelberg/Collusion (CM)*

Here, manufacturers (green and non-green) work cooperatively and manufacture both green and conventional non-green products. They determine the greening level and wholesale prices cooperatively, and after that, the retailer observes these decisions of the manufacturers and determines the retail prices. So, the total profit of the manufacturer is given by,

$$\Pi_m(w_2, \theta) = \Pi_{m_1} + \Pi_{m_2}$$

Now, our problem is

$$\begin{cases} \max\limits_{(w_2,\theta)} \Pi_m(w_2, \theta, \overline{p_1}, \overline{p_2}) \\ \text{subject to} \\ \overline{p_1}, \overline{p_2} \text{ to be obtained from} \\ \max\limits_{(p_1,p_2)} \Pi_r(p_1, p_2) \end{cases}$$

In the reverse induction, the retailer first determines the retail prices as function of the greening level and the wholesale price. As $\frac{\partial^2 \Pi_r}{\partial p_i^2} = -2b_i < 0$ $(i = 1, 2)$, there exists a unique ideal outcome for the retailer, which is given by the accompanying proposition:

**Proposition 6.1.2.** *For the given decisions $\theta$ and $w_2$, decisions of the retailer are given by:*

$$\begin{aligned} \overline{p_1} &= \frac{(b_1^2 - b_2^2)(w_2 + \alpha\theta) + b_1[a\rho + \beta_1\theta] + b_2[a(1-\rho) - \beta_2\theta]}{2(b_1^2 - b_2^2)} \\ \overline{p_2} &= \frac{(b_1^2 - b_2^2)w_2 + b_1[a(1-\rho) - \beta_2\theta] + b_2[a\rho + \beta_1\theta]}{2(b_1^2 - b_2^2)} \end{aligned}$$

**Corollary 6.1.1.**

$(a)$ $\frac{\partial p_i}{\partial w_2} = \frac{1}{2} > 0$, *for* $i = 1, 2$

$(b)$ $\frac{\partial p_1}{\partial \theta} > 0$, *and* $\frac{\partial p_2}{\partial \theta} > 0$, *for* $\frac{b_2}{b_1} > \frac{\beta_2}{\beta_1}$.

Corollary 6.1.1$(a)$ illustrates that the retailer increases the retail price of the conventional non-green product whenever $M_2$ increases the wholesale price of the conventional non-green product. As according to our assumption, the wholesale price of the green product is dependent on that of the conventional non-green product, so the wholesale price of the green product also enhances. As a result, the retailer enhances the retail price of the green product. It is also noted that the rate of increment of the retail prices is half of the rate of increment of the wholesale price. Corollary 6.1.1$(b)$ shows that when $M_1$ improves the greening level, he has to increase the wholesale price of his product, which forces the retailer to increase the retail price of the green product. It also shows that the retailer expands the retail price of the conventional non-green product only when the ratio of cross-price elasticity and self-price elasticity is greater than the ratio of cross-green elasticity and self-green elasticity.

Now, substituting these decisions ($\overline{p_1}$ and $\overline{p_2}$) of the retailer into the profit function of the manufacturers and utilizing the first order optimality conditions for $w_2$ and $\theta$, the ideal outcome can be acquired as follows:

**Proposition 6.1.3.** *If* $\lambda > \frac{1}{2}\left[\frac{B_2^2}{2(b_1-b_2)} + N_1(\beta_1 - \alpha b_1)\right]$ *holds, the ideal outcomes of the manufacturers and the retailer for the centralized intra Stackelberg policy are given by:*

$$\begin{aligned}
w_2^{CM} &= \frac{B_2B_5 - B_3B_4}{2B_1B_4 - B_2^2},\\
\theta^{CM} &= \frac{B_2B_3 - 2B_1B_5}{2B_1B_4 - B_2^2},\\
w_1^{CM} &= w_2^{CM} + \alpha\theta^{CM},\\
p_1^{CM} &= \frac{(b_1^2 - b_2^2)(w_2^{CM} + \alpha\theta^{CM}) + b_1[a\rho + \beta_1\theta^{CM}] + b_2[a(1-\rho) - \beta_2\theta^{CM}]}{2(b_1^2 - b_2^2)},\\
p_2^{CM} &= \frac{(b_1^2 - b_2^2)w_2^{CM} + b_1[a(1-\rho) - \beta_2\theta^{CM}] + b_2[a\rho + \beta_1\theta^{CM}]}{2(b_1^2 - b_2^2)}
\end{aligned}$$

*Expressions for* $B_i, i = 1(1)5$ *are given in the Appendix.*

### B. Nash intra Stackelberg/Bertrand (NM)

Here, we assume that the manufacturers act noncooperatively and simultaneously for expanding their individual profits. The manufacturers determine their wholesale prices and greening level simultaneously and then the retailer observes these decisions of the manufacturers and decides the retail prices. The Bertrand policy is presented as follows:

$$\begin{cases}
\begin{cases}
\max\limits_{\theta} \Pi_{m_1}(\theta, \overline{p_1}, \overline{p_2})\\
\max\limits_{w_2} \Pi_{m_2}(w_2, \overline{p_1}, \overline{p_2})
\end{cases}\\
\text{subject to}\\
\overline{p_1}, \overline{p_2} \text{ to be obtained from}\\
\max\limits_{(p_1,p_2)} \Pi_r(p_1, p_2)
\end{cases}$$

Similar to the previous model, here also we first calculate the retailer's decisions (which are given in Proposition 6.1.2) and then substituting these decisions in the manufacturers' profit functions and utilizing the first-order optimality conditions for $w_2$ and $\theta$, the ideal outcome can be acquired as follows:

**Proposition 6.1.4.** *If $\lambda > \frac{N_1(\beta_1-\alpha b_1)}{2}$ holds, the ideal outcomes of the manufacturers and the retailer for the Bertrand policy are given by:*

$$
\begin{aligned}
w_2^{NM} &= \frac{B_4X_4 - X_2X_3}{X_1X_3 - B_1B_4}, \\
\theta^{NM} &= \frac{B_1X_2 - X_1X_4}{X_1X_3 - B_1B_4}, \\
w_1^{NM} &= w_2^{NM} + \alpha\theta^{NM}, \\
p_1^{NM} &= \frac{(b_1^2 - b_2^2)(w_2^{NM} + \alpha\theta^{NM}) + b_1[a\rho + \beta_1\theta^{NM}] + b_2[a(1-\rho) - \beta_2\theta^{NM}]}{2(b_1^2 - b_2^2)}, \\
p_2^{NM} &= \frac{(b_1^2 - b_2^2)w_2^{NM} + b_1[a(1-\rho) - \beta_2\theta^{NM}] + b_2[a\rho + \beta_1\theta^{NM}]}{2(b_1^2 - b_2^2)}
\end{aligned}
$$

*Expressions for $X_i, i = 1(1)4$ are given in the Appendix.*

## C. Stackelberg intra Stackelberg (M1M)

In this case, two manufacturers decide their decisions sequentially. As $M_1$ is the green manufacturer, we consider $M_1$ as the leader. So, $M_1$ first decides the greening level and then $M_2$ announces the wholesale price of the conventional non-green product. Finally, based on the decisions of the manufacturers, the retailer decides the retail prices. So, the Stackelberg intra Stackelberg policy is presented as follows:

$$
\begin{cases}
\begin{cases}
\max\limits_{\theta} \Pi_{m_1}(\theta, \widetilde{w_2}, p_1^*(\widetilde{w_2}, \theta, \widetilde{p_1}, \widetilde{p_2}), p_2^*(\widetilde{w_2}, \theta, \widetilde{p_1}, \widetilde{p_2})) \\
\text{subject to} \\
\widetilde{w_2} \text{ which is to be obtained from} \\
\max\limits_{w_2} \Pi_{m_2}(w_2, \overline{p_1}, \overline{p_2})
\end{cases} \\
\text{subject to} \\
\overline{p_1}, \overline{p_2} \text{ which are to be obtained from} \\
\max\limits_{(p_1, p_2)} \Pi_r(p_1, p_2)
\end{cases}
$$

Similar to the previous models, here also first we determine the decisions of the retailer, and after that, substitute these decisions into $M_2$'s profit function to determine the unique (as $\frac{\partial^2 \Pi_{m_2}^{M1M}}{\partial w_2^2} = -(b_1 - b_2) < 0$) wholesale price $w_2$ as follows:

$$
\widetilde{w_2} = -\frac{X_3\theta + X_4}{B_1}
$$

Substituting these values of $p_1$, $p_2$ and $w_2$ into $M_1$'s profit function and utilizing the first-order optimality conditions for $\theta$, the ideal outcome can be acquired as follows:

**Proposition 6.1.5.** *If $\lambda > \frac{[\alpha(2b_1+b_2)-(2\beta_1+\beta_2)][2B_1N_1+(\beta_2-\alpha b_2)]}{8(b_1-b_2)}$ holds, the ideal outcomes of the manufacturers and the retailer for the Stackelberg intra Stackelberg policy are given by:*

$$\begin{aligned}
\theta^{M1M} &= \frac{X_5}{X_6},\\
w_2^{M1M} &= -\frac{X_3\theta^{M1M}+X_4}{B_1},\\
w_1^{M1M} &= w_2^{M1M}+\alpha\theta^{M1M},\\
p_1^{M1M} &= \frac{(b_1^2-b_2^2)(w_2^{M1M}+\alpha\theta^{M1M})+b_1[a\rho+\beta_1\theta^{M1M}]+b_2[a(1-\rho)-\beta_2\theta^{M1M}]}{2(b_1^2-b_2^2)},\\
p_2^{M1M} &= \frac{(b_1^2-b_2^2)w_2^{M1M}+b_1[a(1-\rho)-\beta_2\theta^{M1M}]+b_2[a\rho+\beta_1\theta^{M1M}]}{2(b_1^2-b_2^2)}
\end{aligned}$$

*Expressions for $X_5$ and $X_6$ are provided in the Appendix.*

## D. Nash game (N)

Here, all the channel individuals act noncooperatively and simultaneously for expanding their individual profits. The Nash game is presented as follows:

$$\begin{cases}
\max_{\theta} \Pi_{m_1}(\theta)\\
\max_{w_2} \Pi_{m_2}(w_2)\\
\max_{(p_1,p_2)} \Pi_r(p_1,p_2)
\end{cases}$$

Utilizing the first-order optimality conditions for $\theta$, $w_2$, $p_1$ and $p_2$, the ideal outcome can be acquired as follows:

**Proposition 6.1.6.** *At the equilibrium, the ideal outcomes of the manufacturers and the retailer for the Nash game are given by:*

$$\begin{aligned}
w_2^N &= \frac{1}{X_7}\Big[2a(1-\rho)(\beta-\alpha b_1)+3b_2M_2(b_1N_1-b_2)-(b_1-b_2)[2\beta_1(3Z_1-2M_2)\\
&\quad +a(1-4\rho)N_1+(N_1-\alpha)M_2-3\alpha Z_2]\Big],\\
\theta^N &= \frac{[a(1-\rho)+2(b_1-b_2)M_2][4\lambda-3N_1(\beta_1-\alpha b_1)]-(\beta_2-\alpha b_2)[2Z_1(\beta_1-\alpha b_1)-a\rho N_1]}{X_7},\\
w_1^N &= w_2^N+\alpha\theta^N,\\
p_1^N &= \frac{X_8}{(b_1^2-b_2^2)X_7},\\
p_2^N &= \frac{X_9}{(b_1^2-b_2^2)X_7}
\end{aligned}$$

*Expressions for $X_i, i=7,8,9$ are given in the Appendix.*

### 6.1.2.3 Contract

#### A. Cost sharing (CS) contract

According to our assumptions, $M_1$ manufactures the green product and the market demand increases with the greening level. Although the retailer benefits from this increased market demand, the manufacturer only spends the greening cost. To energize $M_1$ in green assembling, here we introduce a cost sharing agreement in which the retailer consents to share a part $\phi$ $(0 < \phi < 1)$ of total greening cost with $M_1$. The profit functions of the manufacturers and the retailer then become

$$\begin{aligned}
\Pi_{m_1}(\theta) &= (w_1 - c_{m_1})D_1 + sD_1 + A_1 D_{R1} - (1-\phi)\lambda\theta^2 \\
\Pi_{m_2}(w_2) &= (w_2 - c_{m_2})D_2 + A_2 D_{R2} \\
\Pi_r(p_1, p_2) &= (p_1 - w_1)D_1 + (p_2 - w_2)D_2 - \phi\lambda\theta^2.
\end{aligned}$$

Among the three Stackelberg policies discussed in the previous subsection, Bertrand policy gives the best possible outcome (see numerical example). In the following, we consider the cost sharing contract for Bertrand policy. Cost sharing contract for the other two policies can be obtained similarly. The ideal outcomes of the manufacturers and the retailer for cost sharing contract can be acquired as follows:

**Proposition 6.1.7.** *At the equilibrium, the ideals of the manufacturers and the retailer under the CS contract are given as follows:*

$$\begin{aligned}
w_2^{CS} &= \frac{(B_4 + 2\lambda\phi)X_4 - X_2X_3}{X_1X_3 - B_1(B_4 + 2\lambda\phi)}, \\
\theta^{CS} &= \frac{B_1X_2 - X_1X_4}{X_1X_3 - B_1(B_4 + 2\lambda\phi)}, \\
w_1^{CS} &= w_2^{CS} + \alpha\theta^{CS}, \\
p_1^{CS} &= \frac{(b_1^2 - b_2^2)(w_2^{CS} + \alpha\theta^{CS}) + b_1[a\rho + \beta_1\theta^{CS}] + b_2[a(1-\rho) - \beta_2\theta^{CS}]}{2(b_1^2 - b_2^2)}, \\
p_2^{CS} &= \frac{(b_1^2 - b_2^2)w_2^{CS} + b_1[a(1-\rho) - \beta_2\theta^{CS}] + b_2[a\rho + \beta_1\theta^{CS}]}{2(b_1^2 - b_2^2)}
\end{aligned}$$

It is clear from Proposition 6.1.7 that, the greening level increases under cost sharing contract. $M_2$ does not participate in this agreement and the higher greening level diminishes the demand for the conventional non-green product. In order to maintain its profitability, $M_2$ increases the wholesale price moderately which increases the wholesale price of the green product. All these issues influence the market demand and diminish the benefit of the retailer but improve those of the manufacturers (see numerical example). Therefore, cost sharing agreement cannot give a mutually advantageous arrangement for all the channel individuals. In the next subsection, we implement a revenue sharing under cost sharing contract.

**Corollary 6.1.2.**

$(a)$ $\frac{\partial \theta^{CS}}{\partial \phi} = \frac{1}{2} > 0,$

$(b)$ $\frac{\partial w_2^{CS}}{\partial \phi} > 0,$

Corollary 6.1.2 reveals that the greening level increases when the retailer offers a higher expense sharing portion to $M_1$. This result is extremely instinctive as the higher share portion can reduce the cost load of product greening. A higher green product negatively affects the conventional non-green product demand. In order to keep its profit intact, $M_2$ increases his wholesale price slightly.

### *B. Revenue sharing under cost sharing (RCS) contract*

In this case, the retailer and the manufacturers sign an agreement in which the retailer consents to share some portions $(1-\mu_1)$ and $(1-\mu_2)(0 < \mu_1, \mu_2 < 1)$ of its revenue with both $M_1$ and $M_2$, respectively and the manufacturers agree to reduce the wholesale prices. Simultaneously, the retailer shares some portion of the green investment cost (similar to the previous model). The profit functions of the manufacturers and the retailer then become

$$\begin{aligned}
\Pi_{m_1}(\theta) &= (w_1 - c_{m_1})D_1 + sD_1 + A_1 D_{R1} - (1-\phi)\lambda\theta^2 + (1-\mu_1)p_1 D_1 \\
\Pi_{m_2}(w_2) &= (w_2 - c_{m_2})D_2 + A_2 D_{R2} + (1-\mu_2)p_2 D_2 \\
\Pi_r(p_1, p_2) &= (\mu_1 p_1 - w_1)D_1 + (\mu_2 p_2 - w_2)D_2 - \phi\lambda\theta^2.
\end{aligned}$$

In the backward induction, the retailer first determines the selling prices as functions of the greening level and the wholesale price, which are given by

$$\begin{aligned}
p_1 &= F_1 w_2 + F_2\theta + F_3 \\
p_2 &= F_4 w_2 + F_4\theta + F_4
\end{aligned}$$

Now, substituting these decisions ($p_1$ and $p_2$) of the retailer into the manufacturers' profit function and utilizing the first order optimality conditions for $w_2$ and $\theta$, the ideal outcome can be acquired as follows:

**Proposition 6.1.8.** *At the equilibrium, the ideal outcomes of the manufacturers and the retailer under the RCS contract are given as follows:*

$$\begin{aligned}
w_2^{RCS} &= \frac{\xi_2\xi_6 - \xi_3\xi_5}{\xi_1\xi_5 - \xi_2\xi_4}, \\
\theta^{RCS} &= \frac{\xi_3\xi_4 - \xi_1\xi_6}{\xi_1\xi_5 - \xi_2\xi_4}, \\
w_1^{RCS} &= w_2^{RCS} + \alpha\theta^{RCS}, \\
p_1^{RCS} &= F_1 w_2^{RCS} + F_2\theta^{RCS} + F_3, \\
p_2^{RCS} &= F_4 w_2^{RCS} + F_5\theta^{RCS} + F_6.
\end{aligned}$$

*Expressions for* $F_i, i = 1(1)6$ *and* $\xi_i, i = 1(1)6$ *are given in the Appendix.*

## 6.1.3 Numerical illustration

Due to complicated forms of analytical results of the developed models, in the previous section, we were unable to compare ideal outcomes and benefit of channel individuals and the entire production network. So, here, a numerical example is considered to compare the ideal greening level, wholesale prices, retail prices, and maximum benefits under different policies. We take $a = 250; \rho = 0.68; b_1 = 0.6; b_2 = 0.25; \beta_1 = 2.5; \beta_2 = 0.15; k = 5; \theta_0 = 1; c_{m_2} = 100; c = 3; \alpha = 5; \tau_1 = 0.25; \tau_2 = 0.2; \lambda = 100; A_1 = 90; A_2 = 80; \phi = 0.1; \mu_1 = 0.74; \mu_2 = 0.65$; in appropriate units.

Table 6.1.1 represents the optimal results for the proposed model under different policies. Comparing green manufacturing cost, greening level, wholesale prices, and retail prices for various models, we have the accompanying proposition:

**Proposition 6.1.9.** *Optimal green manufacturing costs, greening level, wholesale prices, and selling prices for different models follow the accompanying relationship :* $(i)$ $c_{m_1}^{CM} < c_{m_1}^{NM} < c_{m_1}^{N} < c_{m_1}^{M1M} < c_{m_1}^{C}$, $(ii)$ $\theta^{CM} < \theta^{NM} < \theta^{N} < \theta^{M1M} < \theta^{C}$, $(iii)$ $w_i^{N} < w_i^{NM} < w_i^{M1M} < w_i^{CM}$, *and* $(iv)$ $p_i^{C} < p_i^{N} < p_i^{NM} < p_i^{M1M} < p_i^{CM}$, $i = 1, 2$.

As the centralized policy is free from the transfer prices, the green manufacturer puts more effort into producing the higher green product. Due to higher green product, in this case, the green production cost is higher than those of other policies. As the greening level is higher, the green manufacturer can get a higher subsidy from the government under the centralized policy. Among all the decentralized policies, $M_1$-led Stackelberg game gives higher green product and so, in that case, the

**Table 6.1.1:** Optimal results of the proposed models.

| Optimal decisions | Centralized C | Stackelberg CM | Stackelberg M1M | Stackelberg NM | Stackelberg CS | Stackelberg RCS | Nash N |
|---|---|---|---|---|---|---|---|
| $c_{m_1}$ | 108.538 | 105.424 | 106.537 | 105.613 | 106.217 | 108.411 | 105.915 |
| $w_1$ | - | 226.848 | 170.605 | 168.581 | 169.905 | 93.9432 | 144.114 |
| $w_2$ | - | 217.807 | 159.710 | 159.226 | 159.542 | 79.9250 | 134.256 |
| $p_1$ | 250.442 | 322.910 | 295.700 | 293.932 | 295.089 | 274.580 | 281.945 |
| $p_2$ | 196.660 | 262.630 | 233.915 | 233.396 | 233.736 | 220.016 | 221.002 |
| $\theta$ | 2.84608 | 1.80812 | 2.17897 | 1.87109 | 2.07248 | 2.80363 | 1.97154 |
| $s$ | 9.23039 | 4.04062 | 5.89487 | 4.35545 | 5.36239 | 9.01814 | 4.85770 |
| $\Pi_{m_1}$ | - | 6543.29 | 4749.90 | 4740.00 | 4791.67 | 5241.58 | 3611.07 |
| $\Pi_{m_2}$ | - | 385.127 | 1003.10 | 990.316 | 998.666 | 1182.56 | 883.979 |
| $\Pi_r$ | - | 4589.36 | 8051.81 | 8079.73 | 8018.51 | 8292.76 | 9935.22 |
| $\Pi$ | 15113.8 | 11517.8 | 13804.8 | 13810.0 | 13808.8 | 14716.9 | 14430.3 |

green manufacturing cost is also higher than any other decentralized policies. The Collusion behavior of two manufacturers provides fewer green product than any other policy. It is noted that, in this case, the manufacturers charge higher wholesale prices which is consistent with Zhao and Wei (2014). The reason is that, due to joint decision-making of the manufacturers, there is no price competition between them. They can increase the wholesale prices without any hesitation. But in the case of independent decision-making, they reduce the wholesale prices to enjoy competitive advantages. That's why, the Nash game provides lower wholesale prices than all other policies. As the retailer follows the manufacturers' decision, selling prices for different models have the same trend as those of the wholesale prices. The centralized policy being free from the double-marginalization effect provides lower selling prices than all other policies.

**Proposition 6.1.10.** *Optimal benefits of the manufacturers, the retailer, and the entire production network for different models follow the accompanying relationship : $(i)$ $\Pi^{N}_{m_1} < \Pi^{NM}_{m_1} < \Pi^{M1M}_{m_1} < \Pi^{CM}_{m_1}$, $(ii)$ $\Pi^{CM}_{m_2} < \Pi^{N}_{m_2} < \Pi^{NM}_{m_2} < \Pi^{M1M}_{m_2}$, $(iii)$ $\Pi^{CM}_{r} < \Pi^{M1M}_{r} < \Pi^{NM}_{r} < \Pi^{N}_{r}$, and $(iv)$ $\Pi^{CM} < \Pi^{M1M} < \Pi^{NM} < \Pi^{N} < \Pi^{C}$.*

Not surprisingly, the centralized policy provides the most possible outcome as far as the profitability of the entire production network. The Nash game among the players gives a higher benefit to the retailer but a lower benefit to the manufacturers. In the Stackelberg game, the retailer gets higher benefit in the Bertrand policy and lower benefit in the Collusion policy. On the other hand, $M_1$ gets higher benefit in the Collusion policy but $M_2$ gets the higher benefit when $M_1$ is the leader. The reason for these results lies behind the trends of the product's greening level and its prices. For the high level of green product in the Stackelberg game, the buyers consent to pay more and $M_1$ can obtain more subsidies from the government. So, the benefit of $M_1$ increases. Although the higher green product diminishes the buyers' interest for the conventional non-green product, the benefit of $M_2$ increases due to its higher wholesale price. But it reduces the profit of the retailer. When the manufacturers work jointly, they demand much wholesale price for the low level of green product and amplify their overall benefit. Therefore, the Collusion policy is only profitable to $M_1$ while detrimental to the retailer and the entire production network. Moreover, the Collusion policy provides less profit to $M_2$ than all other policies, which is inconsistent with the outcomes of Zhao and Wei (2014) who found that the benefit of the conventional non-green manufacturer under the Collusion policy is only less than that of $M_1$-led Stackelberg game but higher than all other policies. The explanation for this kind of conflicting situation is additionally due to the trends of the product's greening level and its prices.

Although the Bertrand policy provides better benefits to the retailer and the entire production network, it gives lower benefits to the manufacturers. For producing a higher green product and obtaining a higher benefit, $M_1$ makes a contract with the retailer to share some part of green investment cost. The numerical outcomes depict that the CS contract provides a higher greening level and higher benefit to $M_1$. $M_2$ also gets a higher benefit without participating in this contract. But the retailer's benefit diminishes. So, the CS contract cannot accomplish a mutually beneficial arrangement (win-win situation) (see Fig. 6.1.2). This outcome is opposite to the outcomes of Ma et al. (2018) who showed that cost sharing contract between two players could give a mutually advantageous

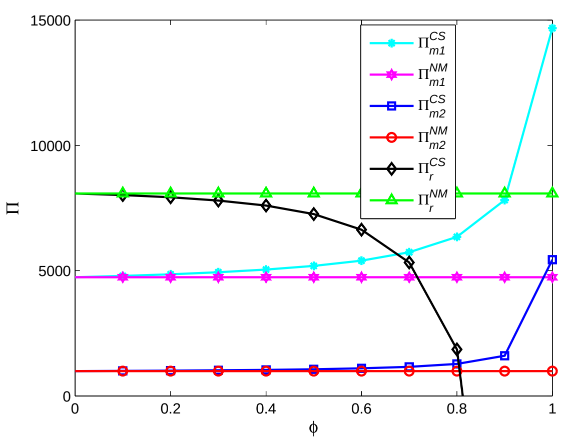



**Fig. 6.1.2:** Win-win outcome w.r.t. $\phi$.

arrangement to all the channel individuals. The reason for this finding of our study lies in the thought of the greening level's effect on non-green product's demand and the presence of government sponsorship. The sharing of green investment costs and government subsidy help $M_1$ to produce more green product. Because of higher green product, $M_1$ sets much wholesale price. $M_2$ also sets much wholesale price for the conventional non-green product. As a result, the retailer also charges higher selling prices which decreases the market demand. This decrement of non-green product sales lessens the benefit of the retailer. On the contrary, in the RCS contract, $M_1$ improves the greening level over 33% and the manufacturers diminish wholesale prices over 44% and 49%, respectively. The retailer also sets lower retail prices which expand the market demand, income of all the individuals and the entire production network. Thus, the RCS contract assists with accomplishing a win-win situation.

**Table 6.1.2:** Optimal results in the case of no subsidy.

| Optimal decisions | Centralized C | Stackelberg | | | Nash N |
|---|---|---|---|---|---|
| | | CM | M1M | NM | |
| $c_{m_1}$ | 102.754 | 101.974 | 102.423 | 101.420 | 101.429 |
| $w_1$ | - | 222.189 | 161.592 | 159.397 | 135.071 |
| $w_2$ | - | 218.899 | 157.555 | 157.030 | 132.689 |
| $p_1$ | 247.425 | 317.753 | 287.823 | 285.904 | 273.748 |
| $p_2$ | 194.926 | 262.142 | 231.604 | 231.041 | 218.874 |
| $\theta$ | 0.91788 | 0.65786 | 0.80751 | 0.47342 | 0.47625 |
| $\Pi_{m_1}$ | - | 6596.99 | 4608.43 | 4597.06 | 3439.04 |
| $\Pi_{m_2}$ | - | 277.140 | 946.800 | 933.333 | 829.730 |
| $\Pi_r$ | - | 4535.28 | 8176.86 | 8207.59 | 10019.6 |
| $\Pi$ | 14794.4 | 11409.4 | 13732.1 | 13738.0 | 14288.4 |

Table 6.1.2 demonstrates the importance of government intervention in green manufacturing and it represents the ideal pricing decision, greening strategy, and benefits of the players when the government offers no financial support. It is obvious that, in this situation, the greening level diminishes and accordingly, the benefits of the entire supply chain in all the cases decrease. It can be noted that the benefits of the manufacturers decrease and that of the retailer increase in all the cases except in the Collusion behavior where the benefit of $M_1$ increases and that of the retailer decreases. This outcome is contrary to the general thought that government

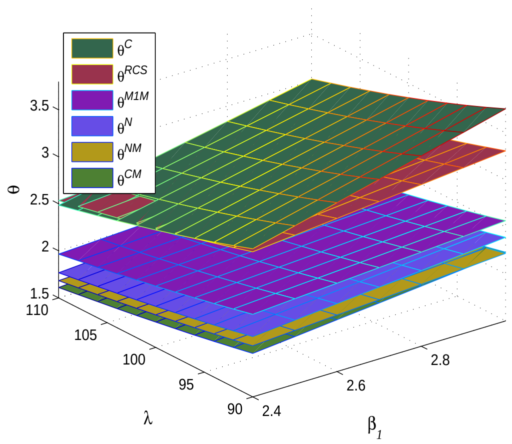
sponsorship improves the benefit of the green manufacturer. The explanation for this result lies in the pricing estimation of $M_2$. As in this case, $M_2$ enhances the wholesale price, the retailer can't diminish the retail price of the conventional non-green product sufficiently while decreasing that of the green product. Due to this type of pricing contest, the buyers' interest in the green product rises while that of the conventional non-green product decreases. A higher market demand of the green product affords a higher benefit to $M_1$ while an elevated wholesale price and a lesser market demand of the conventional non-green product decrease the benefit of the retailer. Consequently, government sponsorship and competing manufacturers' various behaviors play important role in deciding optimal strategies under product substitution.

### 6.1.4 Sensitivity analysis

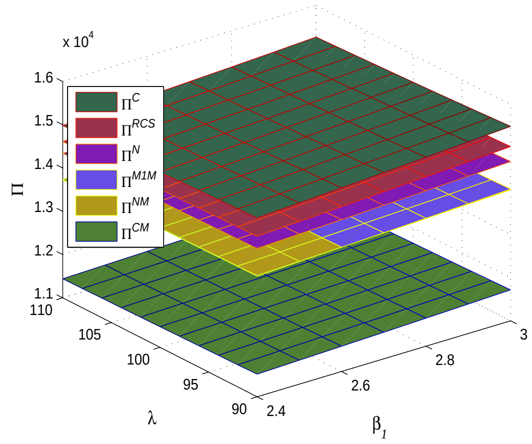
In this part, the sensitivity of few parameters is discussed to investigate their impact on the ideal greening level considering the parameter-values as given above. Figs. 6.1.3–6.1.5 address the sensitivity of the parameters $\lambda$, $\beta_1$, $\beta_2$, $b_1$, $\rho$, $k$, and $\theta_0$, respectively. Fig. 6.1.6 represents the region of a mutually beneficial situation for the parameters $\mu_1$ and $\mu_2$.

#### *6.1.4.1 Impact of green investment and green sensitivity*

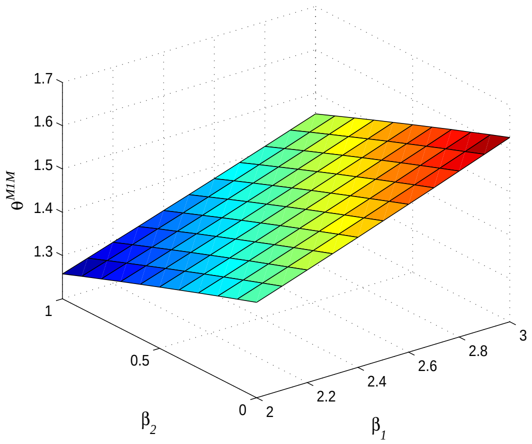
Fig. 6.1.3(a) represents the joint influence of the green investment parameter ($\lambda$) and the green sensitivity parameter of green product demand ($\beta_1$) on the greening level for the proposed policies. As usual, the greening level diminishes in all the policies with $\lambda$. It is additionally noticed that, for higher values of $\lambda$, greening level in RCS contract becomes better than the centralized policy which is not acceptable. So, $\lambda$ must be less than some threshold value. This is the reason why green manufacturers cannot invest in green manufacturing continuously. On the contrary, the greening level increases in all the policies with green sensitivity parameter. The growth rate is better in the centralized policy while it is lower in the Bertrand behavior. It is noticed that, for the lower value of $\beta_1$, greening level in the centralized policy is lower than the RCS contract. So, $\beta_1$ should be greater than a threshold value. It is also noticed that, when the buyers come to be extra touchy to the green product, the manufacturer generates a better green product in their Collusion behavior than their conflicting behavior.




**(a)** $\theta$ w.r.t. $\lambda$ and $\beta_1$.




**(b)** profit change w.r.t. $\lambda$ and $\beta_1$.




**(c)** $\theta^{M1M}$ w.r.t. $\beta_1$ and $\beta_2$.

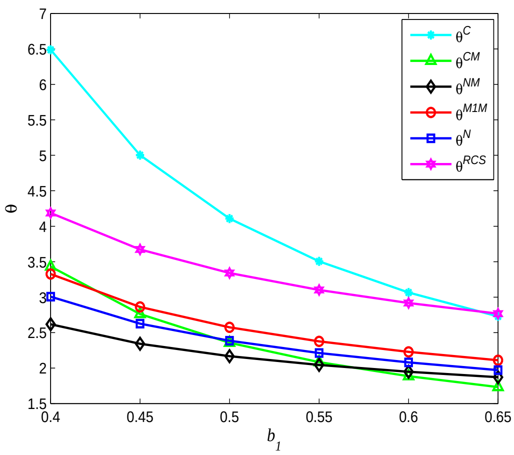
**Fig. 6.1.3:** Changes in optimal $\theta$, $\theta^{M1M}$ and profit w.r.t. $\lambda$ and green sensitivity parameters.

Since the greening level increases with $\beta_1$, the manufacturers and the retailer demand higher retail prices. However, because of higher green product, the market demand expands which builds the benefit of all the policies. In contrast, since the greening level diminishes with $\lambda$, the market demand diminishes. As a result, the benefit of all the policies decreases. The overall benefit of the production network is almost the same in Bertrand policy and $M_1$-led Stackelberg policy (see Fig. 6.1.3(b)).

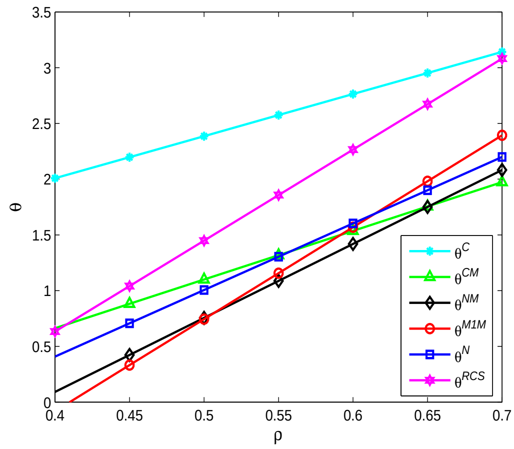
Among the three Stackelberg policies, $M_1$-led Stackelberg behavior gives the higher green product. We present the joint impact of $\beta_1$ and $\beta_2$ on the greening level for $M1M$ behavior in Fig. 6.1.3(c). It shows that the greening level decreases as $\beta_2$ increases. The rate of decrement of greening level for $\beta_2$ is lower than the rate of increment of greening level for $\beta_1$. That means, the greening level sensitivity to the non-green market demand has less impact on the greening level compared to the greening level sensitivity to the green market demand.

### 6.1.4.2 Impact of parameter $b_1$, $\rho$, $k$, and $\theta_0$

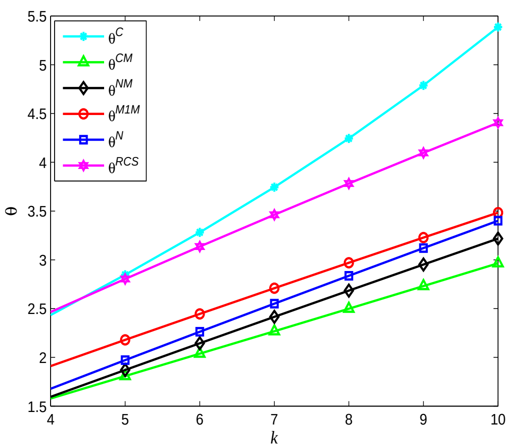
In this subsection, we further investigate the impact of $b_1$, $\rho$, $k$, and $\theta_0$ on the optimal greening level for the proposed policies.



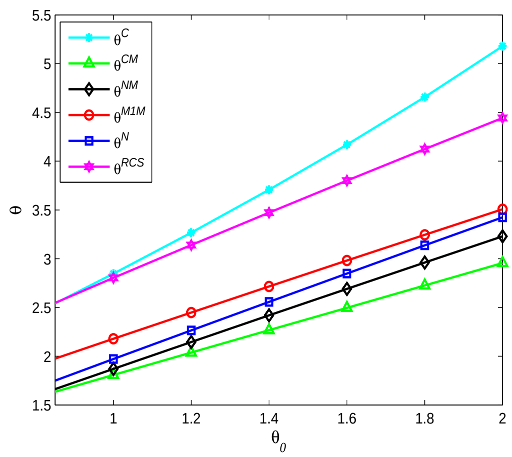

**(a)** $b_1$ vs $\theta$.




**(b)** $\rho$ vs $\theta$.




**(c)** $k$ vs $\theta$.




**(d)** $\theta_0$ vs $\theta$.

**Fig. 6.1.4:** Changes in optimum $\theta$ w.r.t. different parameters.

#### 6.1.4.2.1 Impact of parameter $b_1$

If a market turns out to be more delicate to the cost of any product, the retailer needs to diminish the retail price of that product to keep the market demand intact. The manufacturers are also forced to reduce their wholesale prices. A manufacturer can not sell a better product at a lesser cost without any contract with the retailer. So, the product's greening level diminishes in all the policies. In Fig. 6.1.4(a), we keep all the parameter values same as the preceding section and $b_1 \in [0.4, 0.64]$. The decrement rate is greater in the centralized policy. Among the decentralized policies, Collusion behavior has a higher rate of decrement. Similar to green level sensitivity, self-price sensitivity has a similar effect on greening level in Collusion and Bertrand behavior.

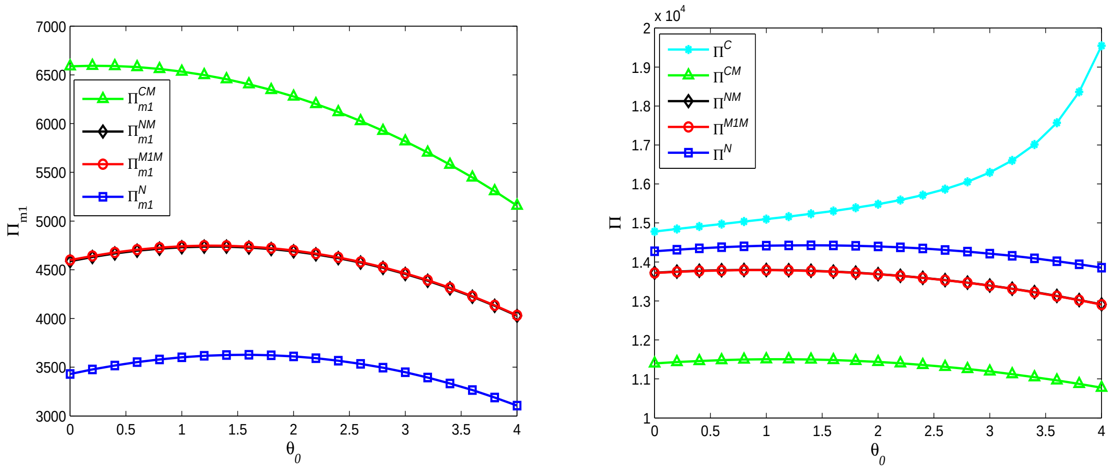
Since the greening level diminishes with $b_1$, the manufacturer and the retailer cannot set a greater cost for the product. So, the cost of the product also decreases with $b_1$. Although the selling price of the product decreases because of lesser green product, the market demand of the product also diminishes which again decreases the benefit of the manufacturers, the retailer, and the whole supply chain. It is interesting to see that the central decision-maker offers the better green product at a lower cost under a centralized policy. For higher values of $b_1$, the retail price and benefit of the whole production network tend to be nearer under all the policies.

#### 6.1.4.2.2 Impact of parameter $\rho$

For higher values of $\rho$, the basic market for the green product increases. The manufacturers and the retailer can demand a higher price in this large market. At the same time, the green manufacturer cannot impose a greater wholesale price for lesser green product. So, the product's greening level enhances in all the policies. Fig. 6.1.4(b) shows the optimal change of $\theta$ with $\rho$, where default values of all the parameters are equivalent to the preceding section and $\rho \in [0.4, 0.7]$. It shows that, for lower values of $\rho$, the greening level under $M_1$-led Stackelberg policy is lower than any other policies but for higher value of $\rho$, this policy provides higher green product than any other decentralized policies.

#### 6.1.4.2.3 Impact of parameter $k$ and $\theta_0$

In this subsection, we discuss the effect of adjustment parameter ($k$) and green level floor ($\theta_0$) for government intervention. Fig. 6.1.4(c) shows that the greening level enhances in all the policies and the increment rate is better in the centralized policy and fewer in Collusion behavior. For larger values of $k$, the greening level turns out to be lower in Collusion behavior. Fig. 6.1.4(d) shows the change of greening level with the green level floor. The greening level follows a similar pattern as that of $k$. As the greening level increases with $\theta_0$, $M_1$ has to invest more which may reduce his profit. Fig. 6.1.5(a) shows that the benefit of the manufacturer enhances with $\theta_0$ up to a certain level; after that, it tends to diminish. As a result, the benefit of the entire production network also follows a similar pattern (see Fig. 6.1.5(b)).

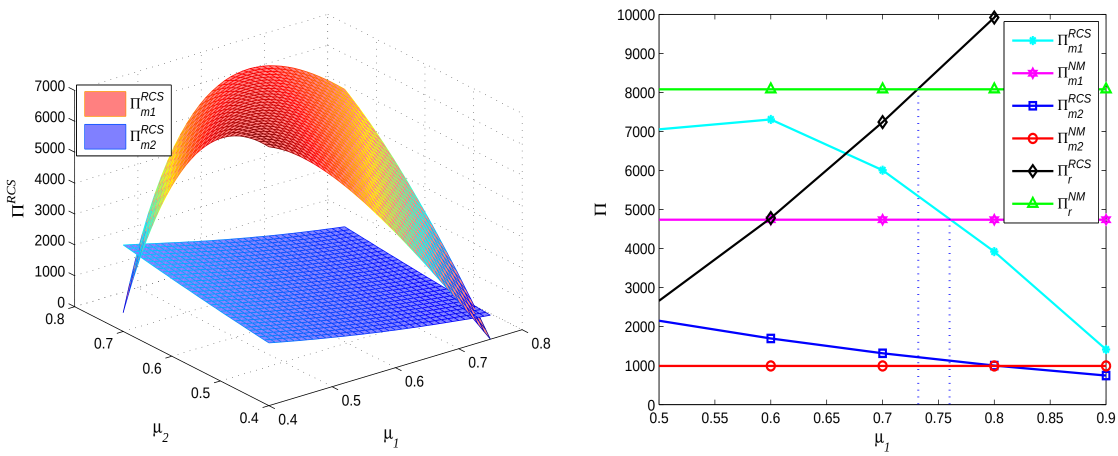



**(a)** $\theta_0$ vs $\Pi_{m_1}$. **(b)** $\theta_0$ vs $\Pi$.

**Fig. 6.1.5:** Changes in profit w.r.t. $\theta_0$.

### *6.1.4.2.4 Impact of revenue sharing parameters $\mu_1$ and $\mu_2$*

By setting all the default values same as the previous section, here, we explore the effect of revenue sharing portions $\mu_1$ and $\mu_2$ on the supply chain. From Fig. 6.1.6(a)




**(a)** win-win outcome w.r.t. $\mu_1$ and $\mu_2$. **(b)** win-win outcome w.r.t. $\mu_1$.

**Fig. 6.1.6:** Win-win outcome w.r.t. $\mu_1$ and $\mu_2$.

we note that $\mu_1$ and $\mu_2$ should lie in [0, 0.76] so that benefit of $M_1$ in the RCS contract remains greater than that of $M_2$. We notice that the benefit of $M_1$ decreases with $\mu_1$

and $\mu_2$ but that of $M_2$ decreases with $\mu_1$ and increases with $\mu_2$. In Fig. 6.1.6(b), we investigate the effect of $\mu_1$ by keeping $\mu_2$ fixed with the value 0.65. It shows that profits of both the manufacturers decrease with $\mu_1$ but that of the retailer increases with $\mu_1$. It is clear from the graph that when $\mu_1$ becomes larger than 0.73, the benefit of the retailer in the RCS contract becomes greater than that in Bertrand behavior and when $\mu_1$ becomes larger than 0.76, the benefit of $M_1$ in the RCS contract becomes less than that in Bertrand behavior. So, in order to achieve win-win situation, $\mu_1$ should lie in [0.73, 0.76]. In this region, the benefit of $M_2$ in the RCS contract is also greater than that in the Bertrand behavior.

# Appendix

The following notations are used in this part for clear representation.

$M_1 = 2c_{m_2} + k\theta_0^2 - A_1\tau_1 - A_2\tau_2,\ M_2 = c_{m_2} - A_2\tau_2,\ M_3 = 2\alpha + k\theta_0 - c,$

$N_1 = (M_3 - \alpha),\ Z_1 = (M_1 - M_2),\ \Psi_i = \beta_i - b_i(k\theta_0 - c),$

$\Phi_i = b_i(c_{m_2} + k\theta_0^2 - A_1\tau_1) - b_jM_2,\ (i = 1, 2; j = 3 - i).$

$\Xi = 4\lambda(b_1^2 - b_2^2) - b_1^3(k\theta_0 - c)^2 - b_1\left(\beta_1^2 + \beta_2^2 - b_2^2(k\theta_0 - c)^2\right) - 2(b_1^2 - b_2^2)\beta_1(k\theta_0 - c) + 2b_2\beta_1\beta_2.$

$Y = \beta_1(c_{m_2} + k\theta_0^2 - A_1\tau_1) - \beta_2M_2 - \rho a(k\theta_0 - c).$

$B_1 = -(b_1 - b_2),\ B_2 = \frac{B_1M_3 + (\beta_1 - \beta_2)}{2},\ B_3 = \frac{a - B_1M_1}{2},\ B_4 = -2\lambda + (\beta_1 - \alpha b_1)N_1,\ B_5 = \frac{\alpha(a\rho + \Phi_1) - Y}{2}.$

$X_1 = \frac{(\beta_1 - \alpha b_1) + B_1N_1}{2},\ X_2 = \frac{a\rho N_1 - (\beta_1 - \alpha b_1)Z_1}{2},\ X_3 = -\frac{(\beta_2 - \alpha b_2)}{2},\ X_4 = \frac{a(1-\rho) - B_1M_2}{2},$

$X_5 = (a\rho - X_4)[(\beta_2 - \alpha b_2) - 2B_1N_1] + [\alpha(2b_1 + b_2) - (2\beta_1 + \beta_2)][B_1Z_1 + X_4],$

$X_6 = 8\lambda(b_1 - b_2) - [\alpha(2b_1 + b_2) - (2\beta_1 + \beta_2)][(\beta_2 - \alpha b_2) + 2B_1N_1],$

$X_7 = 2(\beta_1\beta_2 + b_1b_2\alpha^2) + (b_1 - b_2)[12 - (9\beta_1 + \beta_2)N_1] + \alpha N_1(b_1 - b_2)(9b_1 + b_2),$

$X_8 = \Big[(b_1^2 - b_2^2)\alpha\Big(b_1^2(3\alpha Z_1 + 2M_2(k\theta_0 - c)) - b_2^2M_2N_1 - b_1b_2(M_2N_1 + 2\alpha Z_2)\Big) + b_1^3(4\lambda M_2 - \alpha^2a(1 - \rho) + \alpha a(1 + 5\rho)N_1 - 4\beta_1M_2N_1 - \beta_2\alpha Z_1) + b_2^3(4\lambda M_2 - \alpha a(1 - 2\rho)N_1 - \alpha(3\beta_1 - \beta_2)M_2 - 2\alpha\beta_1Z_2) - b_1b_2^2\Big(4\lambda M_2 + \alpha^2a(3 - \rho) + \big(\alpha a(5 - 3\rho) - 2(\beta_1 - \beta_2)M_2\big)(k\theta_0 - c) - 3\alpha\beta_1Z_1 - 4\alpha\beta_2Z_2\Big) - b_1^2b_2(4\lambda M_2 - 5\alpha a(1 - 2\rho)N_1 - \alpha^2a\rho - 5\beta_2M_2(k\theta_0 - c) - 5\beta_1M_2N_1 + \beta_1\alpha Z_1 + 3\beta_2\alpha Z_2) + b_1^2\Big(2a\lambda(1 + 2\rho) + \beta_1\beta_2Z_1 - \beta_1^2(Z_1 + 2Z_2) - a\big(\beta_1(2 + \rho) + \beta_2\rho\big)N_1 - \alpha a\beta_2\rho\Big) + b_1b_2\Big(6a\lambda(1 - 2\rho) + \beta_1(\beta_1 + \beta_2)(3Z_1 - 2M_2) - aN_1\big(\beta_1(4 - 7\rho) + \beta_2\rho\big) - \alpha a\beta_1\rho\Big) - 2b_2^2\Big(\beta_1\beta_2(Z_1 + Z_2) + a(1 - \rho)(4\lambda - 3N_1\beta_2 + \alpha\beta_1) - a\beta_2\rho N_1\Big) + b_1\alpha\beta_1\big(\beta_1(1 - \rho) + \beta_2\rho\big)\Big],$

$X_9 = \Big[(b_1^2 - b_2^2)\alpha b_1\big(3(b_1 - b_2)N_1M_2 + b_2Z_1\alpha\big) + b_1^3\Big(4\lambda M_2 + 6\alpha a(1 - \rho)N_1 - 3\beta_1M_2N_1 + \beta_2\big(M_2(2\alpha + N_1) - 4\alpha Z_1\big)\Big) + b_2^3(4\lambda M_2 - \alpha a\rho N_1 + \beta_1(\alpha Z_1 - 4M_2N_1)) - b_1^2b_2(4\lambda M_2 + \alpha a(4 - 9\rho)N_1 - \alpha^2a(1 - \rho) -$

$2\beta_1(M_2N_1 + \alpha Z_2) + \beta_2(2M_2N_1 - \alpha M_2 - 3\alpha Z_2)\big) - b_1 b_2^2\big(4\lambda M_2 + 2\alpha a(1+\rho)N_1 - \alpha^2 a\rho + \beta_1(3\alpha Z_2 - 5M_2N_1 + \alpha M_2) - \beta_2(M_2N_1 + \alpha Z_1)\big) + b_2^2\Big(\beta_1^2(M_2 + 3Z_2) - \beta_1\beta_2 Z_1 - 2a\lambda(1+2\rho) + a\beta_2\rho N_1 + \beta_1\big(a(2+\rho)N_1 - \alpha a\rho\big)\Big) + 2b_1^2\big(\beta_1\beta_2(M_2 + 2Z_2) + 4a\lambda(1-\rho) - 3\beta_1 a(1-\rho)N_1 - \beta_2 a\rho N_1\big) - b_1 b_2\Big(\beta_1(\beta_1 + \beta_2)(M_2 + 3Z_2) + 6a\lambda(1-2\rho) + \beta_1\big(2\alpha a(1-\rho) - a(4-7\rho)N_1\big) - \beta_2 a\rho(k\theta_0 - c)\Big) + b_2 a\beta_1\big(\beta_1(1-\rho) + \beta_2\rho\big)\Big].$

$F_1 = \frac{2b_1^2\mu_2 + b_1b_2(\mu_1-\mu_2) - b_2^2(\mu_1+\mu_2)}{4b_1^2\mu_1\mu_2 - b_2^2(\mu_1+\mu_2)^2}$, $F_2 = \frac{2b_1^2\alpha\mu_2 - b_2(\mu_1+\mu_2)(b_2\alpha+\mu_2\beta_2) + 2b_1\mu_1\mu_2\beta_1}{4b_1^2\mu_1\mu_2 - b_2^2(\mu_1+\mu_2)^2}$,

$F_3 = \frac{b_2a(1-\rho)\mu_2(\mu_1+\mu_2) + 2b_1\mu_1\mu_2 a\rho}{4b_1^2\mu_1\mu_2 - b_2^2(\mu_1+\mu_2)^2}$, $F_4 = \frac{2b_1^2\mu_1 - b_1b_2(\mu_1-\mu_2) - b_2^2(\mu_1+\mu_2)}{4b_1^2\mu_1\mu_2 - b_2^2(\mu_1+\mu_2)^2}$,

$F_5 = \frac{b_2\beta_1\mu_1(\mu_1+\mu_2) - b_1b_2\alpha(\mu_1-\mu_2) - 2b_1\mu_1\mu_2\beta_2}{4b_1^2\mu_1\mu_2 - b_2^2(\mu_1+\mu_2)^2}$, $F_6 = \frac{2\mu_1\mu_2 b_1 a(1-\rho) + b_2 a\rho\mu_1(\mu_1+\mu_2)}{4b_1^2\mu_1\mu_2 - b_2^2(\mu_1+\mu_2)^2}$.

$\xi_1 = (\beta_1 + b_2F_5 - b_1F_2)[1 + (1-\mu_1)F_1] - (b_1F_1 - b_2F_4)[N_1 + (1-\mu_1)F_2]$,

$\xi_2 = 2[(\beta_1 + b_2F_5 - b_1F_2)\big(N_1 + (1-\mu_1)F_2\big) - \lambda(1-\phi)]$,

$\xi_3 = (\beta_1 + b_2F_5 - b_1F_2)[(1-\mu_1)F_3 - Z_1] + (a\rho + b_2F_6 - b_1F_3)[N_1 + (1-\mu_1)F_2]$,

$\xi_4 = 2[1 + (1-\mu_2)F_4](b_2F_1 - b_1F_4)$,

$\xi_5 = (1-\mu_2)F_5(b_2F_1 - b_1F_4) - [1 + (1-\mu_2)F_4](\beta_2 + b_1F_5 - b_2F_2)$,

$\xi_6 = [1 + (1-\mu_2)Fa_4][a(1-\rho) - b_1F_6 + b_2F_3] + (b_2F_1 - b_1F_4)[(1-\mu_2)F_6 - M_2]$.

# 6.2

## *Retailers' competition in a green closed-loop supply chain under CTP*

This study seeks to address the horizontal competition and cooperation of competing retailers under cap-and-trade policy (CTP). The manufacturer produces the green product and sells it to the retailers with consistent wholesale price depending on the reaction of the retailers. Market demand is assumed to vary with retail prices and greening level of the product, and its deterministic archetype is known to the manufacturer and the retailers. Besides manufacturing new product from fresh raw materials, the manufacturer also remanufactures used products. To reduce the GHG emissions and encourage the manufacturer in green production, the government gives some emission cap and subsidy. While selling products to customers, retailers can behave differently. Depending on various behavior of retailers, we consider different scenarios such as Collusion (C), Nash (N), and Retailer-led Stackelberg (R) scenarios along with the centralized scenario. A transfer payment mechanism is proposed for achieving the Pareto improvement for the channel individuals and a bargaining model is developed for sharing extra profit obtained through the proposed mechanism. This study aims to answer the following questions:

- Which behavior of the retailers is the best from the point of view of the manufacturer, the retailers, and consumers?
- What are the impacts of government policies on the green supply chain under retailers' different behaviors?
- Does the leader always get higher profit in the case of the Stackelberg game between the retailers?

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This study is based on the work published in *Operational Research*, 2022, 22, 859-894.

### 6.2.1 Notations and assumptions

The following notations are used for developing the proposed models:

| | |
|---|---|
| $w_i$ | unit wholesale price of the manufacturer to the retailer $i$ ($i = 1, 2$). |
| $p_i$ | unit selling price of the retailer $i$ ($i = 1, 2$). |
| $\theta$ | level of green innovation. |
| $D_i$ | demand function of the retailer $i$ ($i = 1, 2$). |
| $D$ | total demand. |
| $D_R$ | collection quantity. |
| $c_m$ | unit manufacturing cost of the end product from raw materials. |
| $c_r(< c_m)$ | unit manufacturing cost of the end product from used products. |
| $c_e$ | unit carbon trading cost. |
| $e$ | carbon emission for unit product. |
| $E_m$ | carbon emission of the manufacturer. |
| $E$ | carbon cap given by the government to the manufacturer. |
| $a_i$ | basic market demand to the retailer $i$ ($i = 1, 2$). |
| $\tau$ | fraction of demand which is returned, $0 \leq \tau \leq 1$. |
| $\lambda$ | green investment cost coefficient. |
| $A_0$ | price paid by the manufacturer to the customer to collect used products. |
| $\Pi_m$ | profit of the manufacturer. |
| $\Pi_{r_i}$ | profit of the retailer $i$ ($i = 1, 2$). |
| $\Pi$ | profit of the whole supply chain. |

The following assumptions are made to establish the proposed models:

**(1)** The market demand faced by retailers is deterministic and linearly dependent on the greening level and the selling prices of the product. The demand functions of two retailers are assumed as $D_i = a_i - \alpha p_i + \beta p_j + \gamma\theta, i = 1, 2; j = 3 - i$. So, the total demand is $D = (a_1 + a_2) - (\alpha - \beta)(p_1 + p_2) + 2\gamma\theta$. The parameters $\alpha$ and $\beta$ represent the self-price and the cross-price sensitivity, respectively. We assume $\alpha > \beta$, which indicates that the self-price effect is greater than the cross-price effect *i.e.* if there is any change in the selling price of retailer $i$, it has more effect on its own demand than the rival's demand (Hanssens et al., 2003; Kurata et al., 2007). $\gamma$ is the sensitivity of greening level.

**(2)** The collection quantity $D_R$ is assumed as $D_R = \tau D$. The manufacturer pays $A_0$ per unit to customers for collecting used products and remanufactures these collected products at a cost of $c_r$ per unit.

**(3)** All the remanufactured products have the same quality as that of the new ones

(Savaskan et al., 2004). So, remanufactured products are sold with the new products in the same market. As we assume $c_m > c_r$, so remanufacturing a used product is more profitable than manufacturing a new product.

**(4)** Carbon emission for a unit product depends on the greening level and is given by $e = e_0 - \psi\theta$, where $e_0$ is the basic emission and $\psi$ is the adjustment factor. Since both the new and the remanufactured products are sold in the same market, in order to avoid complexity in calculation, we assume that carbon emission due to manufacturing is the same as that of remanufacturing. So, the total emission is $E_m = (D - D_R)e$ (due to new production) + $D_R e$ (due to product remanufacturing) *i.e.* $E_m = De$. If $E_m \geq E$, then the manufacturer has to buy the shortage of emission permit at the cost of $c_e$ per unit to produce more. The opposite situation occurs when $E_m < E$ *i.e.* the manufacturer can sell the emission permit in the same emission trading market at the same trading price and get some profit. This produces an additional income (Xu et al., 2016a).

**(5)** In order to ensure that all players of the supply chain are profitable in the business, we assume that $p_1 > w_1 > 0, p_2 > w_2 > 0; c_m - c_r > A_0 > 0$. To avoid complexity in calculation, we assume $C_0 = c_m - c_r - A_0 > 0$.

### 6.2.2 Model formulation and analysis

In this section, we develop the proposed models and derive the optimal results for each model analytically. We consider a two-echelon closed-loop green supply chain consisting of a single manufacturer (remanufacturer) and two competing retailers. The manufacturer produces (at a cost of $c_m$ per unit) and sells the green product with greening level $\theta$ to the retailer $i$ at a price $w_i, i = 1, 2$ per unit. Qi et al. (2017) showed that the consistent pricing strategy of the manufacturer provides the best possible optimal result. Here we consider the consistent pricing strategy of the manufacturer *i.e.* $w_1 = w_2 = w$. The retailers sell the product to potential customers through the traditional retail channel at selling prices $p_1$ per unit and $p_2$ per unit, respectively. In the reverse channel, the manufacturer collects the used products at a cost $A_0$ per unit and remanufactures these products at a cost $c_r$ per unit. So, total cost due to remanufacturing is $(A_0 + c_r)$ per unit. The manufacturer has to invest some extra money to achieve green innovation. We assume an increasing and convex cost component $\lambda\theta^2$, $(\lambda > 0)$ (Ghosh and Shah, 2012) to characterize the diminishing investment with respect to $\theta$.

The profit function for the manufacturer is given by

$$\Pi_m(w,\theta) \;=\; wD + sD - c_m(D - D_R) - (c_r + A_0)D_R - c_e(E_m - E) - \lambda\theta^2 \quad (6.2.1)$$

Here, the first term indicates the revenue obtained from selling the product to the retailers and the second term denotes government subsidy. Production costs (including recycling cost of the returned product) of the new and the remanufactured products are given by the third and the fourth terms, respectively. Carbon trading cost is represented by the fifth term and the last term denotes the extra cost for producing a green product.

The profit function for the retailer $i$ is given by

$$\Pi_{r_i}(p_i) \;=\; (p_i - w)D_i,\ i = 1, 2. \quad (6.2.2)$$

We develop various models under centralized and decentralized scenarios. As we

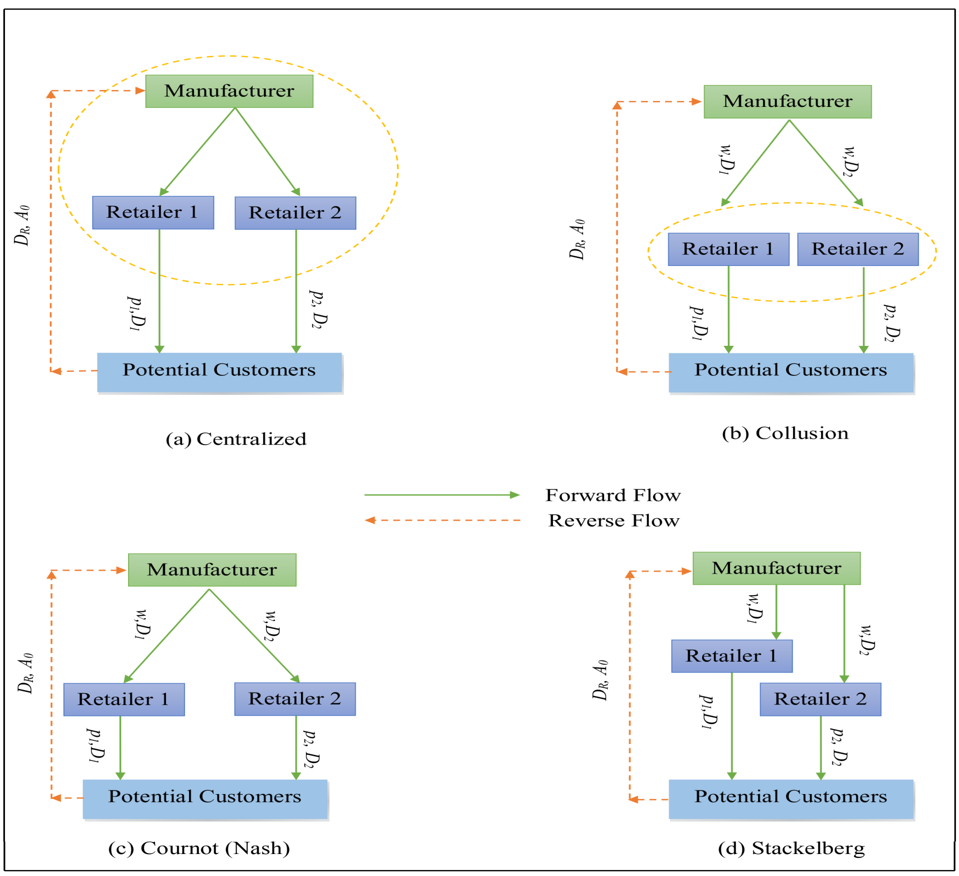



**Fig. 6.2.1:** Graphical representation of the closed-loop supply chain.

are interested in competition and cooperation of the retailers, in the decentralized scenario, we mainly study retailers' different behaviors with the manufacturer as the Stackelberg leader and the retailers as the followers. The duopolistic retailers can implement the following three scenarios:

• *Collusion scenario (C)* - both the retailers act jointly to maximize the total profit of the downstream market (Fig. 6.2.1(b)).

• *Nash scenario (N)* - both the retailers work independently by setting their selling prices and giving service to the customers assuming the rival's decision variable as a parameter (Fig. 6.2.1(c)).

• *Retailer-led Stackelberg (R)* - one retailer (say, retailer 1) acts as the Stackelberg leader and another one (say, retailer 2) as the follower, assuming the rival's decision variable as a parameter and vice-versa (Fig. 6.2.1(d)).

### 6.2.2.1 Centralized policy (J)

In this policy, the manufacturer and the competing retailers work jointly to optimize their decisions viz. greening level and retail prices, through optimizing the joint profit of the manufacturer and the retailers. Due to joint optimization, the internal transfer price $w$ does not play any role (Fig. 6.2.1(a)). The profit function for the centralized policy is given by

$$\Pi^J(p_1, p_2, \theta) = p_1 D_1 + p_2 D_2 + sD - c_m(D - D_R) - (c_r + A_0)D_R - c_e(E_m - E) - \lambda\theta^2$$

Using the first order conditions for optimality of $\Pi^J(p_1, p_2, \theta)$, the equilibrium solution for the centralized policy can be obtained as given in the following proposition:

**Proposition 6.2.1.** *If* $\lambda > \max\left\{2\gamma\Psi_1, \frac{\Psi_3^2}{2(\alpha-\beta)}\right\}$, *the centralized policy has the following unique solution*

$$\begin{aligned} p_1^J &= \frac{a_1 X_1 + a_2 X_2 + 4(\alpha+\beta)X_3}{4(\alpha+\beta)[2\lambda(\alpha-\beta) - \Psi_3^2]}, \\ p_2^J &= \frac{a_2 X_1 + a_1 X_2 + 4(\alpha+\beta)X_3}{4(\alpha+\beta)[2\lambda(\alpha-\beta) - \Psi_3^2]}, \\ \theta^J &= \frac{\Psi_3[a_1 + a_2 - 2(\alpha-\beta)\Psi_2]}{2[2\lambda(\alpha-\beta) - \Psi_3^2]}, \end{aligned}$$

*where* $\Psi_1 = k\theta_0 + c_e\psi$, $\Psi_2 = c_m + k\theta_0^2 - C_0\tau + c_e e_0$, $\Psi_3 = \gamma + (\alpha-\beta)\Psi_1$, $X_1 = 4\alpha\lambda - \Psi_3[\gamma + (3\alpha+\beta)\Psi_1]$, $X_2 = 4\beta\lambda + \Psi_3[\gamma - (\alpha+3\beta)\Psi_1]$, $X_3 = \Psi_2[\lambda(\alpha-\beta) - \gamma\Psi_3]$.

**Proof.** Here,
$\frac{\partial \Pi^J}{\partial p_1} = a_1 - 2\alpha p_1 + 2\beta p_2 + (\gamma - (\alpha-\beta)\Psi_1)\theta + (\alpha-\beta)\Psi_2$, $\frac{\partial^2 \Pi^J}{\partial p_1^2} = -2\alpha < 0$,
$\frac{\partial \Pi^J}{\partial p_2} = a_2 - 2\alpha p_2 + 2\beta p_1 + (\gamma - (\alpha-\beta)\Psi_1)\theta + (\alpha-\beta)\Psi_2$, $\frac{\partial^2 \Pi^J}{\partial p_2^2} = -2\alpha < 0$,
$\frac{\partial \Pi^J}{\partial \theta} = (\gamma - (\alpha-\beta)\Psi_1)(p_1+p_2) + (4\gamma\Psi_1 - 2\lambda)\theta - 2\gamma\Psi_2$, $\frac{\partial^2 \Pi^J}{\partial \theta^2} = -2\lambda + 4\gamma\Psi_1 < 0$,
if $\lambda > 2\gamma\Psi_1$,
$\frac{\partial^2 \Pi^J}{\partial p_1 \partial p_2} = 2\beta$, $\frac{\partial^2 \Pi^J}{\partial p_1 \partial \theta} = \gamma - (\alpha-\beta)\Psi_1$, $\frac{\partial^2 \Pi^J}{\partial p_2 \partial \theta} = \gamma - (\alpha-\beta)\Psi_1$.
The corresponding Hessian matrix is given by

$$H = \begin{pmatrix} \frac{\partial^2 \Pi^J}{\partial p_1^2} & \frac{\partial^2 \Pi^J}{\partial p_1 \partial p_2} & \frac{\partial^2 \Pi^J}{\partial p_1 \partial \theta} \\ \frac{\partial^2 \Pi^J}{\partial p_2 \partial p_1} & \frac{\partial^2 \Pi^J}{\partial p_2^2} & \frac{\partial^2 \Pi^J}{\partial p_2 \partial \theta} \\ \frac{\partial^2 \Pi^J}{\partial \theta \partial p_1} & \frac{\partial^2 \Pi^J}{\partial \theta \partial p_2} & \frac{\partial^2 \Pi^J}{\partial \theta^2} \end{pmatrix} = \begin{pmatrix} -2\alpha & 2\beta & \gamma - (\alpha-\beta)\Psi_1 \\ 2\beta & -2\alpha & \gamma - (\alpha-\beta)\Psi_1 \\ \gamma - (\alpha-\beta)\Psi_1 & \gamma - (\alpha-\beta)\Psi_1 & -2\lambda + 4\gamma\Psi_1 \end{pmatrix}$$

Now, the leading principle minors are $|M_1| = -2\alpha < 0$, $|M_2| = 4(\alpha^2 - \beta^2) > 0$, and $|H| = 4(\alpha+\beta)[\Psi_3^2 - 2\lambda(\alpha-\beta)] < 0$, if $\lambda > \frac{\Psi_3^2}{2(\alpha-\beta)}$. Thus the Hessian matrix is negative definite if $\lambda > \max\left\{2\gamma\Psi_1, \frac{\Psi_3^2}{2(\alpha-\beta)}\right\}$. Using the first order conditions for optimality *i.e.* $\frac{\partial \Pi^J}{\partial p_1} = 0, \frac{\partial \Pi^J}{\partial p_2} = 0$, and $\frac{\partial \Pi^J}{\partial \theta} = 0$, the optimal values of the decision variables can be obtained as given in Proposition 6.2.1. ■

#### 6.2.2.2 *Manufacturer-led-decentralized policy*

There are industries like GM, Toyota (automobile markets), Canon, Xerox, HP (for printing), where the manufacturers are larger than the retailers. So, in such cases, the manufacturer acts as the Stackelberg leader and the retailers as the followers. The retailers first provide their best responses to the manufacturer and then the manufacturer sets his optimal decisions to maximize the profit. With a common manufacturer, the retailers may cooperate or compete or play Stackelberg game while deciding their pricing strategies. In the following subsection, we discuss about the pricing policies and profits of the retailers with different pricing strategies under the manufacturer-led structure.

##### *A. Collusion policy*

In this case, the duopoly retailers agree to act jointly to maximize the total profit in the downstream market. For example, Beijing-based Guotong Electrical Appliance Company and Asia Financial Service Company, GOME with its foreign counterpart Best Buy Inc. (Wang et al., 2011), Europe's largest clothing retailer Inditex and its flagship store Zara, H&M and Alexander Wang (apparel retailer), Samsung Group and Tesco in South Korea as Tesco Home plus, etc. act cooperatively. So, the total profit of the two retailers is given by

$$\Pi_r(p_1, p_2) = \Pi_{r_1} + \Pi_{r_2} = (p_1 - w)D_1 + (p_2 - w)D_2.$$

Now, the problem is reduced to a two-player Stackelberg game. So, the Collusion policy is formulated as follows:

$$\begin{cases} \max\limits_{(w,\theta)} \Pi_m(w, \theta, \overline{p_1}, \overline{p_2}) \\ \text{subject to} \\ \overline{p_1} \text{ and } \overline{p_2} \text{ which are obtained from} \\ \max\limits_{(p_1,p_2)} \Pi_r(p_1, p_2) \end{cases}$$

We first calculate the decisions of the retailers from their joint profit. For any given wholesale price $w$ and greening level $\theta$, the optimal decisions of the retailers' can be obtained from the first order necessary conditions for optimality, which are given as follows:

$$\overline{p_i} = \frac{a_i\alpha + a_j\beta + (\alpha+\beta)[(\alpha-\beta)w + \gamma\theta]}{[2(\alpha^2-\beta^2)]}, \text{ where } i = 1, 2; j = 3 - i. \qquad (6.2.3)$$

Substituting (6.2.3) in the manufacturer's profit function and solving the first order necessary conditions for optimality, we can obtain optimal decisions of the manufacturer and the retailers as follows:

**Proposition 6.2.2.** *If $\lambda > \max\left\{\gamma\Psi_1, \frac{\Psi_3^2}{4(\alpha-\beta)}\right\}$, in Collusion policy, the optimal decisions of the manufacturer are given by*

$$\begin{aligned} w^C &= \frac{(a_1+a_2)(2\lambda - \Psi_1\Psi_3) + 2\Psi_2[2\lambda(\alpha-\beta) - \gamma\Psi_3]}{2\Sigma_1}, \\ \theta^C &= \frac{\Psi_3[a_1 + a_2 - 2(\alpha-\beta)\Psi_2]}{2\Sigma_1} \end{aligned}$$

*and optimal decisions of the retailers are*

$$p_i^C = \frac{a_i Y_i + a_j Y_j + Y_3}{4(\alpha+\beta)\Sigma_1}, \text{ where } i = 1, 2; j = 3 - i.$$

*where $Y_1 = 2\lambda(5\alpha+\beta) - \Psi_3[\gamma + (3\alpha+\beta)\Psi_1]$, $Y_2 = 2\lambda(\alpha+5\beta) + \Psi_3[\gamma - (\alpha+3\beta)\Psi_1]$, $Y_3 = 4(\alpha+\beta)[\lambda(\alpha-\beta) - \gamma\Psi_3]\Psi_2$ and $\Sigma_1 = 4\lambda(\alpha-\beta) - \Psi_3^2$.*

**Proof.** Substituting (6.2.3) in the manufacturer's profit function (6.2.1), we get the profit function of the manufacturer as follows:

$$\Pi_m^C(w, \theta) = (w + \Psi_1\theta - \Psi_2)\Big[\frac{(a_1+a_2) - 2\big((\alpha-\beta)w - \gamma\theta\big)}{2}\Big] + c_e E - \lambda\theta^2$$

Now,
$\frac{\partial \Pi_m^C}{\partial w} = \frac{1}{2}\big[a_1 + a_2 + 2\big(\gamma\theta - (\alpha-\beta)(2w + \Psi_1\theta - \Psi_2)\big)\big]$, $\frac{\partial^2 \Pi_m^C}{\partial w^2} = -2(\alpha-\beta) < 0$,
$\frac{\partial \Pi_m^C}{\partial \theta} = \frac{1}{2}\big[-4\lambda\theta + (a_1+a_2)\Psi_1 + 2\gamma(\Psi_1\theta - \Psi_2) + 2w\big(\gamma - (\alpha-\beta)\Psi_1\big)\big]$,
$\frac{\partial^2 \Pi_m^C}{\partial \theta^2} = -2\lambda + 2\gamma\Psi_1 < 0$, if $\lambda > \gamma\Psi_1$, $\frac{\partial^2 \Pi_m^C}{\partial w \partial \theta} = \gamma - (\alpha-\beta)\Psi_1$.
The corresponding Hessian matrix of the manufacturer's profit function is given by

$$H = \begin{pmatrix} \frac{\partial^2 \Pi_m^C}{\partial w^2} & \frac{\partial^2 \Pi_m^C}{\partial w \partial \theta} \\ \frac{\partial^2 \Pi_m^C}{\partial \theta \partial w} & \frac{\partial^2 \Pi_m^C}{\partial \theta^2} \end{pmatrix} = \begin{pmatrix} -2(\alpha-\beta) & \gamma - (\alpha-\beta)\Psi_1 \\ \gamma - (\alpha-\beta)\Psi_1 & -2\lambda + 2\gamma\Psi_1 \end{pmatrix}$$

Now, $\frac{\partial^2 \Pi_m^C}{\partial \theta^2}$ will be negative if $\lambda > \gamma\Psi_1$ and $|H| = 4\lambda(\alpha-\beta) - \Psi_3^2 > 0$ ,if $\lambda > \frac{\Psi_3^2}{4(\alpha-\beta)}$.
Therefore, the Hessian matrix corresponding to the manufacturer's profit function will be jointly concave w.r.t $w$ and $\theta$ if $\lambda > \max\left\{\gamma\Psi_1, \frac{\Psi_3^2}{4(\alpha-\beta)}\right\}$.
Using the first order conditions for optimality *i.e.* $\frac{\partial \Pi_m^C}{\partial w} = 0$ and $\frac{\partial \Pi_m^C}{\partial \theta} = 0$, the optimal decisions of the manufacturer can be obtained, and putting these decisions in retailers' profit functions, the optimal decisions of the retailers can also be obtained, which are given in Proposition 6.2.2. ■

## B. Nash policy

In this case, we consider that the retailers decide to work independently to maximize their individual profits by determining their respective selling prices. In the real world, GOME and Suning (home appliances), Wal-Mart and Tesco, Amazon and eBay (online retailer), Carrefour and Auchan, H&M and Zara, Walgreens and CVS (drug store in US), Kroger and Publix, Macy's and Belk (https://study.com/academy/lesson/types-of-retail-competition-definition-examples.html), Big Bazaar and Shoppers Stop (family store in India) are few examples where the retailers work independently. The Nash model can be represented as

$$\begin{cases} \max\limits_{(w,\theta)} \Pi_m(w,\theta,\overline{p_1},\overline{p_2}) \\ \text{subject to} \\ \overline{p_1} \text{ and } \overline{p_2} \text{ which are obtained from} \\ \begin{cases} \max\limits_{(p_1)} \Pi_{r_1}(p_1) \\ \max\limits_{(p_2)} \Pi_{r_2}(p_2) \end{cases} \end{cases}$$

Here also, we utilize backward induction method to obtain optimal decisions. Thus, retailer-1 (retailer-2) maximizes its profit $\Pi_{r_1}(\Pi_{r_2})$ with respect to $p_1(p_2)$ treating $p_2(p_1)$ as parameter. As $\frac{\partial^2 \Pi_{r_i}}{\partial p_i^2} = -2\alpha < 0$, for any given wholesale price $w$ and greening level $\theta$, the optimal solution is obtained by solving the equations $\frac{\partial \Pi_{r_1}}{\partial p_1} = 0$

and $\frac{\partial \Pi_{r_2}}{\partial p_2} = 0$, simultaneously. The optimal solution is given by

$$\overline{p_i} = \frac{2a_i\alpha + a_j\beta + (2\alpha+\beta)(\alpha w + \gamma\theta)}{4\alpha^2 - \beta^2}, \text{ where } i = 1,2; j = 3-i \tag{6.2.4}$$

Substituting (6.2.4) into the manufacturer's profit function (6.2.1) and solving the first order conditions for optimality, we obtain optimal decisions of the manufacturer as follows:

**Proposition 6.2.3.** *If* $\lambda > \max\left\{\frac{2\alpha\gamma\Psi_1}{2\alpha-\beta}, \frac{\alpha\Psi_3^2}{2(\alpha-\beta)(2\alpha-\beta)}\right\}$, *in Nash policy, the optimal decisions of the manufacturer are given by*

$$\begin{aligned} w^N &= \frac{(a_1+a_2)[\lambda(2\alpha-\beta) - \alpha\Psi_1\Psi_3] + 2\Psi_2[\lambda(\alpha-\beta)(2\alpha-\beta) - \alpha\gamma\Psi_3]}{2\Sigma_2}, \\ \theta^N &= \frac{\alpha\Psi_3[a_1+a_2-2(\alpha-\beta)\Psi_2]}{2\Sigma_2}, \end{aligned}$$

*and optimal decisions of the retailers are*

$$p_i^N = \frac{a_jZ_i + a_i\alpha Z_j + Z_3}{2(2\alpha+\beta)\Sigma_2}, \text{ where } i = 1,2; j = 3-i.$$

*where* $Z_1 = \lambda(2\alpha^2 - 5\alpha\beta - 4\beta^2) + \alpha\gamma(\gamma - 3\beta\Psi_1) - \alpha(\alpha-\beta)(\alpha+2\beta)\Psi_1^2$, $Z_2 = \lambda(10\alpha - 7\beta) - (\gamma + 3\alpha\Psi_1)\Psi_3$, $Z_3 = 2\alpha(2\alpha+\beta)[\lambda(\alpha-\beta) - \gamma\Psi_2\Psi_3]$, *and* $\Sigma_2 = 2\lambda(\alpha-\beta)(2\alpha-\beta) - \alpha\Psi_3^2$.

**Proof.** The proof is similar to that of Proposition 6.2.2. ■

## C. Retailer-led Stackelberg policy

We now assume that one of the retailers (say, retailer-1) is the Stackelberg leader and other retailer (say, retailer-2) is the Stackelberg follower. This type of situation can be noticed in the business of large retailers. For instance, Tesco launches Jack's, Wal-Mart operates Sam's club, etc. In this case, our problem is

$$\begin{cases} \max\limits_{(w,\theta)} \Pi_m(w,\theta,p_2^*(w,\theta,\widetilde{p_1}),\widetilde{p_1}(w,\theta)) \\ \text{subject to } \widetilde{p_1} \text{ is obtained from} \\ \begin{cases} \max\limits_{(p_1)} \Pi_{r_1}(p_1,\overline{p_2}) \\ \text{subject to } \overline{p_2} \text{ which is obtained from} \\ \max\limits_{(p_2)} \Pi_{r_2}(p_2) \end{cases} \end{cases}$$

In the following, we obtain the best response of the retailer-2 for given values of $w, \theta, p_1$ by equating $\frac{\partial \Pi_{r_2}}{\partial p_2}$ to zero as

$$\overline{p_2} = \frac{a_2 + \alpha w + \beta p_1 + \gamma\theta}{2\alpha} \tag{6.2.5}$$

Substituting (6.2.5) in the profit function of retailer-1 and solving the first order optimality condition for $p_1$, we can obtain the best response of retailer-1 as

$$\widetilde{p_1} = \frac{2a_1\alpha + a_2\beta + (\alpha+\beta)(2\alpha-\beta)w + (2\alpha+\beta)\gamma\theta}{2(2\alpha^2-\beta^2)} \tag{6.2.6}$$

Again, substituting (6.2.5) and (6.2.6) into the manufacturer's profit function and solving the first order conditions for optimality, we can obtain the best response of the manufacturer which is given in the following proposition.

**Proposition 6.2.4.** *If* $\lambda > \max\left\{\frac{\gamma\Psi_1\Psi_4}{4\alpha(2\alpha^2-\beta^2)}, \frac{\Psi_3^2\Psi_4}{16\alpha(\alpha-\beta)(2\alpha^2-\beta^2)}\right\}$, *in Retailer-led Stackelberg policy, the optimal decisions of the manufacturer are given by*

$$\begin{aligned}
w^R &= \frac{\left(\begin{array}{c}[2a_1\alpha(\alpha+\beta)(2\alpha-\beta) + a_2\Psi_4][8\alpha\lambda(2\alpha^2-\beta^2) - \Psi_1\Psi_3\Psi_5] \\ +\Psi_2\Psi_5[8\alpha\lambda(\alpha-\beta)(2\alpha^2-\beta^2) - \gamma\Psi_3\Psi_5]\end{array}\right)}{\Psi_5\Sigma_3}, \\
\theta^R &= \frac{\Psi_3[2a_1\alpha(\alpha+\beta)(2\alpha-\beta) + a_2\Psi_4 - (\alpha-\beta)\Psi_2\Psi_5]}{\Sigma_3}
\end{aligned}$$

*and optimal decisions of the retailers are*

$$\begin{aligned}
p_1^R &= \frac{2a_1\alpha + a_2\beta + (\alpha+\beta)(2\alpha-\beta)w^R + (2\alpha+\beta)\gamma\theta^R}{2(2\alpha^2-\beta^2)}, \\
p_2^R &= \frac{a_2 + \alpha w^R + \beta p_1^R + \gamma\theta^R}{2\alpha}
\end{aligned}$$

*where* $\Psi_4 = 4\alpha^3 + 2\alpha^2\beta - \alpha\beta^2 - \beta^3$, $\Psi_5 = 2\Psi_4 - \beta^2(\alpha-\beta)$ *and* $\Sigma_3 = 16\alpha\lambda(\alpha-\beta)(2\alpha^2-\beta^2) - \Psi_3^2\Psi_5$.

**Proof.** The proof is similar to that of Proposition 6.2.2. ∎

#### 6.2.2.3 Comparison of optimal results

##### Special case

As it is difficult to compare the optimal results of the proposed models derived above, in this subsection, we consider a special case in which both the retailers face the same basic market *i.e.* $a_1 = a_2 = a$. Using the solution procedure shown in the previous subsection, we present optimal solutions of the proposed models for the special case in Table 6.2.1.

**Table 6.2.1:** Optimal results of the proposed models when $a_1 = a_2 = a$.

| | Model J | Model C | Model N | Model R |
|---|---|---|---|---|
| $w^*$ | – | $\frac{a[2\lambda - \Psi_1\Psi_3] + \Psi_2[2\lambda(\alpha-\beta) - \gamma\Psi_3]}{\Sigma_1}$ | $\frac{a[\lambda(2\alpha-\beta) - \alpha\Psi_1\Psi_3] + \Psi_2[\lambda(\alpha-\beta)(2\alpha-\beta) - \alpha\gamma\Psi_3]}{\Sigma_2}$ | $\frac{a[8\alpha\lambda(2\alpha^2-\beta^2) - \Psi_1\Psi_3\Psi_5] + \Psi_2[8\alpha\lambda(\alpha-\beta)(2\alpha^2-\beta^2) - \gamma\Psi_3\Psi_5]}{\Sigma_3}$ |
| $\theta^*$ | $\frac{[a-(\alpha-\beta)\Psi_2]\Psi_3}{2\lambda(\alpha-\beta) - \Psi_3^2}$ | $\frac{\Psi_3[a-(\alpha-\beta)\Psi_2]}{\Sigma_1}$ | $\frac{\alpha\Psi_3[a-(\alpha-\beta)\Psi_2]}{\Sigma_2}$ | $\frac{\Psi_3\Psi_5[a-(\alpha-\beta)\Psi_2]}{\Sigma_3}$ |
| $p_1^*$ | $\frac{a[\lambda - \Psi_1\Psi_3] + \Psi_2[\lambda(\alpha-\beta) - \gamma\Psi_3]}{2\lambda(\alpha-\beta) - \Psi_3^2}$ | $\frac{a[3\lambda - \Psi_1\Psi_3] + \Psi_2[\lambda(\alpha-\beta) - \gamma\Psi_3]}{\Sigma_1}$ | $\frac{a[\lambda(3\alpha-2\beta) - \alpha\Psi_1\Psi_3] + \alpha\Psi_2[\lambda(\alpha-\beta) - \gamma\Psi_3]}{\Sigma_2}$ | $\frac{a[4\alpha\lambda(6\alpha^2-\alpha\beta-3\beta^2) - \Psi_1\Psi_3\Psi_5] + \Psi_2[4\alpha\lambda(2\alpha-\beta)(\alpha^2-\beta^2) - \gamma\Psi_3\Psi_5]}{\Sigma_3}$ |
| $p_2^*$ | $\frac{a[\lambda - \Psi_1\Psi_3] + \Psi_2[\lambda(\alpha-\beta) - \gamma\Psi_3]}{2\lambda(\alpha-\beta) - \Psi_3^2}$ | $\frac{a[3\lambda - \Psi_1\Psi_3] + \Psi_2[\lambda(\alpha-\beta) - \gamma\Psi_3]}{\Sigma_1}$ | $\frac{a[\lambda(3\alpha-2\beta) - \alpha\Psi_1\Psi_3] + \alpha\Psi_2[\lambda(\alpha-\beta) - \gamma\Psi_3]}{\Sigma_2}$ | $\frac{a[\lambda(24\alpha^3-4\alpha^2\beta-14\alpha\beta^2+2\beta^3) - \Psi_1\Psi_3\Psi_5] + \Psi_2[\lambda(8\alpha^4-6\alpha^2\beta^2-4\alpha^3\beta+2\beta^4) - \gamma\Psi_3\Psi_5]}{\Sigma_3}$ |
| $\Pi_m^*$ | – | $c_eE + \frac{\lambda[a-(\alpha-\beta)\Psi_2]^2}{\Sigma_1}$ | $c_eE + \frac{\alpha\lambda[a-(\alpha-\beta)\Psi_2]^2}{\Sigma_2}$ | $c_eE + \frac{\lambda\Psi_5[a-(\alpha-\beta)\Psi_2]^2}{\Sigma_3}$ |
| $\Pi_{r_1}^*$ | – | $\frac{(\alpha-\beta)\lambda^2[a-(\alpha-\beta)\Psi_2]^2}{\Sigma_1^2}$ | $\frac{\alpha(\alpha-\beta)^2\lambda^2[a-(\alpha-\beta)\Psi_2]^2}{\Sigma_2^2}$ | $\frac{8\alpha(2\alpha^2-\beta^2)(2\alpha^2-\alpha\beta-\beta^2)^2\lambda^2[a-(\alpha-\beta)\Psi_2]^2}{\Sigma_3^2}$ |
| $\Pi_{r_2}^*$ | – | $\frac{(\alpha-\beta)\lambda^2[a-(\alpha-\beta)\Psi_2]^2}{\Sigma_1^2}$ | $\frac{\alpha(\alpha-\beta)^2\lambda^2[a-(\alpha-\beta)\Psi_2]^2}{\Sigma_2^2}$ | $\frac{4\alpha(\alpha-\beta)^2(4\alpha^2+2\alpha\beta-\beta^2)^2\lambda^2[a-(\alpha-\beta)\Psi_2]^2}{\Sigma_3^2}$ |
| $\Pi^*$ | $c_eE + \frac{\lambda[a-(\alpha-\beta)\Psi_2]^2}{2\lambda(\alpha-\beta) - \Psi_3^2}$ | $c_eE + \frac{\lambda[a-(\alpha-\beta)\Psi_2]^2[\Sigma_1 + 2\lambda(\alpha-\beta)]}{\Sigma_1^2}$ | $c_eE + \frac{\alpha\lambda[a-(\alpha-\beta)\Psi_2]^2[\Sigma_2 + 2\lambda(\alpha-\beta)^2]}{\Sigma_2^2}$ | – |

**Proposition 6.2.5.** *When the duopolistic retailers face the same basic market they charge the same selling price from customers and get the same profit while playing Nash and Collusion games. But in the case of the Stackelberg game, they charge different selling prices and so get different profits.*

**Proposition 6.2.6.** *In the special case, the greening level of the product follows the pattern* $\theta^J > \theta^N > \theta^R > \theta^C$.

**Proof.** On simplification,

$\theta^J - \theta^N = \frac{2\lambda\Psi_3(\alpha-\beta)^2[a-(\alpha-\beta)\Psi_2]}{2\Sigma_2[2\lambda(\alpha-\beta)-\Psi_3^2]} > 0$

$\theta^N - \theta^R = \frac{2(2\alpha+\beta)(\alpha-\beta)^2\beta^2\lambda\Psi_3[a-(\alpha-\beta)\Psi_2]}{\Sigma_2\Sigma_3} > 0$

$\theta^R - \theta^C = \frac{4\beta(\alpha-\beta)(4\alpha^2+\alpha\beta-\beta^2)\lambda\Psi_3[a-(\alpha-\beta)\Psi_2]}{\Sigma_1\Sigma_3} > 0.$ ■

Proposition 6.2.6 illustrates that the greening level of the product depends on the duopolistic retailers' different competitive behaviors. The centralized policy provides a higher green product. Among the duopolistic retailers' three different behaviors, the Nash behavior helps the manufacturer to produce a higher green product while Collusion behavior forces the manufacturer to produce a lower green product. The reason behind this outcome is described as follows: In a manufacturer-led Stackelberg game, the manufacturer optimizes its decisions after knowing the decisions of the retailers. When the retailers work independently (in Nash situation), in order to get more market demand they tend to sell their products with lower selling prices. This induces the manufacturer to set a lower wholesale price for the retailers. According to our assumption, the manufacturing cost is constant. So, naturally, a lower wholesale price results in a revenue loss to the manufacturer. In order to get more government subsidy and reduce GHG emissions, the manufacturer has no option without increasing the greening level of the product. The opposite situation holds when the retailers work jointly.

**Proposition 6.2.7.** *In the special case, selling prices and wholesale price follow the pattern* $p_i^C > p_i^R > p_i^N > p_i^J$ *and if* $(\alpha - \beta)\Psi_1 > \gamma$, *then* $w^C > w^R > w^N$, *i* = *1, 2.*

**Proof.** On simplification,

$p_1^C - p_1^R = \frac{\beta\lambda[a-(\alpha-\beta)\Psi_2][16\lambda\alpha^2(\alpha-\beta)-\Psi_3\{\gamma[16\alpha^2+3\beta(\alpha-\beta)]-(\alpha-\beta)^2\beta\Psi_1\}]}{\Sigma_1\Sigma_3} > 0$

$p_1^R - p_1^N = \frac{(\alpha-\beta)\beta^2\lambda[a-(\alpha-\beta)\Psi_2][8\alpha\lambda(\alpha-\beta)-\Psi_3\{\gamma(5\alpha+2\beta)+\alpha(\alpha-\beta)\Psi_1\}]}{\Sigma_2\Sigma_3} > 0$

$p_1^N - p_1^J = \frac{2(\alpha-\beta)\lambda[a-(\alpha-\beta)\Psi_2][\lambda(\alpha-\beta)-\gamma\Psi_3]}{\Sigma_2[2\lambda(\alpha-\beta)-\Psi_3^2]} > 0$

$w^C - w^R = \frac{2\beta\lambda(4\alpha^2+\alpha\beta-\beta^2)[a-(\alpha-\beta)\Psi_2][(\alpha-\beta)^2-\gamma^2]}{\Sigma_1\Sigma_3} > 0$ if $(\alpha-\beta)\Psi_1 > \gamma$

$w^R - w^N = \frac{(2\alpha^2-\alpha\beta-\beta^2)\beta^2\lambda[a-(\alpha-\beta)\Psi_2][(\alpha-\beta)^2-\gamma^2]}{\Sigma_2\Sigma_3} > 0$ if $(\alpha-\beta)\Psi_1 > \gamma$. ■

Proposition 6.2.7 shows that duopolistic retailers' different behaviors affect the wholesale price of the manufacturer which is contrary to the result of Yang and Zhou (2006) and Huang et al. (2016) who showed that duopolistic retailers' different behaviors have no effect on the optimal pricing policy of the manufacturer. The reason behind this type of different outcome probably lies in the consideration of green products, government subsidy, and CTP. In our model, if the condition given in Proposition 6.2.7 holds then the wholesale price becomes higher in Collusion policy and lower in Nash policy. As the manufacturer produces the lower green product in Collusion, it gets lower government subsidy. So, in order to maintain profitability, the manufacturer sets higher wholesale price in the case of Collusion behavior. The opposite result can be seen in the case of Nash behavior.

The selling prices of the retailers follow the pattern similar to the wholesale price of the manufacturer. The reason behind this type of outcome is that a higher wholesale price of the manufacturer forces the retailers to set their selling prices higher. In the case of centralized policy, since there is no double-marginalization effect, the centralized decision-maker can set a lower selling price to get more profit from the market.

**Proposition 6.2.8.** *In the special case, the profits of the manufacturer follow the pattern* $\Pi_m^N > \Pi_m^R > \Pi_m^C$.

**Proof.** The proof is similar to the cases of greening level in Proposition 6.2.6. ■

Proposition 6.2.8 shows that the duopolistic retailers under Nash behavior help the manufacturer to get higher profit while the manufacturer's profit becomes lower when the duopolistic retailers play Collusion behavior. This is due to the fact that, in case of Nash behavior of the retailers, the manufacturer produces the higher green product and sells it to the retailers with the lower selling price. The retailers also sell these products with lower selling prices to the potential customers. Higher greening level and lower selling prices of the product help to increase the market demand which in turn increases the profit of the manufacturer.

Due to algebraic complexity, we are unable to compare the profits of the retailers under different competitive behaviors. But one can easily calculate the difference between the profits of the retailers in the Stackelberg game, which is given in the following:

$$\Pi_{r_2}^R - \Pi_{r_1}^R = \frac{4\alpha\beta^3\lambda^2(\alpha-\beta)^2(4\alpha+3\beta)[a-(\alpha-\beta)\Psi_2]^2}{\Sigma_3^2} > 0$$

This means that when the duopolistic retailers face the same basic market and play Stackelberg game, the follower gets higher profit in comparison to the leader. So, it is beneficial to be a follower rather than a leader. This is a contradiction to the intuitive expectation but this result is consistent with the result of Yang and Zhou (2006). Actually, the leader gets a higher profit only when its basic market is higher than the follower. In the case of a similar basic market, in order to get higher market demand, the follower sells the product with lower selling price. The higher market demand produces a higher profit to the follower. That's why, in this particular situation, the follower gets higher profit than the leader although the leader is more powerful.

Now, one question may arise whether all the results given in the propositions for the special case hold for the general case. Due to algebraic complexity, it is difficult to answer this question. However, we discuss this matter taking numerical examples in the next section.

#### 6.2.2.4 Transfer payment through bargaining

To achieve the Pareto improvement for the players of the supply chain, in this subsection, we coordinate through transfer payment mechanism. Suppose that the three players of the supply chain are denoted by 1, 2 and 3 and their profits in two policies (say, (model I) and (model II)) are $(\Pi_1^I, \Pi_2^I, \Pi_3^I)$ and $(\Pi_1^{II}, \Pi_2^{II}, \Pi_3^{II})$, respectively. We assume the profit of any one of the three players (say, player 1) in model II is higher than that in model I and profits of the remaining two players in model II are lower than that in model I. So, the profit gain by player 1 is $\triangle\Pi_1 = \Pi_1^{II} - \Pi_1^I$ and the profit loss by other two players are $\triangle\Pi_2 = \Pi_2^I - \Pi_2^{II}$ and $\triangle\Pi_3 = \Pi_3^I - \Pi_3^{II}$, respectively. If the increment of profit of player 1 is greater than the decrement of the total profit of the other two players, then player 1 can design a transfer payment mechanism to coordinate channel members. Transfer payment $T_1$ to player 2 satisfies $T_1 \in (\triangle\Pi_2, (\triangle\Pi_1 - \triangle\Pi_3))$ and transfer payment $T_2$ to player 3 satisfies $T_2 \in (\triangle\Pi_3, (\triangle\Pi_1 - \triangle\Pi_2))$ such that $T_1 + T_2 < \triangle\Pi_1$. Players' profit shares depend on their bargaining powers. More bargaining power implies more profit share to the channel members. In the following, we discuss the bargaining model following Aust and Buscher (2012) to share the extra profit $\triangle\Pi$.

Let the utility function of the bargaining model be

$$U = (U_m(\triangle\Pi_m))^{\mu_m}(U_{r_1}(\triangle\Pi_{r_1}))^{\mu_{r_1}}(U_{r_2}(\triangle\Pi_{r_2}))^{\mu_{r_2}}$$

where $\mu_m$, $\mu_{r_1}$, and $\mu_{r_2}$ are positive parameters such that $\mu_m + \mu_{r_1} + \mu_{r_2} = 1$, and are called the bargaining powers of the manufacturer and the retailers, respectively; $\triangle\Pi_i$'s $(i = m, r_1, r_2)$ are profit shares to the manufacturer and the retailers, and $U_i$'s $(i = m, r_1, r_2)$ are the utility functions which can be taken as $U_m(\triangle\Pi_m) = \triangle\Pi_m^{\lambda_m}$, $U_{r_1}(\triangle\Pi_{r_1}) = \triangle\Pi_{r_1}^{\lambda_{r_1}}$, $U_{r_2}(\triangle\Pi_{r_2}) = \triangle\Pi_{r_2}^{\lambda_{r_2}}$, where $\lambda_m, \lambda_{r_1}, \lambda_{r_2} > 0$ are the risk attitudes of the players (SeyedEsfahani et al., 2011).

Now, the optimization problem becomes,

$$\begin{aligned} \text{Max } U &= \triangle\Pi_m^{\lambda_m\mu_m}\triangle\Pi_{r_1}^{\lambda_{r_1}\mu_{r_1}}\triangle\Pi_{r_2}^{\lambda_{r_2}\mu_{r_2}} \\ \text{subject to } \triangle\Pi &= \triangle\Pi_m + \triangle\Pi_{r_1} + \triangle\Pi_{r_2}; \;\; \triangle\Pi_m, \triangle\Pi_{r_1}, \triangle\Pi_{r_2} > 0. \end{aligned}$$

The optimal solution of this problem is

$$\begin{aligned} \triangle\Pi_m &= \frac{\lambda_m\mu_m}{\lambda_m\mu_m + \lambda_{r_1}\mu_{r_1} + \lambda_{r_2}\mu_{r_2}}\triangle\Pi \\ \triangle\Pi_{r_1} &= \frac{\lambda_{r_1}\mu_{r_1}}{\lambda_m\mu_m + \lambda_{r_1}\mu_{r_1} + \lambda_{r_2}\mu_{r_2}}\triangle\Pi \\ \triangle\Pi_{r_2} &= \frac{\lambda_{r_2}\mu_{r_2}}{\lambda_m\mu_m + \lambda_{r_1}\mu_{r_1} + \lambda_{r_2}\mu_{r_2}}\triangle\Pi. \end{aligned}$$

## 6.2.3 Numerical analysis

In this section, we perform a numerical study for the developed models to explore answers of the following questions: How do retailers' different pricing strategies affect equilibrium results and profits of channel members? Is there any economic inspiration for the retailers to choose Collusion rather than Nash strategy? Do the government subsidy and CTP help the manufacturer in decision making? We consider the following data sets which are closely related to Xu et al. (2016a), and Yang et al. (2017) with some adjustment:

**Set 1:** $a_1 = 500; a_2 = 450; \alpha = 0.6; \beta = 0.15; \gamma = 0.8; \tau = 0.35; k = 0.5; \theta_0 = 1.5; e_0 = 1; \psi = 0.2; c_m = 150; c_r = 70; c_e = 12; A_0 = 50; \lambda = 300; E = 300.$

**Set 2:** $a_1 = 500; a_2 = 500; \alpha = 0.6; \beta = 0.15; \gamma = 0.8; \tau = 0.35; k = 0.5; \theta_0 = 1.5; e_0 = 1; \psi = 0.2; c_m = 150; c_r = 70; c_e = 12; A_0 = 50; \lambda = 300; E = 300.$

**Set 3:** $a_1 = 500; a_2 = 700; \alpha = 0.6; \beta = 0.15; \gamma = 0.8; \tau = 0.35; k = 0.5; \theta_0 = 1.5; e_0 = 1; \psi = 0.2; c_m = 150; c_r = 70; c_e = 12; A_0 = 50; \lambda = 300; E = 300.$

Here, Set 1 represents the situation where retailer 1 has greater basic market than retailer 2. Set 2 distinguishes from other Sets by making the same basic market for the two retailers. Set 3 is taken by considering that the retailer 2 has greater basic market than retailer 1. Optimal results of the proposed models for each numerical example are presented in Table 6.2.2.

**Table 6.2.2:** Optimal results for general situation.

| Pricing Policy | Set | $w$ | $p_1$ | $p_2$ | $\theta$ | $\Pi_m$ | $\Pi_{r_1}$ | $\Pi_{r_2}$ | $\Pi$ |
|---|---|---|---|---|---|---|---|---|---|
| Centralized | Set 1 | - | 618.425 | 585.092 | 3.39898 | - | - | - | 190858.0 |
| | Set 2 | - | 629.392 | 629.392 | 3.60812 | - | - | - | 214141.0 |
| | Set 3 | - | 673.263 | 806.596 | 4.44465 | - | - | - | 329751.0 |
| Collusion | Set 1 | 602.935 | 847.409 | 814.075 | 1.68387 | 96162.30 | 28117.7 | 19005.4 | 143284.4 |
| | Set 2 | 630.642 | 872.465 | 872.465 | 1.78748 | 107903.0 | 26315.4 | 26315.4 | 160533.8 |
| | Set 3 | 741.468 | 972.691 | 1106.02 | 2.20190 | 161874.0 | 19434.4 | 67096.7 | 248405.1 |
| Nash | Set 1 | 602.768 | 816.807 | 779.770 | 1.92696 | 109525.0 | 27487.5 | 18797.7 | 155810.2 |
| | Set 2 | 630.465 | 838.014 | 838.014 | 2.04552 | 122960.0 | 25846.2 | 25846.2 | 174652.4 |
| | Set 3 | 741.250 | 922.846 | 1070.99 | 2.51977 | 184723.0 | 19786.2 | 65238.6 | 269747.8 |
| Stackelberg | Set 1 | 602.630 | 820.170 | 780.111 | 1.91308 | 108727.0 | 27506.9 | 18899.9 | 155134.8 |
| | Set 2 | 630.474 | 841.357 | 838.428 | 2.03146 | 122140.0 | 25849.0 | 25946.8 | 173935.8 |
| | Set 3 | 741.853 | 926.103 | 1071.69 | 2.50495 | 183838.0 | 19732.5 | 65276.6 | 268847.1 |

From Table 6.2.2, we note that the centralized policy gives better performance than other policies as usual. While considering the decentralized policies, we note that the Nash behavior of the retailers is profitable for the manufacturer and the whole supply chain, but the behavior which is beneficial to the retailers depends on the basic market of the retailers. From Table 6.2.2, we have the following insights on wholesale price, selling prices, greening level, and profitability of the manufacturer and the retailers: (i) The wholesale price of the product does not follow the pattern similar to the special case. In case of different basic markets, the variation of the wholesale price depends on the basic market parameter. Generally, the manufacturer sets a higher wholesale price when the retailers make their decisions jointly but sometimes the Stackelberg game between them forces the manufacturer to set a higher wholesale price. (ii) Similar to the special case, for the general case, the duopolistic retailers set higher selling prices in case of Collusion behavior while, in case of Nash behavior, they demand lower selling prices. (iii) The greening level of the product does not depend on the market size; it is always higher in case of Nash behavior and lower in case of Collusion behavior. A higher market size influences the manufacturer to produce a higher green product. (iv) Similar to the special case, the duopolistic retailers' Nash behavior always promotes the manufacturer and the whole supply chain through improving the profits. The profit of the manufacturer is more than twice the total profit of the retailers. So, being a Stackelberg leader, the manufacturer should try to find out a way that will induce the retailers to work in Nash behavior. (v) Although Nash behavior is profitable to the manufacturer and the whole supply chain, it is not beneficial for the retailers. Moreover, Collusion behavior of the retailers always does not make higher profit to both the retailers. It is not favorable to the retailer with lower value of $a_i/\alpha$, as it produces a lower profit to that retailer. The retailer with a higher basic market gets higher profit. This insight will help the retailers to decide proper selling prices before agreeing to work jointly. (vi) When the duopolistic retailers play the Stackelberg game, the leader gains higher profit only when the basic market to the leader is higher than the rival.

**Table 6.2.3:** Optimal results when no subsidy occurs and both cap and subsidy do not occur.

| Optimal | No subsidy | | | | No cap no subsidy | | | |
|---|---|---|---|---|---|---|---|---|
| decisions | J | C | N | R | J | C | N | R |
| $w$ | - | 603.084 | 603.020 | 602.876 | - | 598.071 | 598.149 | 597.997 |
| $p_1$ | 619.301 | 847.254 | 816.725 | 820.081 | 615.283 | 844.024 | 813.231 | 816.611 |
| $p_2$ | 585.968 | 813.921 | 779.688 | 780.028 | 581.949 | 810.690 | 776.194 | 776.537 |
| $\theta$ | 2.87028 | 1.42569 | 1.63089 | 1.61918 | 1.22431 | 0.61143 | 0.69889 | 0.69391 |
| $\Pi_m$ | - | 96153.90 | 109476.0 | 108681.0 | - | 94517.3 | 108038.0 | 107233.0 |
| $\Pi_{r_1}$ | - | 28049.3 | 27401.8 | 27422.3 | - | 28451.4 | 27756.3 | 27779.1 |
| $\Pi_{r_2}$ | - | 18949.2 | 18726.9 | 18829.6 | - | 19280.0 | 19020.1 | 19126.1 |
| $\Pi$ | 190352.0 | 143152.4 | 155604.7 | 154932.9 | 189676.0 | 142248.0 | 154814.0 | 154138.0 |

Table 6.2.3 represents the optimal results for data Set 1 when the government does not offer any subsidy, and both the government subsidy and carbon cap do not play any role in the supply chain. For the first case, the manufacturer is forced to set a higher wholesale price for the product with a lower greening level in order to maintain profitability. Although the wholesale price increases, due to lower green product, customers refuse to buy the product with higher selling price. So, retailers have to reduce the selling prices. In the centralized policy, due to joint decisions, they manage to sell the lower green product with a slightly higher selling price. In the decentralized policies, as the greening level decreases, the market demand also decreases. So, the profits of the manufacturer, retailers, and the whole supply

chain decrease in all cases. Due to no government subsidy and cap on emission for the second case, the manufacturer can produce less green product and sell it at a lower wholesale price. As a result, retailers also set lower selling prices to hold their markets. The manufacturer tends to emit less and earn some revenue through emission trading under CTP. In that case, his profit is higher than that in the case where CTP does not occur. In the second case, the rate of decrement of the wholesale price is slightly higher than those of selling prices. So, the profits of the retailers are higher in this case than those in the first case. Therefore, a government subsidy to the manufacturer and CTP play important role in sustainable development.

From all the aforementioned results, it can be seen that the duopolistic retailers' Collusion behavior is only helpful to the retailers under certain conditions but their Nash behavior is beneficial to both the manufacturer and the whole supply chain. As the manufacturer produces higher green product in Nash behavior, s/he can get higher subsidy and profit in this policy. So, from the environmental viewpoint, it is necessary for the manufacturer to design a transfer payment mechanism to achieve Pareto improvement of all members in the supply chain. Comparing Nash and Collusion behaviors for Set 1, we note that the profit of the manufacturer is increased by 13362.7 (from 96162.30 to 109525.0), whereas the profit of the retailer 1 is decreased by 630.2 (from 28117.7 to 27487.5) and that of retailer 2 is decreased by 207.7 (from 19005.4 to 18797.7). So, the increment in profit of the manufacturer is greater than the decrement in total profit of the retailer 1 and retailer 2. Thus, the transfer payment $T_1$ to the retailer 1 is such that $T_1 \in (630.2, 13155.0)$ and the transfer payment $T_2$ to the retailer 2 is such that $T_2 \in (207.7, 12732.5)$. It is necessary that $T_1 + T_2 < 13362.7$. Profit shares among the channel members depend on their bargaining powers and risk attitudes. As the manufacturer is the leader, we consider the bargaining power of the manufacturer as $\mu_m = 0.5$ and bargaining powers of the retailers as $\mu_{r_1} = \mu_{r_2} = 0.25$. Also, as the decrement in profit of the retailer 2 is higher, risk attitudes of the manufacturer and the retailers are taken as $\lambda_m = 1.1$, $\lambda_{r_1} = 1.8$, and $\lambda_{r_2} = 2.0$. Then profit shares to the manufacturer and the retailers are obtained as 4592.79, 3757.74 ($\in T_1$), and 4175.27 ($\in T_2$), respectively.

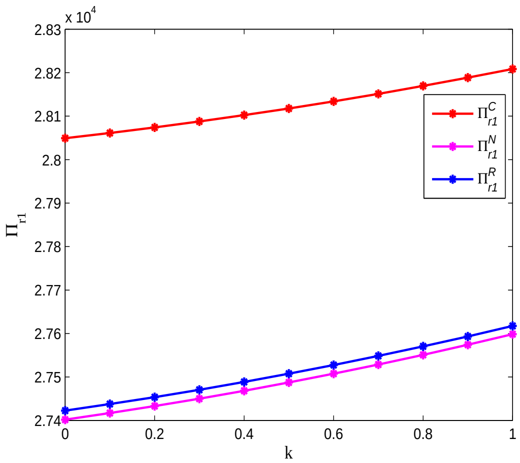
### 6.2.4 Sensitivity analysis

In this section, we discuss the sensitivity of some key parameters to investigate the effect of those parameters on the optimal results considering the parameter-values given in data Set 1. Fig. 6.2.2 represents the sensitivity of parameter $k$ on profits of channel members and Fig. 6.2.3 represents the joint effect of green level floor $\theta_0$ and emission cap $E$ on the total profit of the supply chain.

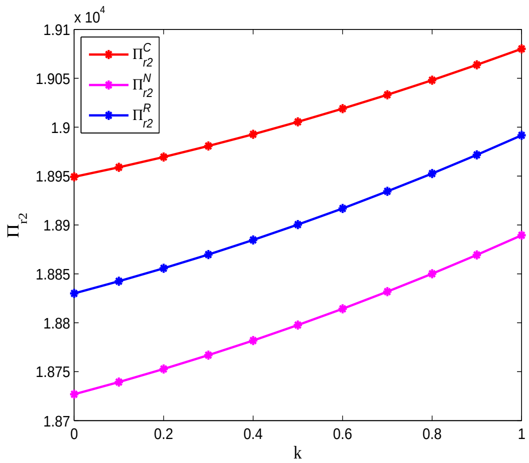
It is obvious that a higher value of green investment parameter $\lambda$ has a negative effect on the greening level *i.e.* if $\lambda$ increases, the greening level decreases. Customers refuse to buy the lower green product at a higher price. So, the retailers decrease the selling prices to increase the market demand and keep the profit intact. A lower green product causes lower government subsidy resulting in a decrease in the manufacturer's profit. Although the selling prices are lower, due to a lower green product, the demand at the retailers' end decreases. As a result, the profit of each retailer decreases. Hence, the overall profit of the supply chain decreases. For brevity, we omit those figures.

**Table 6.2.4:** Sensitivity of the optimal results with respect to $k$.

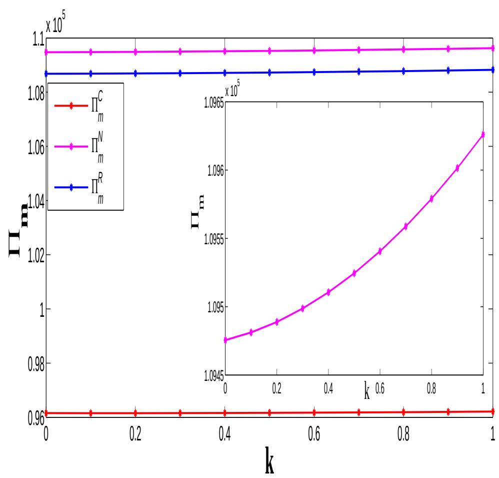
| Policy | $k$ | $w$ | $p_1$ | $p_2$ | $\theta$ |
|---|---|---|---|---|---|
| Centralized | 0.1 | - | 619.158 | 585.825 | 2.97548 |
| | 0.3 | - | 618.824 | 585.490 | 3.18667 |
| | 0.5 | - | 618.425 | 585.092 | 3.39898 |
| | 0.7 | - | 617.961 | 584.628 | 3.61252 |
| | 0.9 | - | 617.433 | 584.099 | 3.82738 |
| Collusion | 0.1 | 603.070 | 847.292 | 813.959 | 1.47722 |
| | 0.3 | 603.018 | 847.358 | 814.025 | 1.58043 |
| | 0.5 | 602.935 | 847.409 | 814.075 | 1.68387 |
| | 0.7 | 602.821 | 847.444 | 814.110 | 1.78756 |
| | 0.9 | 602.675 | 847.463 | 814.130 | 1.89151 |
| Nash | 0.1 | 602.988 | 816.751 | 779.714 | 1.68996 |
| | 0.3 | 602.896 | 816.789 | 779.752 | 1.80830 |
| | 0.5 | 602.768 | 816.807 | 779.770 | 1.92696 |
| | 0.7 | 602.605 | 816.804 | 779.767 | 2.04595 |
| | 0.9 | 602.405 | 816.781 | 779.744 | 2.16531 |
| Stackelberg | 0.1 | 602.844 | 820.109 | 780.054 | 1.67781 |
| | 0.3 | 602.755 | 820.149 | 780.093 | 1.79530 |
| | 0.5 | 602.630 | 820.170 | 780.111 | 1.91308 |
| | 0.7 | 602.469 | 820.171 | 780.110 | 2.03120 |
| | 0.9 | 602.272 | 820.151 | 780.088 | 2.14968 |



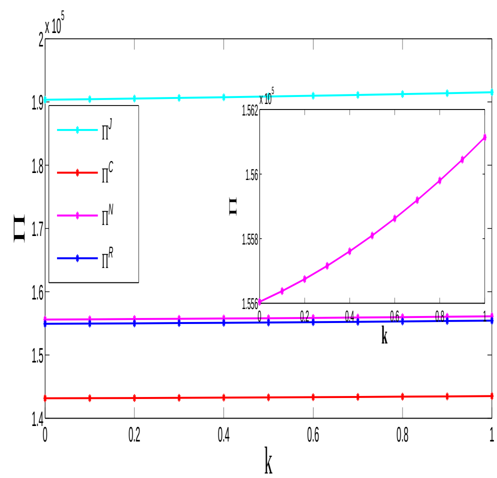

**(a)** $k$ vs $\Pi_{r_1}$.




**(b)** $k$ vs $\Pi_{r_2}$.



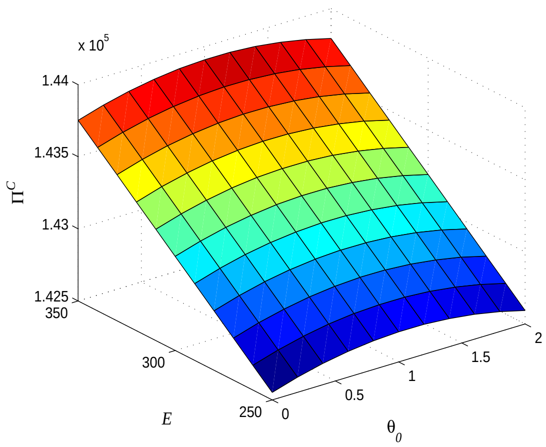

**(c)** $k$ vs $\Pi_m$.



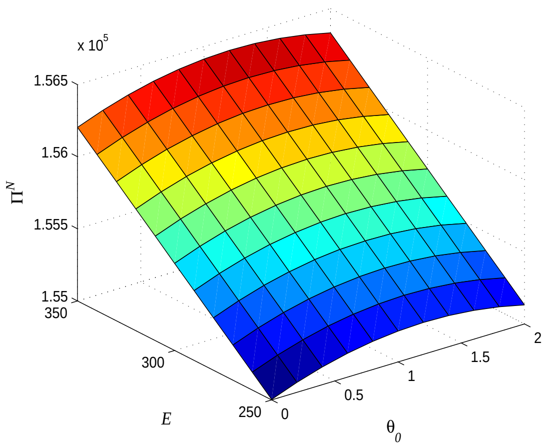

**(d)** $k$ vs $\Pi$.

**Fig. 6.2.2:** Profit change w.r.t. $k$.

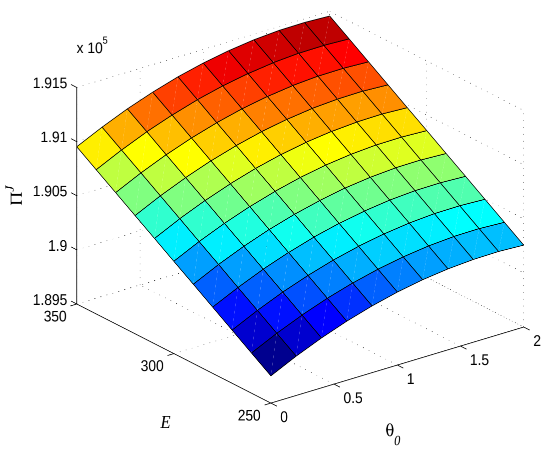
Tables 6.2.4 represents the effect of the adjustment factor $k$ on the optimal decisions in all policies. From Table 6.2.4 we note that, the adjustment factor has a positive impact on the greening level and it can improve the greening level rapidly. A higher value of the greening level helps the manufacturer to get more government subsidy and so s/he can decrease the wholesale price. The rate of decrement is higher in the Nash case. In the centralized policy, the higher greening level helps the decision-maker to obtain higher government subsidy. So, the selling prices decrease as $k$ increases. Due to the improved greening level, the retailers can increase the selling prices up to a certain level of $k$. After that, although the greening level rises with $k$, the selling prices decrease. This outcome is similar to that of Yang et al. (2017). The reason behind this result is that higher selling prices may decrease the market demand and this may harm the profit of the retailers. So, the retailers cannot increase the selling prices infinitely with the greening level; they have to decrease the selling prices after a certain level. Therefore, under strong governmental intervention, the conflict between the selling prices and the greening level tends to reduce which shows that increasing the adjustment factor is beneficial to both customers and the environment. Higher greening level and lower selling prices increase the market demand, which increases the profits of the manufacturer, the retailers, and the whole supply chain. The rate of increment of the retailers' profit is higher than those of the manufacturer and the whole supply chain (see Fig. 6.2.2). From this outcome, one can easily comment that even if government subsidy is given to the manufacturer, with the issue of higher greening level with higher adjustment factor, the retailers actually get more profit.




**(a)** $\theta_0$ and $E$ vs $\Pi^C$.




**(b)** $\theta_0$ and $E$ vs $\Pi^N$.




**(c)** $\theta_0$ and $E$ vs $\Pi^J$.

**Fig. 6.2.3:** Profit change w.r.t. $\theta_0$ and $E$.

Among the four decentralized policies, as the total profit of the supply chain is higher in Nash policy and lower in Collusion policy, we consider the joint effect of green level floor $\theta_0$ and carbon cap $E$ on the total profit of these two policies and the centralized policy in Fig. 6.2.3. As the green level floor increases, the greening level of the product also increases. As a result, the market demand increases. The total profit of the supply chain increases as the green level floor increases up to a certain value. After that, although the green level floor increases, the total profit of the supply chain begins to decrease. The reason behind this outcome is that up to a certain level of the green level floor, the increased profits as a result of increasing customer demand outweigh the green investment costs. After that, an increase in retail price due to higher green product reduces the market demand. Again, the manufacturer has to invest more money to produce the higher green product. This reduces the profits of the manufacturer, retailers, and the whole supply chain. A carbon cap also has a positive impact on the total profit of the supply chain. As the carbon cap increases, the manufacturer gets the license to emit more and produce more products. Due to higher production, the selling prices of the product become lower, which increase the market demand. A higher market demand improves the profits of the manufacturer, the retailers, and the whole supply chain. But due to environmental issues, the manufacturer should produce higher green product, and to do so, the government should lower carbon cap.

## 6.3
# *Conclusions*

From the comparison and analysis of optimal results of Section 6.1 it is observed that, in addition to gaining more profit, the centralized policy gives a better green product. Among the decentralized policies, the Nash game is profitable for the retailer and the whole supply chain. From the Stackelberg game, we note that $M_1$-led Stackelberg game is beneficial for $M_2$ and the environment but Bertrand behavior is preferable for the retailer, which is consistent with the existing literatures (Zhao and Wei, 2014; Ma et al., 2018) on the competitive supply chain. It is additionally noticed that when the manufacturers act jointly or a single manufacturer generates both the green and conventional non-green products, it is beneficial for $M_1$ only however it hurts the retailer, the non-green manufacturer and customers. Moreover, the Collusion behavior provides less profit to the non-green manufacturer than all other policies, which is in opposition to the consequence of Zhao and Wei (2014). Although CS contract expands the greening level and benefit of the manufacturers, it decreases the benefit of the retailer whereas RCS contract expands the greening level as well as accomplishes the win-win situation. The non-existence of government sponsorship decreases the benefits of both manufacturers and increases that of the retailer in all policies except the Collusion behavior. Surprisingly, it provides higher profit to the green manufacturer.

In the classical model, the product greening cost is mainly borne by the green manufacturer only but the retailer benefits from green marketing. For this reason, the green manufacturer does not have enough motivation in green manufacturing and wants the retailer to share some portion of the green investment cost. Although the proposed cost sharing contract improves the greening level, it increases the selling price and affects market demand. The non-green manufacturer does not participate in the contract but he benefits from the higher price of the green product while the retailer losses from this contract due to higher price of the green product. So, the supply chain manager may implement RCS contract in which the non-green manufacturer also participates. Besides increasing the greening level, the RCS contract can decrease the price of the product and achieve win-win situation for both the manufacturers and the retailer. To address the present natural issues and force the manufacturer in producing more green products, they should set suitable green level floor and adjustment factor.

From the analytical comparison and numerical study of Section 6.2, we have the following observations: (i) Among the three different behaviors of the retailers, the Nash behavior is beneficial to customers, the manufacturer, and the whole supply chain but Collusion behavior is beneficial to the retailers only when the difference between their basic markets is small enough. (ii) When both the government subsidy and CTP are considered, the policy becomes profitable to all the channel members. (iii) In case of the retailer-led Stackelberg game, the leader cannot always get higher profit; they can get a higher profit only when the basic market is higher. If the basic market remains the same, it is beneficial to be follower rather than leader.

From the above insights, we can recommend some managerial implication. Firstly, the retailers get higher profit only when they work cooperatively and the difference between their basic markets is sufficiently low but their conflicting (Nash) situation is beneficial to the manufacturer, customers, and the whole supply chain. If a mechanism (here transfer payment mechanism) is developed in which the retailers always agree to work independently, it will be beneficial. Secondly, although a higher value of the green level floor increases the greening level of the product, it affects the profit of the manufacturer. So, a green investment cost sharing contract can encourage the manufacturer to undertake green manufacturing. Thirdly, the nonoccurrence of governmental intervention and CTP decrease the greening level and increase the selling prices of the product. The government sector should discuss about the awareness of environmental issues (GHG emissions, global warming) so that the manufacturer and retailers can agree to obey the governmental intervention and CTP. Lastly, in order to address the environmental issue, a comparatively high adjustment factor and green level floor should be set by the government to motivate the green innovation without worrying about the profit of the supply chain.

# 7

# *Integrating CSR in a sustainable closed-loop supply chain*

## 7.0 Introduction

Due to the growing interest of customers in social and environmental responsibility in recent years, the research of CLSC management has become an important field of investigation among researchers and practitioners in the light of Corporate Social Responsibility (CSR). There are different forms of CSR efforts, such as improving labor policies, eliminating child labor, charitable grants, educational support, health and safety practices, rural development, etc. There are many instances of how organizations all over the globe allocate resources to CSR. For example, Starbucks offers opportunities for students of all ages, the farming communities through its public welfare programs. Apple is imparting costs to its supplier Foxconn Technology Group for enhancing labor safety at the iPad and iPhone assembly factories in China (Biswas et al., 2018). In FY 2018-19, Mahindra & Mahindra has invested INR 8.36 crore to support education for underprivileged girls through the after-school support program. Retailers are also investing in CSR, following the footsteps of manufacturers. As an instance, the giant retailer Wal-Mart invested $100 million to help employees. Consequently, it is vital to concentrate on the effect of the organization's CSR venture on market demand and profitability. From this perspective, the current chapter considers the CSR investments of manufacturer and retailer in a variety of scenarios. Section 7.1 considers the retailer's CSR effort while Section 7.2 considers the CSR investment of both the manufacturer and the retailer.

# 7.1

# *Retailer's CSR investment under government subsidy*

Over the years, various streams of CLSC have been evolved and CLSC literature has been enhanced. Most of the prior literatures considered environmental and economic aspects. Although very few studies considered the social aspects, more specifically, CSR effort of channel members but they ignored the impact of CSR effort on used products collection. This study develops an integrated model and three decentralized models based on different collection options of used products, with the manufacturer as the Stackelberg leader and the other channel members as the followers. The manufacturer produces the product and sells it to the retailer who puts effort in CSR. The market demand is assumed to be affected by the selling price of the product and the CSR effort of the retailer. The retailer is encouraged by the government through CSR dependent subsidy. To address the channel coordination issue, a two-part tariff (TPT) contract is considered. The aim of this study is to find the answer of the following questions:

- Which collection option of used products is the best from the viewpoints of the manufacturer, the retailer and customers, and which one is more socially responsible?
- What are the effects of government subsidy to the retailer on the optimal decisions, the profitability of the channel members, and social welfare?
- How does the TPT contract help to improve the channel performance?

This study is based on the work published in *Flexible Services and Manufacturing Journal*, 2022, 34, 65-100.

### 7.1.1 Model formulation

In this section, we develop an integrated supply chain model as the benchmark case and three decentralized models depending on different collection options of used products. In the forward channel, the manufacturer produces a single type of product at a cost of $c_m$ per unit and sells it to the retailer at a wholesale price $w$ per unit. Besides selling the product to customers at a selling price $p$ per unit, the retailer exerts effort in CSR activity $y$. The government supports the retailer to adopt CSR by providing a certain amount of subsidy $S(y)$. In the reverse channel, either the manufacturer or the retailer or the third-party collects used products from customers in return for an acquisition price $A$ per unit. The manufacturer remanufactures these used products at a cost of $c_r$ per unit and sells it with the brand new product. The following notations and assumptions are used to formulate different models.

**Notations:**

| | |
|---|---|
| $w$ | unit wholesale price of the manufacturer (decision variable). |
| $p$ | unit selling price of the retailer (decision variable). |
| $y$ | CSR effort of the retailer (decision variable). |
| $\tau$ | collection rate of used products ($0 < \tau < 1$) (decision variable). |
| $D$ | demand of the retailer. |
| $D_r$ | collection quantity. |
| $c_m$ | unit manufacturing cost of the finished product from the fresh raw material. |
| $c_r(< c_m)$ | unit manufacturing cost of the finished product from the returned product. |
| $\alpha$ | basic market demand. |
| $y_0$ | CSR level floor set by the government. |
| $s$ | adjustment factor of the government. |
| $\lambda$ | CSR investment cost coefficient. |
| $\mu$ | collection cost coefficient. |
| $A$ | unit price paid to customers for returning used products. |
| $B$ | unit price paid by the manufacturer to the retailer/ third-party collector to collect used products ($B > A$). |
| $\Pi_i^j$ | profit function where superscript $j$ denotes the supply chain model (I, M, R, C) while the subscript $i$ denotes the supply chain member and the profit of the whole supply chain, respectively (m, r, c, w). |

**Assumptions:**

**(1)** The market demand is deterministic and linearly dependent on the selling price of the product and the CSR effort of the retailer. The CSR promises to intensify the corporate image and as a result, it can improve market demand for products but selling price is negatively related to the market. So, we take the market demand as $D(p, y) = \alpha - \beta p + \gamma y$, where $\beta$ and $\gamma$ are price sensitivity coefficients and CSR effort sensitivity coefficient, respectively (Liu et al., 2019).

**(2)** The collection quantity of used products is a fraction of total demand. We take $D_r = \tau D$, where $\tau$ depends on $y$. To reduce the negative effect of used products, the more the CSR effort, the more the used products return will be. Shu et al. (2018) suggested that the CSR effort has a positive impact on recycling rate. Hosseini-Motlagh et al. (2019) also considered that the collector's CSR investment affects the supply function of used products. So, we take $\tau = \tau_0 + \tau_1 y$, where $\tau_0 (< 1)$ is the collection rate independent of CSR and $\tau_1$ is a sufficiently small constant such that $\tau$ is a non-negative fraction.

**(3)** As the retailer is responsible for CSR effort, the government offers a subsidy $S(y)$ to the retailer to encourage in CSR, where $S(y)$ is defined as

$$S(y) = \begin{cases} sy_0(y - y_0), & \text{if } y > y_0 \\ 0, & \text{if } y \leq y_0 \end{cases}$$

**(4)** The retailer bears some extra cost for undertaking CSR, which is taken as a quadratic function of $y$, *i*.e. $\lambda y^2$ (Liu et al., 2019), and the players have to invest some extra cost for collecting used products, which is taken as $\mu \tau^2$ (Savaskan et al., 2004).

**(5)** In order to ensure that all players of the supply chain are profitable in the business, we assume that $p > w > 0; c_m - c_r > A > 0; c_m - c_r > B > 0; 2\beta\lambda - \gamma^2 > 0$. To avoid complexity in derivation, we assume $\Delta = c_m - c_r$; $Z_1 = \Delta - A > 0, Z_2 = \Delta - B > 0$, and $X = \mu(4\beta\lambda - \gamma^2) - Z_1^2\beta^2\lambda$.

#### 7.1.1.1 *Model I: Integrated supply chain*

In this model, all the members of the supply chain are willing to work jointly to optimize their decisions such as the retail price $p$, the CSR effort $y$, and the basic collection rate of used products $\tau_0$ through maximizing the total profit of the supply chain (see Fig. 7.1.1(a)). Since a single decision-maker handles all the activities, the internal transfer prices $w$ and $B$ don't play any role.

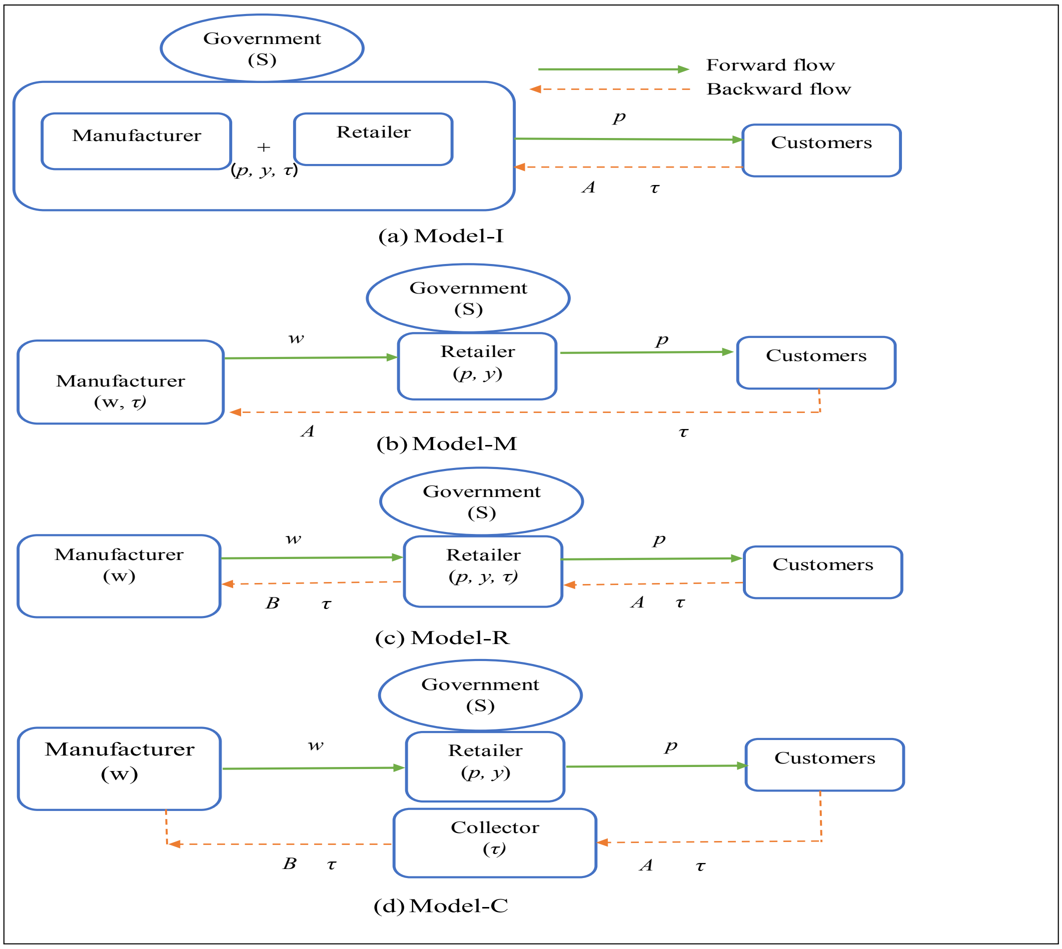



**Fig. 7.1.1:** Proposed closed-loop supply chain models.

Hence, the objective function for the integrated model is given by

$$\max_{(p,y,\tau)} \Pi^I = (p - c_m)D + (\Delta - A)D_r - \lambda y^2 - \mu\tau^2 + S(y) \tag{7.1.1}$$

The optimal decisions of Model I can be obtained by solving the first order necessary conditions for optimality of the objective function (7.1.1), which give

$$p^I = \frac{sy_0\gamma(2\mu - Z_1^2\beta) + 2[2(\alpha + c_m\beta)\mu\lambda - c_m\gamma^2\mu - Z_1^2\alpha\beta\lambda]}{2X},$$

$$y^I = \frac{sy_0\beta(4\mu - Z_1^2\beta) + 2(\alpha - c_m\beta)\gamma\mu}{2X}, \quad \tau^I = \frac{Z_1\beta[sy_0\gamma + 2(\alpha - c_m\beta)\lambda]}{2X}$$

The corresponding optimum profit of the integrated supply chain is given by

$$\Pi^I = \frac{\mu[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2 + Xsy_0^2(s - 4\lambda)}{4\lambda X}$$

As the optimal decisions and profit cannot be negative, we have to restrict ourself in the region where the required situation holds *i.e.* Hessian matrix is negative definite. The Hessian matrix will be negative definite if $\mu > \frac{Z_1^2\beta^2\lambda}{4\beta\lambda - \gamma^2}$.

**Proof.** The Hessian matrix associated with the profit function of the integrated supply chain is given by

$$H^I = \begin{pmatrix} -2\beta & -\beta Z_1 & \gamma - \beta\tau_1 Z_1 \\ -\beta Z_1 & -2\mu & \gamma Z_1 - 2\mu\tau_1 \\ \gamma - \beta\tau_1 Z_1 & \gamma Z_1 - 2\mu\tau_1 & -2(\lambda + \mu\tau_1^2 - \gamma Z_1\tau_1) \end{pmatrix}$$

Now, the principal minors are: $|M_1| = -2\beta < 0$, $|M_2| = 4\beta\mu - Z_1^2\beta^2 > 0$, if $\mu > \frac{Z_1^2\beta}{4}$ and $|H^I| = -2[\beta(4\mu - Z_1^2\beta)\lambda - \gamma^2\mu] < 0$, if $\mu > \frac{Z_1^2\beta^2\lambda}{4\beta\lambda-\gamma^2}$. $\mu(4\beta\lambda - \gamma^2) - Z_1^2\beta^2\lambda = \beta\lambda(4\mu - Z_1^2\beta) - \gamma^2\mu > 0$ implies $\mu > \frac{Z_1^2\beta}{4}$. Therefore, if $\mu > \frac{Z_1^2\beta^2\lambda}{4\beta\lambda-\gamma^2}$, the Hessian matrix $H^I$ becomes negative definite. ■

Again, from the condition that the optimal return rate is always $\leq 1$, we get $\mu \geq \frac{Z_1\beta[sy_0\gamma+2\lambda(\alpha-c_m\beta+Z_1\beta)]}{2(4\beta\lambda-\gamma^2)}$. Thus, we have to choose $\mu$ large enough such that $\mu \geq \frac{Z_1\beta[sy_0\gamma+2\lambda(\alpha-c_m\beta+Z_1\beta)]}{2(4\beta\lambda-\gamma^2)}$.

#### 7.1.1.2 Model M: Manufacturer collects used products

Here we assume that in the forward channel, the manufacturer produces and sells the product to customers through the retailer while in the reverse channel, he collects used products directly from customers by paying a price $A$ per unit and remanufactures these used products (see Fig. 7.1.1(b)). This type of collection strategy is used by Xerox, Canon, Apple, etc.

The objective functions of the manufacturer and the retailer are given by

$$\max_{(w,\tau)} \Pi_m^M = (w - c_m)D + (\Delta - A)D_r - \mu\tau^2, \text{ and} \tag{7.1.2}$$

$$\max_{(p,y)} \Pi_r^M = (p - w)D - \lambda y^2 + S(y) \tag{7.1.3}$$

As we are interested in the manufacturer-led Stackelberg game, we use backward induction method. So, the retailer optimizes her best responses through determining the selling price $p$ and CSR $y$ which can be obtained by solving the first order necessary conditions for optimality of the retailer's objective function (7.1.3) simultaneously. For given decisions of the manufacturer, the retailer's decision can be obtained as

$$p^M(w,\tau) = \frac{\gamma(sy_0 - \gamma w) + 2\lambda(\alpha + \beta w)}{4\beta\lambda - \gamma^2}, \quad y^M(w,\tau) = \frac{\gamma(\alpha - \beta w) + 2\beta s y_0}{4\beta\lambda - \gamma^2}.$$

With these reactions of the retailer, the manufacturer will optimize his objective function (7.1.2) through determining the wholesale price $w$ and the collection rate of used products $\tau$. The optimal solution can be obtained by solving the first order necessary conditions for optimality of the manufacturer's objective function (7.1.2) simultaneously. The optimal profits of the manufacturer and the retailer are obtained by substituting corresponding optimal decisions in Eqs. (7.1.2) and (7.1.3), and the total profit $\Pi_w^M$ of the whole supply chain can be obtained by summing the channel members' optimal profits. The optimal results of the manufacturer and the retailer are summarized in Table 7.1.1.

**Proof.** *The retailer's reaction*

The Hessian matrix associated with $\Pi_r^M$ is given by

$$H_R^M = \begin{pmatrix} -2\beta & \gamma \\ \gamma & -2\lambda \end{pmatrix}$$

Now, the principal minors are: $|M_1| = -2\beta < 0$ and $|H_R^M| = 4\beta\lambda - \gamma^2 > 0$, if $\lambda > \frac{\gamma^2}{4\beta}$. Thus, the Hessian matrix $H_R^M$ is negative definite under this condition.

*The manufacturer's reaction*

With the optimal decisions of the retailer, the Hessian matrix of $\Pi_m^M$ is given by

$$H_M^M = \begin{pmatrix} -2\mu & \frac{2\mu(\gamma\mu\tau_1 - Z_1\beta\lambda)}{4\beta\lambda-\gamma_1^2} \\ \frac{2\mu(\gamma\mu\tau_1 - Z_1\beta\lambda)}{4\beta\lambda-\gamma_1^2} & \frac{2\beta^2[-8\beta\lambda^2+2Z_1\beta\gamma\lambda\tau_1+\gamma^2(2\lambda-\mu\tau_1^2)]}{(4\beta\lambda-\gamma^2)^2} \end{pmatrix}$$

Now, the principal minors are: $|M_1| = -2\mu < 0$ and $|H_M^M| = \frac{4\beta^2\lambda X_1}{(4\beta\lambda-\gamma^2)^2} > 0$, if $\mu > \frac{\beta_1^2 Z_1^2 \lambda}{2(4\beta\lambda-\gamma^2)}$. Under this condition, the Hessian matrix $H_M^M$ becomes negative definite, and using the first order optimality conditions, the optimal decisions can be obtained. ■

### 7.1.1.3 Model R: Retailer collects used products

Here, we assume that the manufacturer contracts with the retailer for collecting used products. So, the retailer collects the used products from customers by paying a price $A$ per unit and transfers it to the manufacturer in return for a transfer price $B$ per unit (see Fig. 7.1.1(c)). Kodak contracts with retailers for collecting used disposable cameras (Savaskan et al., 2004). Car, refrigerator, and furniture are collected by the same retailer who sells them earlier with comparable value or exchange offer.

The objective functions of the manufacturer and the retailer are given by

$$\max_{(w)} \Pi_m^R = (w - c_m)D + (\Delta - B)D_r, \text{ and} \tag{7.1.4}$$

$$\max_{(p,y,\tau)} \Pi_r^R = (p - w)D + (B - A)D_r - \lambda y^2 - \mu\tau^2 + S(y) \tag{7.1.5}$$

Similar to Model M, we use backward induction method. So, the retailer optimizes her best responses through determining the selling price $p$, CSR $y$ and collection rate $\tau$ of used products, which can be obtained by solving the first order necessary conditions for optimality of the retailer's objective function (7.1.5) simultaneously. For given decisions of the manufacturer, the retailer's decisions can be obtained as

$$\begin{aligned} p^R(w) &= \frac{2\gamma\mu(sy_0 - w\gamma) - sy_0\beta\gamma(B-A)^2 - 2\lambda[\alpha\beta(B-A)^2 - 2\mu(\alpha+\beta w)]}{\lambda[4\beta\mu - \beta^2(B-A)^2] - \gamma^2\mu}, \\ y^R(w) &= \frac{2\mu[2sy_0\beta + \gamma(\alpha - \beta w)] - sy_0\beta^2(B-A)^2}{\lambda[4\beta\mu - \beta^2(B-A)^2] - \gamma^2\mu}, \\ \tau^R(w) &= \frac{\beta(B-A)[sy_0\gamma + 2\lambda(\alpha - \beta w)]}{\lambda[4\beta\mu - \beta^2(B-A)^2] - \gamma^2\mu}. \end{aligned}$$

With these reactions of the retailer, the manufacturer optimizes his objective function (7.1.4) through determining the wholesale price $w$. The optimal solution can be obtained by solving the first order necessary conditions for optimality of the manufacturer's objective function (7.1.4). The optimal profits of the manufacturer and the retailer are obtained by substituting corresponding optimal decisions in Eqs. (7.1.4) and (7.1.5), respectively and the total profit ($\Pi_w^R$) of the whole supply chain can be obtained by summing the channel members' optimal profits. The optimal results of the manufacturer and the retailer are summarized in Table 7.1.1.

**Proof.** *The retailer's reaction*

The Hessian matrix associated with $\Pi_r^R$ is given by

$$H_R^R = \begin{pmatrix} -2\beta & -(B-A)\beta & \gamma - \beta\tau_1(B-A) \\ -(B-A)\beta & -2\mu & (B-A)\gamma - 2\mu\tau_1 \\ \gamma - \beta\tau_1(B-A) & (B-A)\gamma - 2\mu\tau_1 & -2[\lambda + \mu\tau_1^2 - (B-A)\gamma\tau_1] \end{pmatrix}$$

Now, the principal minors are: $|M_1| = -2\beta < 0, |M_2| = 4\beta\mu - (B-A)^2\beta^2 > 0$, if $\mu > \frac{(B-A)^2\beta}{4}$, and $|H_R^R| = -2[\beta\lambda[4\mu - \beta(B-A)^2] - \gamma^2\mu] < 0$, if $\mu > \frac{\beta^2\lambda(B-A)^2}{4\beta\lambda - \gamma^2}$. Thus, the Hessian matrix $H_R^R$ is negative definite under this condition.

*The manufacturer's reaction*

$\frac{\partial^2\Pi_m^R}{\partial w^2} = -\frac{4\beta^2\mu\lambda X_2}{[\beta\lambda[4\mu-\beta(B-A)^2]-\gamma^2\mu]^2} < 0$, if $\mu > \frac{(B-A)Z_1\beta^2\lambda}{4\beta\lambda-\gamma^2}$. Under this condition, $\Pi_m^R$ will be negative definite and unique optimal solution can be obtained by solving the first order necessary condition for of $\Pi_m^R$. ■

### 7.1.1.4 Model C: Third-party collects used products

In this model, the manufacturer contracts with an independent third-party collector for collecting used products. So, the collector collects used products from customers by paying a price $A$ per unit and transfers it to the manufacturer in return for a transfer price $B$ per unit (see Fig. 7.1.1(d)). Dell and Acer contract with the independent third-party collector for collecting used desktop and laptop. This type of collection strategy is also common in glass, metal, and plastic industries.

The objective functions of the manufacturer, the retailer and the third-party are given by

$$\max_{(w)} \Pi_m^C = (w - c_m)D + (\Delta - B)D_r, \tag{7.1.6}$$

$$\max_{(p,y)} \Pi_r^C = (p - w)D - \lambda y^2 + S(y) \text{ and} \tag{7.1.7}$$

$$\max_{(\tau)} \Pi_c^C = (B - A)D_r - \mu\tau^2 \tag{7.1.8}$$

Here also we use backward induction method. So, the retailer optimizes her best responses through determining the selling price $p$ and CSR $y$, which can be obtained by solving the first order necessary conditions for optimality of the retailer's objective function (7.1.7) simultaneously. For given decisions of the manufacturer, the retailer's decisions can be obtained as

$$p^C(w) = \frac{\gamma(sy_0 - w\gamma) + 2\lambda(\alpha + \beta w)}{4\beta\lambda - \gamma^2}, \quad y^C(w) = \frac{2\beta sy_0 - \gamma(\alpha - \beta w)}{4\beta\lambda - \gamma^2}.$$

With these reactions of the retailer, the third-party collector optimizes his/her objective function (7.1.8) through determining the collection rate of used products $\tau_0$. As $\frac{\partial^2 \Pi_c^C}{\partial \tau_0^2} = -2\mu < 0$, the unique optimal solution of the collector is given by $\tau_0 = \frac{(B-A)\beta\{sy_0\gamma + 2\lambda(\alpha-\beta w)\} - 2\mu\tau_1\{2s\beta + \gamma(\alpha-\beta w)\}}{2\mu(4\beta\lambda-\gamma^2)}$.

Finally, the manufacturer optimizes his objective function (7.1.6) by deciding the wholesale price $w$. The optimal solution can be obtained by solving the first order necessary condition for optimality of the manufacturer's objective function (7.1.6). The optimal profit of the manufacturer, the retailer, and the collector are obtained by substituting corresponding optimal decisions in Eqs. (7.1.6), (7.1.7), and (7.1.8), and the total profit $\Pi_w^C$ of the whole supply chain can be obtained by summing the channel members' optimal profits. Optimal results of the manufacturer, the retailer, and the third-party collector are summarized in Table 7.1.1.

**Proof.** *The retailer's reaction*

The Hessian matrix associated with $\Pi_r^C$ is given by

$$H_R^C = \begin{pmatrix} -2\beta & \gamma \\ \gamma & -2\lambda \end{pmatrix}$$

Now, the principal minors are: $|M_1| = -2\beta < 0$, and $|H_R^C| = 4\beta\lambda - \gamma^2 < 0$, if $\lambda > \frac{\gamma^2}{4\beta}$. Thus, the Hessian matrix $H_R^C$ is negative definite under this condition.

*The collector's reaction*

As $\frac{\partial^2 \Pi_c^C}{\partial \tau_0^2} = -2\mu < 0$, $\Pi_c^C$ is negative definite and unique optimal solution can be obtained by solving the first order optimality condition of $\Pi_c^C$.

*The manufacturer's reaction*

As $\frac{\partial^2 \Pi_m^C}{\partial w^2} = -\frac{4\beta^2\lambda X_3}{\mu(4\beta\lambda-\gamma^2)^2} < 0$, $\Pi_m^C$ is negative definite and unique optimal solution can be obtained by solving the first order optimality condition of $\Pi_m^C$. ■

#### 7.1.1.5 Social welfare

In this subsection, we will determine the social welfare 'SW' which is composed of total profit $\Pi_w$ of the whole supply chain, consumer surplus 'CS' and environmental damage 'ED', for the proposed policies. Consumer surplus is the deference between the maximum price ($p_{max}$) what customers are willing to pay for a product and the price what they actually pay for that product *i.e.* market price ($p_{mar}$). So, consumer surplus is

$$\int_{p_{mar}}^{p_{max}} D dp = \int_{(\alpha+\gamma y - D)/\beta}^{(\alpha+\gamma y)/\beta} (\alpha - \beta p + \gamma y) dp = \frac{D^2}{2\beta}$$

The environmental damage is defined as the damage cost $\epsilon$ multiplied by total amount of uncollected used products $(1-\tau)D$ (Wang et al., 2015). The optimal values of consumer surplus and environmental damage for the integrated policy are given below and those for the three proposed decentralized models are given in Table 7.1.1.

$$CS^I = \frac{\beta\mu^2[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2}{2X^2},$$

$$ED^I = \frac{\epsilon\beta\mu[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]\{2X - Z_1\beta[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]\}}{2X^2}.$$

Hence, social welfare will be calculated as $SW^* = \Pi_w^* + CS^* - ED^*$.

### 7.1.2 Comparative analysis

In this section, we compare optimal results of the proposed models to get some insights. Moreover, to investigate the influence of government subsidy, we compare the results of the proposed models with those of the models without government

**Table 7.1.1:** Optimal results of the proposed models.

| | Model M | Model R | Model C |
|---|---|---|---|
| $w^*$ | $\frac{sy_0\gamma X_1 + 4(\alpha + c_m\beta)\mu\lambda(4\beta\lambda - \gamma^2) - Z_1^2\beta^2\lambda(4\alpha\lambda + sy_0\gamma)}{4\beta\lambda X_1}$ | $\frac{(sy_0\gamma + 2(\alpha + c_m\beta)\lambda)(X_2 - \beta^2\lambda(B-A)Z_2) + 4Z_2\beta^3\lambda^2 c_m(B-A)}{4\beta\lambda X_2}$ | $\frac{2X_3(sy_0\gamma + (\alpha + c_m\beta)\lambda) + sy_0\gamma(\gamma^2\mu - 4\beta\mu\lambda) - 2Z_2\beta^2\lambda^2(\alpha - c_m\beta)(B-A)}{4\beta\lambda X_3}$ |
| $p^*$ | $\frac{sy_0\gamma X_1 + 4(\alpha + c_m\beta)\mu\lambda(2\beta\lambda - \gamma^2) + (4\mu - Z_1^2\beta)\beta\lambda(4\alpha\lambda + sy_0\gamma)}{4\beta\lambda X_1}$ | $\frac{(sy_0\gamma + 2(\alpha - c_m\beta)\lambda)(\gamma^2\mu - 2\beta\mu\lambda) + 2X_2(sy_0\gamma + 2\alpha\lambda)}{4\beta\lambda X_2}$ | $\frac{2X_3(sy_0\gamma + (\alpha + c_m\beta)\lambda) + sy_0\gamma(\gamma^2\mu - 2\beta\mu\lambda) + \lambda(\alpha - c_m\beta)(X_3 + \gamma^2\mu - \beta^2\lambda Z_2(B-A))}{4\beta\lambda X_3}$ |
| $y^*$ | $\frac{2(\alpha - c_m\beta)\gamma\mu\lambda + s(\gamma^2\mu + X_1)}{2\lambda X_1}$ | $\frac{2(\alpha - c_m\beta)\gamma\mu\lambda + s(\gamma^2\mu + 2X_2)}{4\lambda X_2}$ | $\frac{2(\alpha - c_m\beta)\gamma\mu\lambda + s(\gamma^2\mu + 2X_3)}{4\lambda X_3}$ |
| $\tau^*$ | $\frac{Z_1\beta[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]}{2X_1}$ | $\frac{(B-A)\beta[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]}{4X_2}$ | $\frac{(B-A)\beta[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]}{4X_3}$ |
| $\Pi_m^*$ | $\frac{\mu[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2}{4\lambda X_1}$ | $\frac{\mu[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2}{8\lambda X_2}$ | $\frac{\mu[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2}{8\lambda X_3}$ |
| $\Pi_r^*$ | $\frac{(4\beta\lambda - \gamma^2)\mu^2[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2 + X_1^2 sy_0^2(s - 4\lambda)}{4\lambda X_1^2}$ | $\frac{\mu(X_2 + \beta^2\lambda Z_2(B-A))[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2 + 4X_2^2 sy_0^2(s - 4\lambda)}{16\lambda X_2^2}$ | $\frac{\mu^2(4\beta\lambda - \gamma^2)[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2 + 4X_3^2 sy_0^2(s - 4\lambda)}{16\lambda X_3^2}$ |
| $\Pi_c^*$ | N/A | N/A | $\frac{(B-A)^2\beta^2\mu[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2}{16X_3^2}$ |
| $CS^*$ | $\frac{\beta\mu^2[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2}{2X_1^2}$ | $\frac{\beta\mu^2[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2}{8X_2^2}$ | $\frac{\beta\mu^2[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2}{8X_3^2}$ |
| $ED^*$ | $\frac{\epsilon\beta\mu[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]\{2X_1 - Z_1\beta[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]\}}{2X_1^2}$ | $\frac{\epsilon\beta\mu[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]\{4X_2 - (B-A)\beta[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]\}}{8X_2^2}$ | $\frac{\epsilon\beta\mu[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]\{4X_3 - (B-A)\beta[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]\}}{8X_3^2}$ |

Note: $X_1 = 2\mu(4\beta\lambda - \gamma^2) - Z_1^2\beta^2\lambda;\ X_2 = \mu(4\beta\lambda - \gamma^2) - (B-A)Z_1\beta^2\lambda;\ X_3 = \mu(4\beta\lambda - \gamma^2) - (B-A)Z_2\beta^2\lambda.$

subsidy. Comparing the optimal values of the different models, we get the following proposition.

**Proposition 7.1.1.** *(i) The optimal collection rate of used products follows the sequence $\tau^I > \tau^M \geq \tau^R > \tau^C$, if $B \leq \frac{\Delta+A}{2}$, (ii) the optimal wholesale price follows the sequence $w^C > w^R > w^M$, (iii) the optimal selling price follows the sequence $p^C > p^R \geq p^M > p^I$, if $B \leq \frac{\Delta+A}{2}$, (iv) the optimal CSR follows the sequence $y^I > y^M \geq y^R > y^C$, if $B \leq \frac{\Delta+A}{2}$.*

**Proof.** (i) For collection rate of used products

$\tau^I - \tau^M = \frac{Z_1\beta\mu(4\beta\lambda-\gamma^2)[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{2XX_1} > 0;$

$\tau^M - \tau^R = \frac{\beta\mu(2Z_2-Z_1)(4\beta\lambda-\gamma^2)[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{4X_1X_2} > 0$, if $B < \frac{\Delta+A}{2}$;

$\tau^R - \tau^C = \frac{(B-A)^3\beta^3\lambda[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{4X_2X_3} > 0.$

(ii) For wholesale price

$w^C - w^R = \frac{(B-A)^3Z_2\beta^3\lambda[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{4X_2X_3} > 0,$

$w^R - w^M = \frac{\beta[sy_0\gamma+2\lambda(\alpha-c_m\beta)][\mu(4\beta\lambda-\gamma^2)\left((Z_1-Z_2)^2+Z_2^2\right)-Z_1^2\beta^2\lambda(B-A)^2]}{4X_1X_2} > 0$, $\mu$ being sufficiently large.

(iii) For selling price

$p^C - p^R = \frac{(B-A)^2\beta\mu(2\beta\lambda-\gamma^2)[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{4X_2X_3} > 0;$

$p^R - p^M = \frac{\beta\mu Z_1(2Z_2-Z_1)(2\beta\lambda-\gamma^2)[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{4X_1X_2} > 0$, if $B < \frac{\Delta+A}{2}$;

$p^M - p^I = \frac{\mu^2(4\beta\lambda-\gamma^2)(2\beta\lambda-\gamma^2)[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{2\beta\lambda XX_1} > 0.$

(iv) For CSR

$y^I - y^M = \frac{\gamma\mu^2(4\beta\lambda-\gamma^2)[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{2\beta\lambda XX_1} > 0;$

$y^M - y^R = \frac{\beta^2\gamma\mu Z_1(2Z_2-Z_1)(2\beta\lambda-\gamma^2)[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{4X_1X_2} > 0$, if $B < \frac{\Delta+A}{2}$;

$y^R - y^C = \frac{(B-A)^2\beta^2\gamma\mu[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{4X_2X_3} > 0.$ ■

It can be observed from Proposition 7.1.1 that the collection rate of used products is higher in Model I. This is because of the joint-decision making in Model I. While comparing the collection rate of used products among three decentralized models, we note that it is lower in Model C. The marginal benefit of the collector from collecting used products in Model C being lower than that of the manufacture in Model M (*i.e.* $(B-A) < (\Delta - A)$), the collector in Model C tends to invest less money in collecting used products. Although, the marginal benefit of the retailer in Model R and that of the collector in Model C is same (*i.e.* equal to $(B - A)$), the wholesale price can indirectly influence the collection rate of used products in Model R. Therefore, the collection rate of used products is always lower in Model C. The positioning of the collection rate of used products in Model M and Model R depends on the transfer price that the manufacturer pays to the retailer for collecting used products. If the manufacturer pays less amount of transfer price, then the retailer shows less interest in collecting used products. The opposite situation holds if the manufacturer agrees to pay higher amount of transfer price. From the comparison of optimal wholesale price, we obtain that the manufacturer wants higher wholesale price from the retailer when the third-party collector collects used products and the lowest wholesale price when the manufacturer himself collects used products. This is because in Model M, the manufacturer need not bear any transfer price and he may try to influence the market demand by lowering the wholesale price. Although, the manufacturer has to pay transfer price in both Model R and Model C, the lower collection rate of used products in Model C produces less profit which forces him to set higher wholesale price in Model C. As the wholesale price in Model C is higher among the three decentralized models, the retailer also charges higher selling price when the collector collects the used products. The transfer price in Model R also helps the retailer in deciding appropriate selling price. If the manufacturer pays less transfer price, in order to maintain profitability, the retailer sets higher selling price. While comparing with integrated model, one can observe that the selling price in the integrated model is lower than the decentralized models. This is because, the decentralized models suffer from double-marginalization effect. As the selling price in Model C is higher, the market demand and consequently the profit of the retailer decrease. So, she cannot invest more in CSR. Therefore, CSR will be lower in Model C. The integrated model being fully coordinated gives higher CSR effort.

**Proposition 7.1.2.** *If $B \leq \frac{\Delta+A}{2}$, the optimal profit of the manufacturer follows the sequence $\Pi_m^M \geq \Pi_m^R > \Pi_m^C$.*

**Proof.** $\Pi_m^M - \Pi_m^R = \frac{\beta^2\mu\lambda Z_1(2Z_2-Z_1)[sy_0\gamma+2\lambda(\alpha-c_m\beta)]^2}{8\lambda X_1X_2} > 0$, if $B < \frac{\Delta+A}{2}$;
$\Pi_m^R - \Pi_m^C = \frac{(B-A)^2\beta^2\mu[sy_0\gamma+2\lambda(\alpha-c_m\beta)]^2}{8X_2X_3} > 0.$ ■

In one hand, a higher selling price and a lower CSR effort diminish market demand; on the other hand, a lower collection rate of used products collects less amount of used products. Lower market demand and less amount of used products decrease the profit of the manufacturer in Model C, which is presented in Proposition 7.1.2. So, the manufacturer never contracts with the third-party collector for collecting used products. Whether the profit of the manufacturer will be higher in Model M or Model R depends on the amount of transfer price. A less amount of transfer price helps the manufacturer in enhancing his profitability. Therefore, Model M seems to provide a better strategy for the manufacturer if he has to pay less amount of transfer price; otherwise Model R will be favourable for the manufacturer. Due to algebraic complexity, profits of the retailer in different decentralized models will be compared numerically.

**Proposition 7.1.3.** *If $B \leq \frac{\Delta+A}{2}$, the optimal consumer surplus of the proposed models follows the sequence $CS^I > CS^M \geq CS^R > CS^C$.*

**Proof.** $CS^I - CS^M = \frac{\beta\mu^3(4\beta\lambda-\gamma^2)[sy_0\gamma+2\lambda(\alpha-c_m\beta)]^2(X+X_1)}{2X^2X_1^2} > 0$,
$CS^M - CS^R = \frac{\beta^3\mu^2\lambda Z_1(2Z_2-Z_1)(2X_2+X_1)[sy_0\gamma+2\lambda(\alpha-c_m\beta)]^2}{8X_1^2X_2^2} > 0$, if $B < \frac{\Delta+A}{2}$;
$CS^R - CS^C = \frac{(B-A)^2\beta^3\mu^2\lambda[sy_0\gamma+2\lambda(\alpha-c_m\beta)]^2}{8X_2^2X_3^2} > 0$. ■

Proposition 7.1.3 suggests that the consumer surplus in the integrated model is higher than those of the decentralized models. This is because, due to lower selling price and higher CSR effort in the integrated model, the market demand increases, which increases the consumer surplus. Among the decentralized models, the market demand in Model C is lower which in turn decreases the consumer surplus while due to lower selling price and higher CSR effort (for lower transfer price), the market demand in Model M is higher resulting an increase in the consumer surplus.

In the following Propositions, we compare the optimal results of the proposed models with those of the models without government subsidy. Here our aim is to investigate the influence of government intervention on the optimal decisions of the channel members. To distinguish the results from those of the proposed models, we use the subscript 'S0'. The optimal solutions for the models without government intervention are presented in Table 7.1.2.

**Proposition 7.1.4.** *(i) The optimal wholesale prices with and without government subsidy follow the sequence $w^M > w^M_{S0}; w^R > w^R_{S0}; w^C > w^C_{S0}$, (ii) the optimal selling prices with and without government subsidy follow the sequence $p^I > p^I_{S0}; p^M > p^M_{S0}; p^R > p^R_{S0}; p^C > p^C_{S0}$, (iii) the optimal CSRs with and without government subsidy follow the sequence $y^I >$*

**Table 7.1.2:** Optimal results of the proposed models without government subsidy ($S = 0$).

| | Model I | Model M | Model R | Model C |
|---|---|---|---|---|
| $w^*$ | N/A | $\frac{(\alpha+c_m\beta)\mu(4\beta\lambda-\gamma^2)-Z_1^2\beta^2\alpha\lambda}{\beta X_1}$ | $\frac{(\alpha+c_m\beta)[X_2-\beta^2\lambda(B-A)Z_2]+2Z_2\beta^3\lambda c_m(B-A)}{2\beta X_2}$ | $\frac{(\alpha+c_m\beta)X_3-Z_2\beta^2\lambda(\alpha-c_m\beta)(B-A)}{2\beta X_3}$ |
| $p^*$ | $\frac{2\mu\lambda(\alpha+c_m\beta)-c_m\gamma^2\mu-Z_1^2\alpha\beta\lambda}{X}$ | $\frac{(\alpha+c_m\beta)\mu(2\beta\lambda-\gamma^2)+(4\mu-Z_1^2\beta)\alpha\beta\lambda}{\beta X_1}$ | $\frac{(\alpha-c_m\beta)(\gamma^2\mu-2\beta\mu\lambda)+2X_2\alpha\lambda}{2\beta X_2}$ | $\frac{(\alpha+c_m\beta)X_3+(\alpha-c_m\beta)[X_3+\gamma^2\mu-\beta^2\lambda Z_2(B-A)]}{2\beta X_3}$ |
| $y^*$ | $\frac{(\alpha-c_m\beta)\gamma\mu}{X}$ | $\frac{(\alpha-c_m\beta)\gamma\mu}{X_1}$ | $\frac{(\alpha-c_m\beta)\gamma\mu}{2X_2}$ | $\frac{(\alpha-c_m\beta)\gamma\mu}{2X_3}$ |
| $\tau^*$ | $\frac{Z_1\beta\lambda(\alpha-c_m\beta)}{X}$ | $\frac{Z_1\beta\lambda(\alpha-c_m\beta)}{X_1}$ | $\frac{\beta\lambda(B-A)(\alpha-c_m\beta)}{2X_2}$ | $\frac{\beta\lambda(B-A)(\alpha-c_m\beta)}{2X_3}$ |
| $\Pi_m^*$ | N/A | $\frac{\mu\lambda(\alpha-c_m\beta)^2}{X_1}$ | $\frac{\mu\lambda(\alpha-c_m\beta)^2}{2X_2}$ | $\frac{\mu\lambda(\alpha-c_m\beta)^2}{2X_3}$ |
| $\Pi_r^*$ | N/A | $\frac{(4\beta\lambda-\gamma^2)\lambda\mu^2(\alpha-c_m\beta)^2}{X_1^2}$ | $\frac{\mu\lambda(X_2+\beta^2\lambda Z_2(B-A))(\alpha-c_m\beta)^2}{4X_2^2}$ | $\frac{\mu^2\lambda(4\beta\lambda-\gamma^2)(\alpha-c_m\beta)^2}{4X_3^2}$ |
| $\Pi_c^*$ | N/A | N/A | N/A | $\frac{(B-A)^2\beta^2\mu\lambda(\alpha-c_m\beta)^2}{4X_3^2}$ |
| $CS^*$ | $\frac{2\beta\mu^2\lambda^2(\alpha-c_m\beta)^2}{X^2}$ | $\frac{2\beta\mu^2\lambda^2(\alpha-c_m\beta)^2}{X_1^2}$ | $\frac{\beta\mu^2\lambda^2(\alpha-c_m\beta)^2}{2X_2^2}$ | $\frac{\beta\mu^2\lambda^2(\alpha-c_m\beta)^2}{2X_3^2}$ |
| $ED^*$ | $\frac{2\epsilon\beta\mu\lambda(\alpha-c_m\beta)[X-Z_1\beta\lambda(\alpha-c_m\beta)]}{X^2}$ | $\frac{\epsilon\beta\mu\lambda(\alpha-c_m\beta)[X_1-Z_1\beta\lambda(\alpha-c_m\beta)]}{X_1^2}$ | $\frac{\epsilon\beta\mu\lambda(\alpha-c_m\beta)[2X_2-(B-A)\beta\lambda(\alpha-c_m\beta)]}{2X_2^2}$ | $\frac{\epsilon\beta\mu\lambda(\alpha-c_m\beta)[2X_3-(B-A)\beta\lambda(\alpha-c_m\beta)]}{2X_3^2}$ |

*$y^I_{S0}; y^M > y^M_{S0}; y^R > y^R_{S0}; y^C > y^C_{S0}$, (iv) the optimal collection rates of used products with and without government subsidy follow the sequence $\tau^I > \tau^I_{S0}; \tau^M > \tau^M_{S0}; \tau^R > \tau^R_{S0}; \tau^C > \tau^C_{S0}$.*

**Proof.** (i) For the wholesale price

$w^M - w^M_{S0} = \frac{sy_0\gamma[\mu(4\beta\lambda-\gamma^2)-Z_1^2\beta^2\lambda]}{2\beta\lambda X_1} > 0;\ w^C - w^C_{S0} = \frac{sy_0\gamma[\mu(4\beta\lambda-\gamma^2)-2\beta^2\lambda(B-A)Z_2]}{4\beta\lambda X_3} > 0,$

$w^R - w^R_{S0} = \frac{sy_0\gamma[\mu(4\beta\lambda-\gamma^2)-\beta^2\lambda(B-A)(Z_1+Z_2)]}{4\beta\lambda X_2} > 0.$

(ii) For the selling price

$p^I - p^I_{S0} = \frac{sy_0\gamma(2\mu-Z_1^2\beta)}{2[\mu(4\beta\lambda-\gamma^2)-Z_1^2\beta^2\lambda]} > 0;\ \ p^M - p^M_{S0} = \frac{sy_0\gamma[\mu(6\beta\lambda-\gamma^2)-Z_1^2\beta^2\lambda]}{2\beta\lambda X_1} > 0,$

$p^R - p^R_{S0} = \frac{sy_0\gamma[\mu(6\beta\lambda-\gamma^2)-2\beta^2\lambda(B-A)Z_1]}{4\beta\lambda X_2} > 0;$

$p^C - p^C_{S0} = \frac{sy_0\gamma[\mu(6\beta\lambda-\gamma^2)-2\beta^2\lambda(B-A)Z_2]}{4\beta\lambda X_3} > 0.$

(iii) For CSR

$y^I - y^I_{S0} = \frac{sy_0\beta(4\mu-Z_1^2\beta)}{2[\mu(4\beta\lambda-\gamma^2)-Z_1^2\beta^2\lambda]} > 0;\ \ y^M - y^M_{S0} = \frac{sy_0[\mu(8\beta\lambda-\gamma^2)-Z_1^2\beta^2\lambda]}{2\lambda X_1} > 0,$

$y^R - y^R_{S0} = \frac{sy_0[\mu(8\beta\lambda-\gamma^2)-2\beta^2\lambda(B-A)Z_1]}{4\lambda X_2} > 0; y^C - y^C_{S0} = \frac{sy_0[\mu(8\beta\lambda-\gamma^2)-2\beta^2\lambda(B-A)Z_2]}{4\lambda X_3} > 0.$

(iv) For the collection rate of used products

$\tau^I - \tau^I_{S0} = \frac{sy_0\gamma\beta Z_1}{2[\mu(4\beta\lambda-\gamma^2)-Z_1^2\beta^2\lambda]} > 0;\ \ \tau^M - \tau^M_{S0} = \frac{sy_0\gamma\beta Z_1}{2\lambda X_1} > 0,$

$\tau^R - \tau^R_{S0} = \frac{sy_0\gamma\beta(B-A)}{4\lambda X_2} > 0;\ \ \tau^C - \tau^C_{S0} = \frac{sy_0\gamma\beta(B-A)}{4\lambda X_3} > 0.$ ■

It is clear from Proposition 7.1.4 that the proposed models with government subsidy provide the best possible outcomes than those without government intervention. This is because, the government subsidy is proportional to the CSR effort of the retailer. The more the CSR effort, the more the subsidy will be. Again, the market demand is positively dependent on the CSR effort. So, in order to get more subsidy from the government and more profit from the increased market demand, the retailer increases the CSR effort. Due to higher CSR effort, the retailer demands higher selling price of the product. The manufacturer also demands higher wholesale price from the retailer. Due to the increased market demand and higher CSR effort, the collection rate of used products also increases.

**Proposition 7.1.5.** *(i) The optimal profits of the manufacturer with and without government subsidy follow the sequence $\Pi^M_m > \Pi^M_{mS0}; \Pi^R_m > \Pi^R_{mS0}; \Pi^C_m > \Pi^C_{mS0}$, (ii) the optimal profits of the retailer with and without government subsidy follow the sequence $\Pi^M_r > \Pi^M_{rS0}; \Pi^R_r >$*

$\Pi_{rS0}^{R}; \Pi_{r}^{C} > \Pi_{rS0}^{C}$.

**Proof.** (i) For profit of the manufacturer

$\Pi_m^M - \Pi_{mS0}^M = \frac{sy_0\gamma\mu[sy_0\gamma+4\lambda(\alpha-c_m\beta)]}{4\lambda X_1} > 0$; $\Pi_m^R - \Pi_{mS0}^R = \frac{sy_0\gamma\mu[sy_0\gamma+4\lambda(\alpha-c_m\beta)]}{8\lambda X_2} > 0$,

$\Pi_m^C - \Pi_{mS0}^C = \frac{sy_0\gamma\mu[sy_0\gamma+4\lambda(\alpha-c_m\beta)]}{8\lambda X_3} > 0$.

The proof for the retailer's profit being similar, we have omitted those proofs. ■

From Proposition 7.1.4 one can notice that government subsidy helps to increase the market demand as well as return quantity of used products. From this increased market demand, both the manufacturer and the retailer can earn higher profit. Proposition 7.1.5 shows that both the manufacturer and the retailer get higher profit when the government provides subsidy to the retailer for CSR effort. The results of Propositions 7.1.4 and 7.1.5 reveal that in order to increase CSR, the government should encourage the channel members by providing subsidy. In the following Proposition, we present the effect of government subsidy on consumer surplus.

**Proposition 7.1.6.** *The optimal consumer surpluses of the proposed models with and without government subsidy follow the sequence* $CS^I > CS_{S0}^I; CS^M > CS_{S0}^M; CS^R > CS_{S0}^R; CS^C > CS_{S0}^C$.

**Proof.** $CS^I - CS_{S0}^I = \frac{\beta\mu^2 sy_0\gamma[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{2X^2} > 0$,

$CS^M - CS_{S0}^M = \frac{\beta\mu^2 sy_0\gamma[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{2X_1^2} > 0$,

$CS^R - CS_{S0}^R = \frac{\beta\mu^2 sy_0\gamma[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{8X_2^2} > 0$,

$CS^C - CS_{S0}^C = \frac{\beta\mu^2 sy_0\gamma[sy_0\gamma+2\lambda(\alpha-c_m\beta)]}{8X_3^2} > 0$. ■

From the aforementioned propositions, we come to the conclusion that if the manufacturer denies to pay higher transfer price, Model M among the three decentralized policies gives the best possible outcome under government subsidy. Although Model M gives better result, due to double-marginalization effect it fails to compete with the integrated model. So, channel coordination is necessary to reduce double-marginalization effect and achieve better performance. In the next section, we present a TPT contract for channel coordination.

#### 7.1.2.1 Supply chain coordination

In this section, we consider a TPT contract which is signed by the upstream member (manufacturer) and the downstream member (retailer) in order to modify profits of both the channel members. Under this contract, the manufacturer guarantees to sell the product to the retailer in a comparatively lower wholesale price $w^{CO}$ than that of the decentralized model, and in turn, charges a lump sum fee $F$ from the retailer. As the manufacturer is the leader of the supply chain and a lower transfer price gives better result in Model M, here we consider the TPT contract for Model M only. Results for other two models can be obtained in a similar way.

Under the proposed contract, the profit functions of the manufacturer and the retailer are given by

$$\max_{(w^{CO},\tau)} \Pi_m^{CO} = (w^{CO} - c_m)D + (\Delta - A)D_r - \mu\tau^2 + F, \text{ and} \tag{7.1.9}$$

$$\max_{(p,y)} \Pi_r^{CO} = (p - w^{CO})D - \lambda y^2 + S(y) - F \tag{7.1.10}$$

Similar to the previous decentralized models, here also the retailer first optimizes her best responses through determining the selling price $p$ and CSR $y$, and then the manufacturer optimizes the wholesale price and charges lump sum fee $F$. For given decisions of the manufacturer, the retailer's optimal decisions can be obtained as

$$p^{CO} = \frac{\gamma(sy_0 - \gamma w^{CO}) + 2\lambda(\alpha + \beta w^{CO})}{4\beta\lambda - \gamma^2}, \; y^{CO} = \frac{\gamma(\alpha - \beta w^{CO}) + 2\beta s y_0}{4\beta\lambda - \gamma^2}.$$

For channel coordination, these values of selling price and CSR will be equal to those of the integrated policy. So, equating $p^{CO}$ and $p^I$, and $y^{CO}$ and $y^I$ we get

$$w^{CO} = \frac{2c_m\mu(4\beta\lambda - \gamma^2) - Z_1^2\beta(sy_0\gamma + 2\alpha\lambda)}{2X}$$

Putting this value of $w^{CO}$ in Eq. (7.1.9), and using the first order necessary condition for optimality of $\Pi_m^{CO}$ with respect to $\tau_0$, we get $\tau_0^{CO} = \tau_0^I$ and consequently, $\tau^{CO} = \tau^I$. After coordination, the profits of the manufacturer and the retailer will be

$$\Pi_m^{CO} = F - \frac{Z_1^2\beta^2\mu[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2}{4X^2}, \text{ and}$$

$$\Pi_r^{CO} = \frac{\mu^2(4\beta\lambda - \gamma^2)[sy_0\gamma + 2\lambda(\alpha - c_m\beta)]^2 + X^2 s(s - 4\lambda y_0)}{4\lambda X^2} - F$$

Now, one can note that $\Pi_m^{CO} + \Pi_r^{CO} = \Pi^I$, *i.e.* sum of individual profits after contract is equal to the profit of the integrated model. Therefore, the proposed TPT contract can coordinate the supply chain. Hence, we have the following proposition.

We use the superscript 'CO' to indicate two-part tariff contract

**Proposition 7.1.7.** *If the manufacturer sets the wholesale price $w^{CO}$, then the proposed TPT contract can coordinate the supply chain.*

As the proposed contract coordinates the supply chain, it will undergo some surplus profit which is the difference between the profit of the integrated model and the decentralized model. The channel members can divide this surplus profit according to their bargaining powers. In any contract, the channel members will accept the contract if their individual profits after contract are higher than or equal to those before contract *i.e.* if $\Pi_m^{CO} \geq \Pi_m^M$ and $\Pi_r^{CO} \geq \Pi_r^M$. From $\Pi_m^{CO} \geq \Pi_m^M$, we get $F \geq \frac{\mu^2(4\beta\lambda-\gamma^2)^2[sy_0\gamma+2\lambda(\alpha-c_m\beta)]^2}{4\lambda X_1 X^2} (= F_1)$. Again, from $\Pi_r^{CO} \geq \Pi_r^M$, we get $F \leq \frac{\mu^2(4\beta\lambda-\gamma^2)[sy_0\gamma+2\lambda(\alpha-c_m\beta)]^2(X_1^2-X^2)}{4\lambda X_1^2 X^2} (= F_2)$. Thus, for the win-win outcome of both the manufacturer and the retailer, we have the following proposition.

**Proposition 7.1.8.** *A "win-win" situation under the proposed two-part tariff contract is permissible for both the channel members when the lump sum fee F is such that $F \in [F_1, F_2]$.*

## 7.1.3 Numerical analysis

In this section, numerical analysis of the optimal decisions, the profitability of the channel members and the whole supply chain, consumer surplus, environmental damage, and social welfare are presented for the proposed models. A set of fictitious parameter-values which agree with the assumptions of our study are considered to demonstrate the proposed models. We take $\alpha = 100; \beta = 0.11; \gamma = 0.87; c_m = 80; c_r = 35; A = 20; B = 25; \lambda = 50; \mu = 700; \tau_1 = 0.007; y_0 = 1; s = 30; \epsilon = 10$; in appropriate units.

Table 7.1.3 represents the optimal results of the proposed models with and without government intervention. The integrated model gives better outcomes. A higher market demand in this model assists to increase consumer surplus, and a higher collection rate of used products helps to reduce environmental damage. As a result, integrated supply chain becomes more social-friendly. Among the three decentralized models, Model C gives the worst outcome and Model M provides better outcomes. The optimal collection rate of used products in Model M is at least five times as much as that in Model R and Model C. As a result, both the manufacturer and the retailer get higher profit. As the transfer price in the proposed example is less than a threshold value, the retailer charges higher selling price while providing lower CSR effort in Model R. A lower transfer price also diminishes the collection rate of used products. Consequently, profits of the manufacturer and the retailer in Model R are lower than those in Model M.

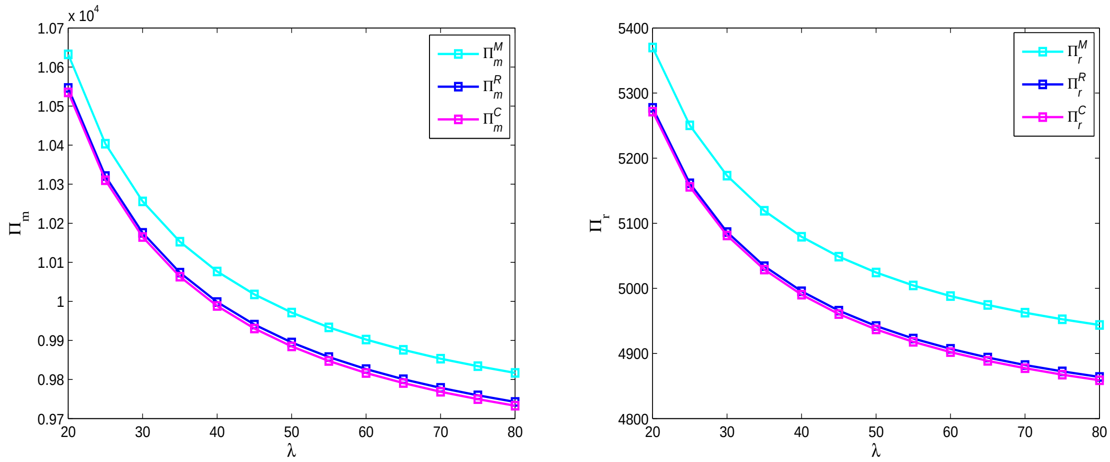
**Table 7.1.3:** Optimal results of the proposed models.

| Optimal | With subsidy | | | | | Without subsidy | | | |
|---|---|---|---|---|---|---|---|---|---|
| results | Model I | Model M | Model R | Model C | CO | Model I | Model M | Model R | Model C |
| $w$ | - | 490.378 | 494.032 | 494.033 | 58.3055 | - | 489.207 | 492.850 | 492.852 |
| $p$ | 500.084 | 708.423 | 709.979 | 710.185 | 500.084 | 498.885 | 706.629 | 708.182 | 708.387 |
| $y$ | 4.14347 | 2.19699 | 2.18244 | 2.18052 | 4.14347 | 3.83250 | 1.89157 | 1.87707 | 1.87515 |
| $\tau$ | 0.86778 | 0.42830 | 0.08500 | 0.08492 | 0.86778 | 0.86530 | 0.42708 | 0.08476 | 0.08467 |
| $\Pi_m$ | - | 9971.28 | 9894.83 | 9884.72 | 12562.1 | - | 9914.46 | 9838.44 | 9828.39 |
| $\Pi_r$ | - | 5024.35 | 4942.15 | 4937.05 | 7615.15 | - | 5021.07 | 4939.33 | 4934.27 |
| $\Pi_c$ | - | - | - | 5.04760 | - | - | - | - | 5.01883 |
| $\Pi$ | 20177.2 | 14995.6 | 14837.0 | 14826.8 | 20177.2 | 20087.6 | 14935.5 | 14777.8 | 14767.7 |

Although Model M delivers the best channel performance among the three decentralized models, it fails to compete with the integrated model. CSR effort and collection rate of used products in the integrated model are almost doubled than those of Model M. The integrated policy has 34.6% higher profit than Model M which shows the importance of channel coordination. Under the proposed TPT contract, the manufacturer sells the product to the retailer at a wholesale price of 58.3055 to coordinate the supply chain. The lump sum fee $F \in [10498.4, 15680.0]$ for the win-win situation of the manufacturer and the retailer. The surplus profit obtained through coordination is equal to 5181.6 which the manufacturer and the retailer can divide between them using their respective bargaining powers. Without loss of generality, we consider that this surplus profit is equally divided between the manufacturer and the retailer, and after coordination the profit of the manufacturer and the retailer are 12562.1 and 7615.15, respectively.

#### 7.1.3.1 Impact of CSR investment cost coefficient

Increasing CSR investment cost forces the retailer to reduce the CSR effort, which again reduces the market demand. To stimulate more customers, the retailer lowers the selling price. It results in degeneration in the profit of the retailer. Due to the lower selling price of the retailer, the manufacturer also charges lower wholesale price, which decreases the profit of the manufacturer. As the market demand decreases, consumer surplus also decreases. As a result, overall social welfare decreases. It is also clear from Fig. 7.1.2 that the profits of the channel members in Model M are higher than those of Model R and Model C. The profits of the channel members in Model R and Model C are nearly equal.




(a) $\lambda$ vs manufacturer's profit.

(b) $\lambda$ vs retailer's profit.

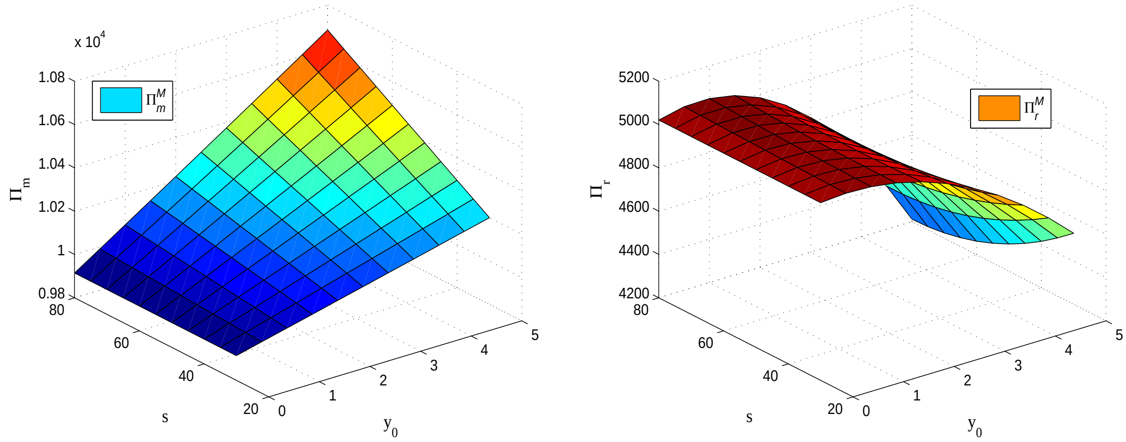
**Fig. 7.1.2:** Change (%) in optimal results w.r.t. $\lambda$.

### 7.1.3.2 Impact of adjustment factor

The adjustment factor has a positive impact on CSR effort and it helps the retailer to enhance CSR effort rapidly. A higher value of CSR effort helps the retailer to get more government subsidy. Due to higher CSR effort, customers are also willing to pay more for products. A higher CSR effort results in higher market demand, eventually the profit of the retailer increases. As the retailer sells the product with higher selling price, the manufacturer also charges higher wholesale price. The higher wholesale price and higher market demand increase the profit of the manufacturer. Both the consumer surplus and social welfare increase with the higher market demand. As Model M gives the best possible outcome, Fig. 7.1.3 represents the profit of the channel members for Model M only.

### 7.1.3.3 Impact of CSR level floor

As the CSR level floor increases, CSR effort also increases. Consequently, the market demand also increases. Due to higher CSR effort, the retailer sells the product with higher selling price. At the same time, the manufacturer also wants higher wholesale price. The higher wholesale price and higher market demand increase the profit of the manufacturer. The retailer's profit increases with the CSR level floor up to a




(a) manufacturer's profit vs $s$ and $y_0$. (b) retailer's profit vs $s$ and $y_0$.

**Fig. 7.1.3:** Change (%) in optimal results w.r.t. $s$ and $y_0$.

certain value. After that, although the CSR level floor increases, the retailer's profit decreases. The reason behind this result is the CSR investment cost. For higher CSR effort, the retailer has to invest more.

From the above discussion, we come to the conclusion that the government should offer higher subsidy to the retailer by setting higher CSR level floor and higher adjustment factor. The higher CSR level floor and higher adjustment factor encourage CSR effort. However, a higher CSR effort leads to higher investment cost for the retailer. The retailer will then think to transfer this extra cost to customers by increasing selling price. Due to the higher selling price, customers will try to find an alternative product, which decreases the profit of the retailer. Thus, the total social welfare also diminishes but it can help to create a competitive business environment.

# 7.2

# *Both manufacturer's and retailer's CSR investment under recycling competition*

Due to several importance of product remanufacturing, designing suitable reverse channels for collecting used products is a vital issue in any CLSC. There are a variety of options for collecting used products, which can be deployed by manufacturers. To ascertain the smooth progress of remanufacturing activities, many manufacturers use dual recycling channels (Zhao et al., 2017). For instance, Xerox collects used products directly by providing prepaid mailboxes. At the same time, the company contracts with its retailers for collecting used products (Hong et al., 2013). USA's largest cellphone remanufacturing company ReCellular Inc. uses retailers and third-party collectors (TPCs) for collecting used products (Liu et al., 2017a). There is also a situation where the manufacturer and the TPC take charge of used products collection. For instance, Kodak has to compete with the TPC to collect used products (Bulmus et al., 2014). Xiaomi Corporation collects used products through its own website; at the same time, it entrusts the collection activity to Aihuishou.com (Wang et al., 2020a). Generally, if manufacturers utilize dual channels to collect used products in a similar market then the channel competition unavoidably exists. Accordingly, it is a very important task for manufacturers to select appropriate reverse channels. The quality of products produced from used products being an important issue, nowadays, manufacturers eagerly want to advertise the quality levels of their products to ensure the consistent quality of remanufactured products and create an environment-friendly brand image. For instance, Samsung Electronics claims that its latest smartphone Galaxy S10 is made by using bio-plastic (for earphone jack, packing materials), renewed plastic (20% of charger case), and renewed paper (70% of unit box). So, the impact of recycling competition and

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product quality management on market demand needs to be properly investigated.

This investigation aims to merge three research streams, namely, product quality improvement, CSR investments, and used products recovery competition with the channel coordination problem in CLSC. We assume that the manufacturer invests in quality improvement and CSR, and the retailer contributes in CSR investment. Depending on different recovery competition among the manufacturer, the retailer, and the TPC, we develop three decentralized models and a centralized model. Finally, a joint revenue-and-cost sharing contract is proposed to resolve the channel coordination issue. This research is aimed to answer the following research queries:

- Among three decentralized models, which one is the best from the viewpoint of the manufacturer, the retailer, the TPC, and consumers?
- How do the competition and collection cost coefficients, quality improvement, CSR investments affect optimal decisions and profits of the channel members?
- Can the proposed contract perfectly coordinate the supply chain and provide better profit to channel individuals than decentralized models? Can it improve all three dimensions of sustainability?
- How to strike the right balance between product quality and selling price by optimizing entire channel profit and benefiting all channel members?

## 7.2.1 Problem description

In the present study, we consider a sustainable CLSC consisting of a manufacturer, a retailer and/or an independent TPC. The manufacturer focuses on improving product quality and investing in CSR while the retailer invests in CSR and acts as a means of communication between the manufacturer and customers to sell the product. The manufacturer produces new product from fresh raw materials at a manufacturing cost of $c_m$ per unit and remanufactures used products, which are collected by any two out of three members under competition, at a remanufacturing cost of $c_r$ per unit. During collection, each collector provides an acquisition price $A$ per unit to consumers. The retailer and the TPC transfer used products to the manufacturer in return for the transfer price of $B_r$ and $B_t$ per unit, respectively. The qualities of both new and remanufactured products are assumed to be equal, and both products are sold in the same market. The manufacturer sells the product to the retailer at wholesale price of $w$ per unit and the retailer sells it to consumers at

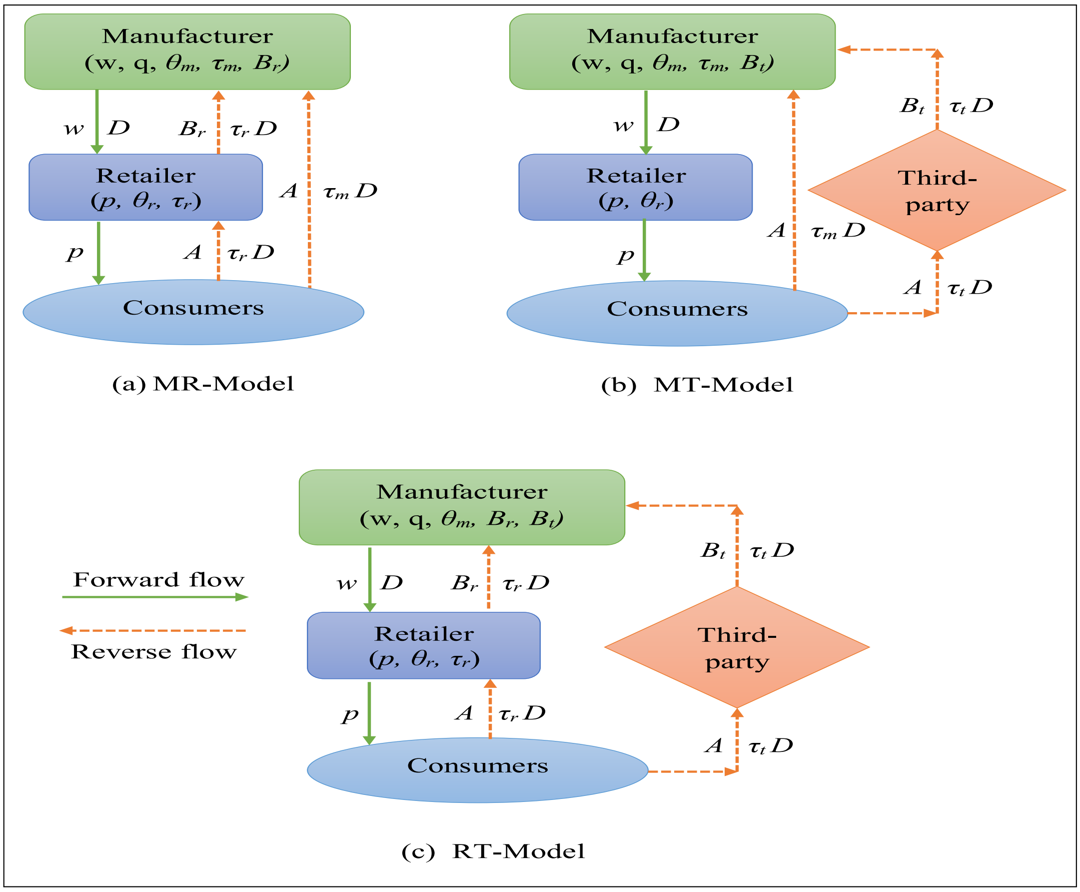



**Fig. 7.2.1:** Proposed closed-loop supply chain models.

a selling price of $p$ per unit. The manufacturer's and the retailer's investments in CSR are $\theta_m$ and $\theta_r$, respectively. Depending on various combinations of competing collectors, we first formulate three decentralized CLSC models viz. (1) MR-Model, where the manufacturer and the retailer competitively collect used products (see Fig. 7.2.1(a)), (2) MT-Model, where the manufacturer and the TPC competitively collect used products (see Fig. 7.2.1(b)), and (3) RT-Model, where the retailer and the TPC competitively collect used products (see Fig. 7.2.1(c)). After that, we develop the centralized model (C-Model) under manufacturer-retailer joint collection. In each decentralized model, the supply chain members aim to boost their own profits. The manufacturer acts as the Stackelberg leader and first decides his decisions. Then, the retailer and/or the TPC simultaneously decide their decisions. In the following, we present the required notations and assumptions for developing proposed models.

#### 7.2.1.1 Notations and assumptions

The following notations are used to establish the proposed models.

| | |
|---|---|
| **(a) Decision variables** | |
| $w_0$ | unit basic wholesale price of the manufacturer. |
| $w$ | unit wholesale price of the manufacturer. |
| $p_0$ | unit basic retail price of the retailer. |
| $p$ | unit retail price of the retailer. |
| $q$ | quality of the product, $0 < q < 1$. |
| $\theta_m$ | CSR investment of the manufacturer. |
| $\theta_r$ | CSR investment of the retailer. |
| $\tau_m$ | collection rate of used products for the manufacturer. |
| $\tau_r$ | collection rate of used products for the retailer. |
| $\tau_t$ | collection rate of used products for the TPC. |
| $B_r$ | unit transfer price paid to the retailer. |
| $B_t$ | unit transfer price paid to the TPC. |
| **(b) Parameters** | |
| $D$ | market demand. |
| $D_r$ | collection quantity. |
| $c_m$ | unit manufacturing cost of the new product. |
| $c_r$ | unit remanufacturing cost of used products. |
| $\Delta$ | unit cost saving from remanufacturing, where $\Delta = c_m - c_r$. |
| $D_0$ | basic market demand. |
| $\lambda$ | manufacturer's CSR investment-related cost coefficient. |
| $\eta$ | retailer's CSR investment-related cost coefficient. |
| $\xi$ | quality investment-related cost coefficient. |
| $\mu$ | collection cost coefficient. |
| $\epsilon$ | competition coefficient. |
| $\phi,\ x$ | fraction related to sharing. |
| $A$ | unit price paid to customers for used products. |
| $\Pi_i$ | profit function of the manufacturer, the retailer, the TPC and the whole supply chain, respectively ($i = m, r, t, w$). |
| $(.)^j$ | optimal decisions for $j$-model, where $j = MR, MT, RT, C, CO$. |

The following assumptions are made for building up the proposed models:

**(1)** Both the manufacturer and the retailer are responsible for CSR investment. For each unit of the product, the manufacturer's and the retailer's contributions in CSR are $\theta_m$ and $\theta_r$, respectively. The manufacturer and the retailer decide their selling prices based on their own CSR investments. The wholesale price is taken as $w = w_0 + b\theta_m$ and the retail price is taken as $p = p_0 + d\theta_r$, where

$b$ and $d$ $(> 0)$ are CSR investment related sensitivity factors to the wholesale price and the retail price, respectively.

**(2)** Besides investing in CSR, the manufacturer also focuses on the product quality improvement. The more the product quality, the more the market demand will be. Also, the market demand at the retailer's end is positively related to CSR investments and negatively related to the retail price. We consider the market demand as $D(p, \theta_m, \theta_r, q) = D_0 - \alpha p + \beta\theta_m + \gamma\theta_r + \delta q$, where $\alpha$, $\beta$, $\gamma$, and $\delta$ are respectively the price sensitivity factor, CSR sensitivity factors, and the quality sensitivity factor of the market demand. Here, $D_0$, $\alpha$, $\beta$, $\gamma$, $\delta > 0$ and $D_0 > \alpha c_m$. For the remainder of the study, $D(p, \theta_m, \theta_r, q)$ and $D$ will be interchangeable.

**(3)** Generally, it is not possible to collect all used products. So, the collection quantity is taken as a fraction of total demand *i.e.* $\tau_i D$, where $0 < \tau_i < 1$, $i = m, r, t$. It is assumed that the sum of collection rates of used products (say, $\tau$) lies in $(0, 1)$.

**(4)** In reality, the quality of all used products and remanufactured products may not be the same. In order to avoid complexity, we consider that quality of used products and remanufactured products are the same, remanufacturing costs for all used products are the same, and remanufacturing of used products is more profitable than producing new ones *i*.e. $c_r < c_m$ (Savaskan et al., 2004).

**(5)** The manufacturer has to bear some additional cost for quality improvement and CSR investment, the retailer has to bear some additional cost for CSR investment, and collectors have to invest in collecting used products, which are taken as $\xi q^2$, $\lambda\theta_m^2$, $\eta\theta_r^2$, and $\mu\tau_i^2$, $i = m, r, t$, respectively. Due to collection competition, the collection cost of one member is also affected by that of the competitor. So, the investment due to the collection of used products is taken as $\mu\frac{\tau_i^2 + \epsilon\tau_j^2}{1-\epsilon^2}$ *i.e.* for manufacturer-retailer joint collection, the investment cost of the manufacturer and the retailer will be $\mu\frac{\tau_m^2 + \epsilon\tau_r^2}{1-\epsilon^2}$ and $\mu\frac{\tau_r^2 + \epsilon\tau_m^2}{1-\epsilon^2}$, respectively. Similar situation holds for other strategies (Huang et al., 2013; Zhao et al., 2017).

**(6)** In order to ensure the profitability of all channel members, we consider $p > w > 0$, $\Delta \geq B_r \geq A > 0$, $\Delta \geq B_t \geq A > 0$.

### 7.2.2 Model formulation and analysis

Here, we formulate three decentralized models viz. MR-Model, MT-Model, and RT-Model by employing manufacturer-led Stackelberg game-theoretic approach, and a centralized model (C-Model). Then we compare optimal results of different models to determine the most efficient CLSC model. Finally, we propose a joint revenue-and-cost sharing contract (CO-Model) to address channel coordination issue.

#### 7.2.2.1 MR-Model

In this model, both the manufacturer and the retailer competitively collect used products from customers with collection rate $\tau_m$ and $\tau_r$, respectively. Here, the manufacturer first decides the basic wholesale price $w_0$, quality $q$, CSR investment $\theta_m$, collection rate of used products $\tau_m$, and transfer price $B_r$. After that, the retailer optimizes basic retail price $p_0$, CSR investment $\theta_r$, and collection rate of used products $\tau_r$. So, the profit functions of the manufacturer and the retailer will be:

$$\begin{aligned}\Pi_m^{MR}(w_0,\theta_m,q,\tau_m,B_r) &= (w-c_m-\theta_m)D+(\Delta-A)\tau_m D+(\Delta-B_r)\tau_r D \\ &\quad -\lambda\theta_m^2-\xi q^2-\frac{\mu(\tau_m^2+\epsilon\tau_r^2)}{1-\epsilon^2}, \end{aligned} \tag{7.2.1}$$

$$\Pi_r^{MR}(p_0,\theta_r,\tau_r) = (p-w-\theta_r)D+(B_r-A)\tau_r D-\eta\theta_r^2-\frac{\mu(\tau_r^2+\epsilon\tau_m^2)}{1-\epsilon^2} \tag{7.2.2}$$

Hence, MR-Model is presented as follows:

$$\begin{cases} \max\limits_{(w_0,\theta_m,q,\tau_m,B_r)} \Pi_m^{MR}(w_0,\theta_m,q,\tau_m,B_r,\tilde{p_0}(w_0,\theta_m,q,\tau_m,B_r),\tilde{\theta_r}(w_0,\theta_m,q,\tau_m,B_r),\tilde{\tau_r}(w_0,\theta_m,q,\tau_m,B_r)) \\ \text{subject to} \\ \tilde{p_0}(w_0,\theta_m,q,\tau_m,B_r),\tilde{\theta_r}(w_0,\theta_m,q,\tau_m,B_r) \text{ and } \tilde{\tau_r}(w_0,\theta_m,q,\tau_m,B_r) \text{ are obtained from solving} \\ \max\limits_{(p_0,\theta_r,\tau_r)} \Pi_r^{MR}(p_0,\theta_r,\tau_r) \end{cases}$$

During calculation we use backward induction method. So, we first calculate the retailer's best reactions by tackling the first order necessary conditions for optimality, and those reactions are given by

$$\begin{aligned}\tilde{p_0}(w_0,\theta_m,q,\tau_m,B_r) &= \frac{\begin{pmatrix} \mu[[2\eta+(\gamma-\alpha)(1-d)][D_0+\alpha w_0+(\beta-b\alpha)\theta_m+\delta q] \\ -w_0(\gamma-\alpha)(\gamma+\alpha-d\alpha)+\theta_m[4b\alpha\eta+(\gamma-\alpha)(d\alpha-b\gamma)]] \\ -\alpha\eta(D_0+\beta\theta_m+\delta q)(B_r-A)^2(1-\epsilon^2) \end{pmatrix}}{\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)}, \\ \tilde{\theta_r}(w_0,\theta_m,q,\tau_m,B_r) &= \frac{\mu(\gamma-\alpha)[D_0-\alpha w_0+(\beta-b\alpha)\theta_m+\delta q]}{\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)},\end{aligned}$$

$$\begin{aligned}\tilde{\tau}_r(w_0,\theta_m,q,\tau_m,B_r) &= \frac{\alpha\eta(B_r-A)[D_0-\alpha w_0+(\beta-b\alpha)\theta_m+\delta q](1-\epsilon^2)}{\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)},\\ \text{where } \Xi_1 &= 4\alpha\eta-(\gamma-\alpha)^2.\end{aligned}$$

After getting these reactions from the retailer, the manufacturer optimizes his decisions which can be obtained by tackling the first order necessary conditions of optimality. The optimal reactions of the manufacturer and the retailer are given in the following proposition:

**Proposition 7.2.1.** *If* $\mu > \frac{\alpha^2\lambda\eta\xi(\Delta-A)^2(3-\epsilon)(1-\epsilon^2)}{\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta}$ *holds, then the manufacturer's optimal wholesale price, product quality, CSR investment, collection rate of used products and transfer price, and the retailer's optimal retail price, CSR investment and collection rate of used products for MR-Model are given respectively by*

$$\begin{aligned}
w^{MR} &= \frac{\begin{pmatrix}(D_0+c_m\alpha)\xi\big[\mu\big(\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\alpha^2\lambda\eta(\Delta-A)^2(1-\epsilon^2)\big]\\ -D_0\eta\xi[\mu\beta(\beta-\alpha)+\alpha^2\lambda(\Delta-A)^2(1-\epsilon)(1-\epsilon^2)]-c_m\alpha\eta\mu[\xi\alpha(\beta-\alpha)+\delta^2\lambda]\end{pmatrix}}{\alpha\Big[\mu\big[\xi\big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\delta^2\lambda\eta\big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3-\epsilon)(1-\epsilon^2)\Big]},\\
q^{MR} &= \frac{\delta\lambda\eta\mu(D_0-c_m\alpha)}{\mu\big[\xi\big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\delta^2\lambda\eta\big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3-\epsilon)(1-\epsilon^2)},\\
\theta_m^{MR} &= \frac{\eta\mu\xi(\beta-\alpha)(D_0-c_m\alpha)}{\mu\big[\xi\big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\delta^2\lambda\eta\big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3-\epsilon)(1-\epsilon^2)},\\
\tau_m^{MR} &= \frac{\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(1-\epsilon^2)}{\mu\big[\xi\big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\delta^2\lambda\eta\big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3-\epsilon)(1-\epsilon^2)},\quad B_r^{MR}=\Delta,\\
p^{MR} &= \frac{\begin{pmatrix}D_0\xi\big[\mu\big(6\alpha\lambda\eta-\lambda(\gamma-\alpha)(\gamma-2\alpha)+\eta\alpha(\beta-\alpha)\big)-\alpha^2\lambda\eta(\Delta-A)^2(3-\epsilon)(1-\epsilon^2)\big]\\ +c_m\alpha\mu\big[\xi\big(2\alpha\lambda\eta-\lambda\gamma(\gamma-\alpha)-\eta\beta(\beta-\alpha)\big)-\delta^2\lambda\eta\big]\end{pmatrix}}{\alpha\Big[\mu\big[\xi\big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\delta^2\lambda\eta\big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3-\epsilon)(1-\epsilon^2)\Big]},\\
\theta_r^{MR} &= \frac{\lambda\mu\xi(\gamma-\alpha)(D_0-c_m\alpha)}{\mu\big[\xi\big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\delta^2\lambda\eta\big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3-\epsilon)(1-\epsilon^2)},\\
\tau_r^{MR} &= \frac{\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(1-\epsilon^2)}{\mu\big[\xi\big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\delta^2\lambda\eta\big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3-\epsilon)(1-\epsilon^2)}.
\end{aligned}$$

**Proof.** ***The retailer's reaction***
$\frac{\partial\Pi_r^{MR}}{\partial p_0} = D_0-2\alpha p_0+\alpha w_0+\delta q+(\beta+b\alpha)\theta_m+(\alpha+\gamma-2d\alpha)\theta_r-\alpha(B_r-A)\tau_r$; $\frac{\partial^2\Pi_r^{MR}}{\partial p_0^2}=-2\alpha<0$,
$\frac{\partial\Pi_r^{MR}}{\partial\theta_r} = -(1-d)[D_0-\alpha p_0+\delta q+\beta\theta_m+(\gamma-d\alpha)\theta_r]+(\gamma-d\alpha)[p_0-w_0-b\theta_m-(1-d)\theta_r+(B_r-A)\tau_r]-2\eta\theta_r$; $\frac{\partial^2\Pi_r^{MR}}{\partial\theta_r^2}=-2\eta-(\gamma-d\alpha)(1-d)<0$;
$\frac{\partial\Pi_r^{MR}}{\partial\tau_r}=(B_r-A)[D_0-\alpha p_0+\delta q+\beta\theta_m+(\gamma-d\alpha)\theta_r]-\frac{2\mu\tau_r}{1-\epsilon^2}$; $\frac{\partial^2\Pi_r^{MR}}{\partial\tau_r^2}=-\frac{2\mu}{1-\epsilon^2}<0$;
$\frac{\partial^2\Pi_r^{MR}}{\partial p_0\partial\theta_r}=\alpha(1-d)+\gamma$; $\frac{\partial^2\Pi_r^{MR}}{\partial p_0\partial\tau_r}=-\alpha(B_r-A)$; $\frac{\partial^2\Pi_r^{MR}}{\partial\theta_r\partial\tau_r}=(\gamma-d\alpha)(B_r-A)$.

The Hessian matrix associated with $\Pi_r^{MR}$ is given by

$$H_R^{MR} = \begin{pmatrix} -2\alpha & \alpha(1-d)+\gamma & -\alpha(B_r-A) \\ \alpha(1-d)+\gamma & -2\eta-(\gamma-d\alpha)(1-d) & (\gamma-d\alpha)(B_r-A) \\ -\alpha(B_r-A) & (\gamma-d\alpha)(B_r-A) & -\frac{2\mu}{1-\epsilon^2} \end{pmatrix}$$

The principal minors are: $|M_1| = -2\alpha < 0$, $|M_2| = \Xi_1 > 0$, if $\eta > \frac{(\gamma-\alpha)^2}{4\alpha}$ and $|H_R^{MR}| = -\frac{2\left[\mu\Xi_1-\alpha^2\eta(B_r-A)(1-\epsilon^2)\right]}{1-\epsilon^2} < 0$, if $\mu > \frac{\alpha^2\eta(B_r-A)(1-\epsilon^2)}{\Xi_1}$. Therefore, if $\mu > \frac{\alpha^2\eta(B_r-A)(1-\epsilon^2)}{\Xi_1}$ holds, then the Hessian matrix $H_R^{MR}$ is negative definite.

***The manufacturer's reaction***

With these reactions of the retailer, the profit function of the manufacturer becomes

$$\begin{aligned} \Pi_m^{MR} &= \frac{2\alpha\eta\mu[w_0-c_m-(1-b)\theta_m][D_0-\alpha w_0+(\beta-b\alpha)\theta_m+\delta q]}{\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)} \\ &+\frac{2\alpha\eta\mu(\Delta-A)\tau_m[D_0-\alpha w_0+(\beta-b\alpha)\theta_m+\delta q]}{\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)} \\ &+\frac{2\alpha^2\eta^2\mu(B_r-A)(\Delta-B_r)(1-\epsilon^2)[D_0-\alpha w_0+(\beta-b\alpha)\theta_m+\delta q]}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2}-\lambda\theta_m^2-\xi q^2 \\ &-\frac{\mu\epsilon\alpha^2\eta^2(B_r-A)^2(1-\epsilon^2)[D_0-\alpha w_0+(\beta-b\alpha)\theta_m+\delta q]^2}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2}-\frac{\mu\tau_m^2}{1-\epsilon^2} \end{aligned} \tag{7.2.3}$$

$\frac{\partial^2\Pi_m^{MR}}{\partial w_0^2} = A_{11} = -\frac{2\alpha^2\eta\mu\left[2\mu\Xi_1-\alpha^2\eta\Xi_2(B_r-A)(1-\epsilon^2)\right]}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2}$;

$\frac{\partial^2\Pi_m^{MR}}{\partial\theta_m^2} = A_{22} = -2\lambda-\frac{2\alpha\eta\mu(\beta-b\alpha)\left[2\mu(1-b)\Xi_1+\alpha\eta(B_r-A)\left((\beta-\alpha)(B_r-A)-(\beta-b\alpha)\Xi_2\right)(1-\epsilon^2)\right]}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2}$;

$\frac{\partial^2\Pi_m^{MR}}{\partial q^2} = A_{33} = -2\xi+\frac{2\alpha^2\eta^2\delta^2\mu(B_r-A)\Xi_2(1-\epsilon^2)]}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2}$; $\frac{\partial^2\Pi_m^{MR}}{\partial\tau_m^2} = A_{44} = -\frac{2\mu}{(1-\epsilon^2)}$;

$\frac{\partial^2\Pi_m^{MR}}{\partial w_0\partial\theta_m} = A_{12} = A_{21} = \frac{2\alpha\eta\mu\left[\mu\Xi_1\left(\beta+\alpha(1-2b)\right)+\alpha^2\eta(B_r-A)\left((\beta-\alpha)B_r-(\beta-b\alpha)\Xi_2\right)(1-\epsilon^2)\right]}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2}$;

$\frac{\partial^2\Pi_m^{MR}}{\partial w_0\partial q} = A_{13} = A_{31} = -\frac{2\alpha\eta\delta\mu\left[\mu\Xi_1-\alpha^2\eta(B_r-A)\left(\Xi_2-(B_r-A)\right)(1-\epsilon^2)\right]}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2}$;

$\frac{\partial^2\Pi_m^{MR}}{\partial w_0\partial\tau_m} = A_{14} = A_{41} = -\frac{2\alpha^2\eta\mu(\Delta-A)}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2}$;

$\frac{\partial^2\Pi_m^{MR}}{\partial q\partial\theta_m} = A_{23} = A_{32} = -\frac{2\alpha\eta\delta\mu\left[\mu(1-b)\Xi_1+\alpha\eta(B_r-A)\left((\beta-\alpha)(B_r-A)+(\beta-b\alpha)[\Xi_2+(B_r-A)]\right)(1-\epsilon^2)\right]}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2}$;

$\frac{\partial^2\Pi_m^{MR}}{\partial\tau_m\partial\theta_m} = A_{24} = A_{42} = \frac{2\alpha\eta\mu(\beta-b\alpha)(\Delta-A)}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2}$;

$\frac{\partial^2\Pi_m^{MR}}{\partial q\partial\tau_m} = A_{34} = A_{43} = \frac{2\alpha\eta\delta\mu(\Delta-A)}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2}$, where $\Xi_2 = 2(\Delta-A)-\epsilon(B_r-A)$.

The Hessian matrix associated with $\Pi_m^{MR}$ is given by

$$H_M^{MR} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{pmatrix}$$

The principal minors are:

$|M_1| = -\frac{2\alpha^2\eta\mu\left[2\mu\Xi_1-\alpha^2\eta\Xi_2(B_r-A)(1-\epsilon^2)\right]}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2} < 0$, if $\mu > \frac{\alpha^2\eta\Xi_2(B_r-A)(1-\epsilon^2)}{2\Xi_1}$;

$|M_2| = \frac{4\alpha^2\eta\mu\left[\mu\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\alpha^2\lambda\eta\Xi_2(B_r-A)(1-\epsilon^2)\right]}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2} > 0$, if $\mu > \frac{\alpha^2\lambda\eta\Xi_2(B_r-A)(1-\epsilon^2)}{2\lambda\Xi_1-\eta(\beta-\alpha)^2}$;
$|M_3| = -\frac{8\alpha^2\eta\mu\left[\mu\left(\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta\right)-\alpha^2\lambda\eta\xi\Xi_2(B_r-A)(1-\epsilon^2)\right]}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2} < 0$,
if $\mu > \frac{\alpha^2\lambda\eta\xi\Xi_2(B_r-A)(1-\epsilon^2)}{\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta}$ and
$|H_M^{MR}| = \frac{16\alpha^2\eta\mu^2\left[\mu\left(\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta\right)-\alpha^2\lambda\eta\xi\left((\Delta-A)^2+\Xi_2(B_r-A)\right)(1-\epsilon^2)\right]}{[\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)]^2(1-\epsilon^2)} > 0$,
if $\mu > \frac{\alpha^2\lambda\eta\xi\left((\Delta-A)^2+\Xi_2(B_r-A)\right)(1-\epsilon^2)}{\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta}$.
Therefore, if $\mu > \max\left\{\frac{\alpha^2\eta\Xi_2(B_r-A)(1-\epsilon^2)}{2\Xi_1}, \frac{\alpha^2\lambda\eta\Xi_2(B_r-A)(1-\epsilon^2)}{2\lambda\Xi_1-\eta(\beta-\alpha)^2}, \frac{\alpha^2\lambda\eta\xi\Xi_2(B_r-A)(1-\epsilon^2)}{\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta},\right.$ $\left.\frac{\alpha^2\lambda\eta\xi\left((\Delta-A)^2+\Xi_2(B_r-A)\right)(1-\epsilon^2)}{\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta}\right\}$ *i.e.* if $\mu > \frac{\alpha^2\lambda\eta\xi\left((\Delta-A)^2+\Xi_2(B_r-A)\right)(1-\epsilon^2)}{\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta}$ holds, for a given $B_r$, the Hessian matrix $H_M^{MR}$ is negative definite which indicates that the profit function $\Pi_m^{MR}$ is jointly concave in $w_0$, $\theta_m$, $q$, and $\tau_m$. Then, using the first order optimality conditions, optimal reactions in terms of $B_r$ can be obtained as

$$\begin{aligned}
w_0^{MR}(B_r) &= \frac{\begin{pmatrix} (D_0+c_m\alpha)\xi\left[\mu\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\alpha^2\lambda\eta(B_r-A)^2(1-\epsilon^2)\right] \\ -c_m\alpha\eta\mu[\xi\alpha(\beta-\alpha)(1-b)+\delta^2\lambda]+D_0\eta\xi[\mu(\beta-b\alpha)(\beta-\alpha) \\ -\alpha^2\lambda\left(2(\Delta-A)^2-(\Delta-B_r)^2-(1+\epsilon)(B_r-A)^2\right)(1-\epsilon^2)] \end{pmatrix}}{\alpha\left[\mu\left(\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta\right)-\alpha^2\lambda\eta\xi\left((\Delta-A)^2+\Xi_2(B_r-A)\right)(1-\epsilon^2)\right]}, \\
\theta_m^{MR}(B_r) &= \frac{\eta\mu\xi(\beta-\alpha)(D_0-c_m\alpha)}{\mu\left(\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta\right)-\alpha^2\lambda\eta\xi\left((\Delta-A)^2+\Xi_2(B_r-A)\right)(1-\epsilon^2)}, \\
q^{MR}(B_r) &= \frac{\delta\lambda\eta\mu(D_0-c_m\alpha)}{\mu\left(\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta\right)-\alpha^2\lambda\eta\xi\left((\Delta-A)^2+\Xi_2(B_r-A)\right)(1-\epsilon^2)}, \\
\tau_m^{MR}(B_r) &= \frac{\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(1-\epsilon^2)}{\mu\left(\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta\right)-\alpha^2\lambda\eta\xi\left((\Delta-A)^2+\Xi_2(B_r-A)\right)(1-\epsilon^2)}.
\end{aligned}$$

Putting these values in Eq. (7.2.3), one can get the profit function of the manufacturer in terms of $B_r$ as

$$\Pi_m^{MR}(B_r) = \frac{\lambda\eta\xi\mu(D_0-c_m\alpha)}{\mu\left(\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta\right)-\alpha^2\lambda\eta\xi\left((\Delta-A)^2+\Xi_2(B_r-A)\right)(1-\epsilon^2)}$$

Now, $\frac{\partial\Pi_m^{MR}}{\partial B_r} = \frac{2\alpha^2\lambda^2\eta^2\xi^2\mu(D_0-c_m\alpha)^2(1-\epsilon^2)[(\Delta-A)-\epsilon(B_r-A)]}{\left[\mu\left(\xi[2\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta\right)-\alpha^2\lambda\eta\xi\left((\Delta-A)^2+\Xi_2(B_r-A)\right)(1-\epsilon^2)\right]^2} > 0.$
Therefore, the profit function of the manufacturer is increasing with respect to $B_r$ and it becomes maximum if $B_r$ takes its upper bound *i.e.* $B_r = \Delta$. With $B_r = \Delta$, the optimal reactions of the manufacturer and the retailer can be obtained as given in Proposition 7.2.1. Hence, Proposition 7.2.1 is proved. ■

With these reactions, the optimal market demand, collection quantity and profits of the manufacturer, the retailer, and the whole supply chain for MR-Model will be

$$D^{MR} = \frac{\alpha\lambda\eta\mu\xi(D_0 - c_m\alpha)}{\left[\mu\left[\xi\left(2\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - \alpha^2\lambda\eta\xi(\Delta - A)^2(3-\epsilon)(1-\epsilon^2)\right]},$$

$$D_r^{MR} = \frac{4\alpha^2\lambda^2\eta^2\xi^2\mu(\Delta - A)(D_0 - c_m\alpha)^2(1-\epsilon^2)}{\left[\mu\left[\xi\left(2\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - \alpha^2\lambda\eta\xi(\Delta - A)^2(3-\epsilon)(1-\epsilon^2)\right]^2},$$

$$\Pi_m^{MR} = \frac{\lambda\eta\mu\xi(D_0 - c_m\alpha)^2}{\left[\mu\left[\xi\left(2\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - \alpha^2\lambda\eta\xi(\Delta - A)^2(3-\epsilon)(1-\epsilon^2)\right]},$$

$$\Pi_r^{MR} = \frac{\lambda^2\eta\mu\xi^2(D_0 - c_m\alpha)^2\left[\mu\Xi_1 - \alpha^2\eta(\Delta - A)^2(1+\epsilon)(1-\epsilon^2)\right]}{\left[\mu\left[\xi\left(2\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - \alpha^2\lambda\eta\xi(\Delta - A)^2(3-\epsilon)(1-\epsilon^2)\right]^2},$$

$$\Pi_w^{MR} = \frac{\lambda\eta\mu\xi(D_0 - c_m\alpha)^2\left[\mu\left[\xi\left(3\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - 4\alpha^2\lambda\eta\xi(\Delta - A)^2(1-\epsilon^2)\right]}{\left[\mu\left[\xi\left(2\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - \alpha^2\lambda\eta\xi(\Delta - A)^2(3-\epsilon)(1-\epsilon^2)\right]^2}.$$

**Observation 7.2.1.** *Proposition 7.2.1 shows that in spite of the fact that the manufacturer and the retailer collect used products simultaneously and competitively, the collection rates of used products for both the manufacturer and the retailer are the same. This happens due to the extreme estimation of the transfer price ($\Delta$) which the manufacturer provides to the retailer to transfer used products. As the retailer gets more transfer price, she applies more exertion in collecting used products. The marginal profit of the manufacturer from collecting used products directly i.e. $(\Delta - A)$ being equal to that of the retailer i.e. $(B_r^{MR} - A)$, the collection rates of used products are also the same.*

**Corollary 7.2.1.** *The effects of product quality and CSR investment related parameters on optimal reactions and profits of the manufacturer, the retailer, and the whole supply chain in the MR-Model are summed up in Table 7.2.1.*

**Table 7.2.1:** Effects of CSR investment and product quality related parameters.

| Parameters | $w$ | $p$ | $q$ | $\theta_m$ | $\theta_r$ | $\tau_m$ | $\tau_r$ | $\Pi_m$ | $\Pi_r$ | $\Pi_w$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $\beta$ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ |
| $\gamma$ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ |
| $\delta$ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ | ↗ |
| $\lambda$ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ |
| $\eta$ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ |
| $\xi$ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ | ↘ |

Note: '↗' means increase; '↘' means decrease.

CSR investment can greatly influence the performance of the supply chain by motivating channel members to improve those investments. When the market demand turns out to be more delicate towards CSR investments, the manufacturer and the retailer need to improve those investments to survive in a competitive business environment. A higher CSR investment demands a higher price. Hence, the wholesale price and the retail price increase. Moreover, CSR investments have a secondary impact on the collection rate of used products. So, collection rates of used products also tend to increase. Higher market demand and collection rates of used products enhance the profits of channel members and the whole supply chain. Similar to CSR investments, product quality also has a positive impact on optimal reactions and the profitability of channel members. These outcomes suggest that when a supply chain encounters a market with higher socially-conscious and quality-sensitive consumers, channel individuals need to improve CSR investments and product quality.

It is obvious that when CSR investments and quality improvement related costs increase, respective firms have to decrease those decisions. As CSR investments and product quality decrease, consumers refuse to buy those products with higher prices. So, the manufacturer and the retailer decrease their respective selling prices. Although the selling price decreases, less CSR investments and product quality have an adverse effect on the market demand. Again, higher costs force channel individuals to reduce their respective collection rates of used products which in turn lessen their profitability as well as the whole supply chain.

### 7.2.2.2 MT-Model

In this model, both the manufacturer and the TPC competitively collect used products from potential customers with collection rate $\tau_m$ and $\tau_t$, respectively. Here, the manufacturer first decides the basic wholesale price $w_0$, quality $q$, CSR investment $\theta_m$, collection rate of used products $\tau_m$, and transfer price $B_t$. After that, the retailer optimizes basic retail price $p_0$, CSR investment $\theta_r$, and the TPC optimizes collection rate of used products $\tau_t$ simultaneously. The profit functions of the manufacturer, the retailer, and the TPC are given by

$$\begin{aligned}\Pi_m^{MT}(w_0,\theta_m,q,\tau_m,B_t) &= (w-c_m-\theta_m)D+(\Delta-A)\tau_m D+(\Delta-B_t)\tau_t D\\ &\quad -\lambda\theta_m^2-\xi q^2-\frac{\mu(\tau_m^2+\epsilon\tau_t^2)}{1-\epsilon^2} \qquad (7.2.4)\\ \Pi_r^{MT}(p_0,\theta_r) &= (p-w-\theta_r)D-\eta\theta_r^2 \qquad (7.2.5)\\ \Pi_t^{MT}(\tau_t) &= (B_t-A)\tau_t D-\frac{\mu(\tau_t^2+\epsilon\tau_m^2)}{1-\epsilon^2} \qquad (7.2.6)\end{aligned}$$

The MT-Model is presented as follows:

$$\begin{cases} \max\limits_{(w_0,\theta_m,q,\tau_m,B_t)} \Pi_m^{MT}(w_0,\theta_m,q,\tau_m,B_t,\tilde{p_0}(w_0,\theta_m,q,\tau_m,B_t),\tilde{\theta_r}(w_0,\theta_m,q,\tau_m,B_t),\tilde{\tau_t}(w_0,\theta_m,q,\tau_m,B_t)) \\ \text{subject to} \\ \tilde{p_0}(w_0,\theta_m,q,\tau_m,B_t),\tilde{\theta_r}(w_0,\theta_m,q,\tau_m,B_t) \text{ and } \tilde{\tau_t}(w_0,\theta_m,q,\tau_m,B_t) \text{ are obtained from solving} \\ \begin{cases} \max\limits_{(p_0,\theta_r)} \Pi_r^{MT}(p_0,\theta_r) \\ \max\limits_{(\tau_t)} \Pi_t^{MT}(\tau_t) \end{cases} \end{cases}$$

Here also we use backward induction and calculate the best reactions of the retailer and the TPC by tackling the first order necessary conditions for optimality. Those reactions are given by

$$\begin{aligned} \tilde{p_0}(w_0,\theta_m,q,\tau_m,B_t) &= \frac{\begin{pmatrix} 2[\eta+(\gamma-d\alpha)(1-d)][D_0+\alpha w_0+(\beta-b\alpha)\theta_m+\delta q] \\ -(\gamma+\alpha-2d\alpha)[(\gamma-d\alpha)(w_0+b\theta_m)+(1-d)(D_0+\beta\theta_m+\delta q)] \end{pmatrix}}{\Xi_1} \\ \tilde{\theta_r}(w_0,\theta_m,q,\tau_m,B_t) &= \frac{(\gamma-\alpha)[D_0-\alpha w_0+(\beta-b\alpha)\theta_m+\delta q]}{\Xi_1} \\ \tilde{\tau_t}(w_0,\theta_m,q,\tau_m,B_t) &= \frac{\alpha\eta(B_t-A)[D_0-\alpha w_0+(\beta-b\alpha)\theta_m+\delta q](1-\epsilon^2)}{\mu\Xi_1}. \end{aligned}$$

The optimal reactions of the manufacturer, the retailer, and the TPC are summed up in the following proposition:

**Proposition 7.2.2.** *If* $\mu > \frac{\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)}{\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right](2+\epsilon)}$ *holds, then the manufacturer's optimal wholesale price, product quality, CSR investment, collection rate of used products and transfer price, the retailer's optimal retail price and CSR investment, and the TPC's collection rate of used products for MT-Model are given respectively by*

$$\begin{aligned} w^{MT} &= \frac{\begin{pmatrix} (D_0+c_m\alpha)\xi\mu(2+\epsilon)\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)+D_0\eta\xi[\mu\beta(\beta-\alpha)(2+\epsilon) \\ -\alpha^2\lambda(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)]-c_m\alpha\eta\mu(2+\epsilon)[\xi\alpha(\beta-\alpha)+\delta^2\lambda] \end{pmatrix}}{\alpha\left[\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)\right]}, \\ q^{MT} &= \frac{\delta\lambda\eta\mu(D_0-c_m\alpha)(2+\epsilon)}{\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)}, \\ \theta_m^{MT} &= \frac{\eta\mu\xi(\beta-\alpha)(D_0-c_m\alpha)(2+\epsilon)}{\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)}, \\ \tau_m^{MT} &= \frac{\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(2+\epsilon)(1-\epsilon^2)}{\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)}, \\ B_t^{MT} &= \frac{\Delta+A(1+\epsilon)}{(2+\epsilon)}, \end{aligned}$$

$$\begin{aligned}
p^{MT} &= \frac{\begin{pmatrix} D_0\xi\big[\mu(2+\epsilon)\big(6\alpha\lambda\eta-\lambda(\gamma-\alpha)(\gamma-2\alpha)+\eta\alpha(\beta-\alpha)\big) \\ -\alpha^2\lambda\eta(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)\big] \\ +c_m\alpha\mu(2+\epsilon)\big[\xi\big(2\alpha\lambda\eta-\lambda\gamma(\gamma-\alpha)-\eta\beta(\beta-\alpha)\big)-\delta^2\lambda\eta\big] \end{pmatrix}}{\alpha\Big[\mu(2+\epsilon)\big[\xi\big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\delta^2\lambda\eta\big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)\Big]}, \\
\theta_r^{MT} &= \frac{\lambda\mu\xi(\gamma-\alpha)(D_0-c_m\alpha)(2+\epsilon)}{\mu(2+\epsilon)\big[\xi\big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\delta^2\lambda\eta\big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)}, \\
\tau_t^{MT} &= \frac{\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(1-\epsilon^2)}{\mu(2+\epsilon)\big[\xi\big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\delta^2\lambda\eta\big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)}.
\end{aligned}$$

**Proof.** The proof is similar to that of Proposition 7.2.1. ■

With these reactions, the optimal market demand, collection quantity and profits of channel individuals and the whole supply chain for MT-Model are given by

$$\begin{aligned}
D^{MT} &= \frac{2\alpha\lambda\eta\mu\xi(D_0-c_m\alpha)(2+\epsilon)}{\Big[\mu(2+\epsilon)\Big[\xi\Big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\Big)-\delta^2\lambda\eta\Big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)\Big]}, \\
D_r^{MT} &= \frac{2\alpha^2\lambda^2\eta^2\xi^2\mu(\Delta-A)(D_0-c_m\alpha)^2(2+\epsilon)(1-\epsilon^2)}{\Big[\mu(2+\epsilon)\Big[\xi\Big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\Big)-\delta^2\lambda\eta\Big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)\Big]^2}, \\
\Pi_m^{MT} &= \frac{\lambda\eta\mu\xi(D_0-c_m\alpha)^2(2+\epsilon)}{\Big[\mu(2+\epsilon)\Big[\xi\Big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\Big)-\delta^2\lambda\eta\Big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)\Big]}, \\
\Pi_r^{MT} &= \frac{\lambda^2\eta\mu^2\xi^2\Xi_1(D_0-c_m\alpha)^2(2+\epsilon)^2}{\Big[\mu(2+\epsilon)\Big[\xi\Big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\Big)-\delta^2\lambda\eta\Big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)\Big]^2}, \\
\Pi_t^{MT} &= \frac{\alpha^2\lambda^2\eta^2\mu\xi^2(D_0-c_m\alpha)^2\Big(1-\epsilon(2+\epsilon)^2\Big)(1-\epsilon^2)}{\Big[\mu(2+\epsilon)\Big[\xi\Big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\Big)-\delta^2\lambda\eta\Big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)\Big]^2}, \\
\Pi_w^{MT} &= \frac{\lambda\eta\mu\xi(D_0-c_m\alpha)^2\Big[\mu(2+\epsilon)^2\Big[\xi\Big(3\lambda\Xi_1-\eta(\beta-\alpha)^2\Big)-\delta^2\lambda\eta\Big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(1+\epsilon)^2(5-\epsilon-3\epsilon^2-\epsilon^3)\Big]}{\Big[\mu(2+\epsilon)\Big[\xi\Big(2\lambda\Xi_1-\eta(\beta-\alpha)^2\Big)-\delta^2\lambda\eta\Big]-\alpha^2\lambda\eta\xi(\Delta-A)^2(3+\epsilon)(1-\epsilon^2)\Big]^2}.
\end{aligned}$$

**Observation 7.2.2.** *Proposition 7.2.2 shows that the collection rate of used products for the manufacturer is $(2+\epsilon)$ times that of the TPC. This is due to the fact that the marginal profit of the manufacturer from collecting used products directly from customers i.e. $(\Delta - A)$ is $(2+\epsilon)$ times that of the TPC i.e. $(B_t^{MT} - A)$.*

### 7.2.2.3 RT-Model

In the reverse channel of this model, both the retailer and the TPC competitively collect used products from the potential customers with collection rate $\tau_r$ and $\tau_t$, respectively. The manufacturer first decides the basic wholesale price $w_0$, quality $q$, CSR investment $\theta_m$, and transfer prices $B_r$, $B_t$. After that, the retailer optimizes basic retail price $p_0$, CSR investment $\theta_r$, collection rate of used products $\tau_r$ and the TPC optimizes collection rate of used products $\tau_t$ simultaneously. The profit functions of the manufacturer, the retailer, and the TPC are given by

$$\begin{aligned}
\Pi_m^{RT}(w_0,\theta_m,q,B_r,B_t) &= (w-c_m-\theta_m)D+(\Delta-B_r)\tau_r D+(\Delta-B_t)\tau_t D \\
&\quad -\lambda\theta_m^2-\xi q^2, \qquad (7.2.7)\\
\Pi_r^{RT}(p_0,\theta_r,\tau_r) &= (p-w-\theta_r)D-(B_r-A)\tau_r D-\eta\theta_r^2-\frac{\mu(\tau_r^2+\epsilon\tau_t^2)}{1-\epsilon^2}, \qquad (7.2.8)\\
\Pi_t^{RT}(\tau_t) &= (B_t-A)\tau_t D-\frac{\mu(\tau_t^2+\epsilon\tau_r^2)}{1-\epsilon^2} \qquad (7.2.9)
\end{aligned}$$

Hence, RT-Model is presented as follows:

$$\begin{cases}
\max\limits_{(w_0,\theta_m,q,B_r,B_t)} \Pi_m^{RT}(w_0,\theta_m,q,B_r,B_t,\tilde{p_0}(w_0,\theta_m,q,B_r,B_t),\tilde{\theta_r}(w_0,\theta_m,q,B_r,B_t),\\
\tilde{\tau_r}(w_0,\theta_m,q,B_r,B_t),\tilde{\tau_t}(w_0,\theta_m,q,B_r,B_t))\\
\text{subject to}\\
\tilde{p_0}(w_0,\theta_m,q,B_r,B_t),\tilde{\theta_r}(w_0,\theta_m,q,B_r,B_t),\tilde{\tau_r}(w_0,\theta_m,q,B_r,B_t) \text{ and } \tilde{\tau_t}(w_0,\theta_m,q,B_r,B_t)\\
\quad \text{are obtained from solving}\\
\quad \begin{cases}
\max\limits_{(p_0,\theta_r,\tau_r)} \Pi_r^{RT}(p_0,\theta_r,\tau_r)\\
\max\limits_{(\tau_t)} \Pi_t^{RT}(\tau_t)
\end{cases}
\end{cases}$$

Using backward induction method, we calculate the best reactions of the retailer and the TPC by tackling the first order necessary conditions for optimality. Those reactions are given by

$$\begin{aligned}
\tilde{p_0}(w_0,\theta_m,q,B_r,B_t) &= \frac{\begin{pmatrix}\mu\big[[2\eta+(\gamma-\alpha)(1-d)][D_0+\alpha w_0+(\beta-b\alpha)\theta_m+\delta q]\\ -w_0(\gamma-\alpha)(\gamma+\alpha-d\alpha)+\theta_m[4b\alpha\eta+(\gamma-\alpha)(d\alpha-b\gamma)]\big]\\ -\alpha\eta(D_0+\beta\theta_m+\delta q)(B_r-A)^2(1-\epsilon^2)\end{pmatrix}}{\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)},\\
\tilde{\theta_r}(w_0,\theta_m,q,B_r,B_t) &= \frac{\mu(\gamma-\alpha)[D_0-\alpha w_0+(\beta-b\alpha)\theta_m+\delta q]}{\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)},\\
\tilde{\tau_r}(w_0,\theta_m,q,B_r,B_t) &= \frac{\alpha\eta(B_r-A)[D_0-\alpha w_0+(\beta-b\alpha)\theta_m+\delta q](1-\epsilon^2)}{\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)},\\
\tilde{\tau_t}(w_0,\theta_m,q,B_r,B_t) &= \frac{\alpha\eta(B_t-A)[D_0-\alpha w_0+(\beta-b\alpha)\theta_m+\delta q](1-\epsilon^2)}{\mu\Xi_1-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)}.
\end{aligned}$$

The optimal reactions of the manufacturer, the retailer and the TPC are summed up in the following proposition:

**Proposition 7.2.3.** *If* $\mu > \frac{5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)}{2\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]}$ *holds, then the manufacturer's optimal wholesale price, product quality, CSR investment and transfer prices, the retailer's optimal retail price, CSR investment and collection rate of used products, and the TPC's collection* *rate of used products for RT-Model are given respectively by*

$$
\begin{aligned}
w^{RT} &= \frac{\left(\begin{array}{c}(D_0+c_m\alpha)\xi\left[2\mu\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-2\alpha^2\lambda\eta(\Delta-A)^2(1-\epsilon^2)\right]\\ +D_0\eta\xi[2\mu\beta(\beta-\alpha)-\alpha^2\lambda(\Delta-A)^2(1-\epsilon^2)]-2c_m\alpha\eta\mu[\xi\alpha(\beta-\alpha)+\delta^2\lambda]\end{array}\right)}{\alpha\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)\right]},\\
q^{RT} &= \frac{2\delta\lambda\eta\mu(D_0-c_m\alpha)}{2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)},\\
\theta_m^{RT} &= \frac{2\eta\mu\xi(\beta-\alpha)(D_0-c_m\alpha)}{2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)},\\
B_r^{RT} &= \Delta,\ \ B_t^{RT}=\frac{\Delta+A}{2},\\
p^{RT} &= \frac{\left(\begin{array}{c}D_0\xi\left[2\mu\left(6\alpha\lambda\eta-\lambda(\gamma-\alpha)(\gamma-2\alpha)+\eta\alpha(\beta-\alpha)\right)-5\alpha^2\lambda\eta(\Delta-A)^2(1-\epsilon^2)\right]\\ +2c_m\alpha\mu\left[\xi\left(2\alpha\lambda\eta-\lambda\gamma(\gamma-\alpha)-\eta\beta(\beta-\alpha)\right)-\delta^2\lambda\eta\right]\end{array}\right)}{\alpha\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)\right]},\\
\theta_r^{RT} &= \frac{2\lambda\mu\xi(\gamma-\alpha)(D_0-c_m\alpha)}{2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)},\\
\tau_r^{RT} &= \frac{2\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(1-\epsilon^2)}{2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)},\\
\tau_t^{RT} &= \frac{\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(1-\epsilon^2)}{2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)}.
\end{aligned}
$$

**Proof.** The proof is similar to that of Proposition 7.2.1. ■

With these reactions, the optimal market demand, collection quantity and profits of the manufacturer, the retailer, the TPC, and the whole supply chain for RT-Model are

$$
\begin{aligned}
D^{RT} &= \frac{4\alpha\lambda\eta\mu\xi(D_0-c_m\alpha)}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)\right]},\\
D_r^{RT} &= \frac{12\alpha^2\lambda^2\eta^2\xi^2\mu(\Delta-A)(D_0-c_m\alpha)^2(1-\epsilon^2)}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)\right]^2},\\
\Pi_m^{RT} &= \frac{2\lambda\eta\mu\xi(D_0-c_m\alpha)^2}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)\right]},\\
\Pi_r^{RT} &= \frac{\lambda^2\eta\mu\xi^2(D_0-c_m\alpha)^2\left[4\mu\Xi_1-\alpha^2\eta(\Delta-A)^2(4+\epsilon)(1-\epsilon^2)\right]}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)\right]^2},\\
\Pi_t^{RT} &= \frac{\alpha^2\lambda^2\eta^2\mu\xi^2(\Delta-A)^2(D_0-c_m\alpha)^2(1-4\epsilon)(1-\epsilon^2)}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)\right]^2},\\
\Pi_w^{RT} &= \frac{\lambda\eta\mu\xi(D_0-c_m\alpha)^2\left[4\mu\left[\xi\left(3\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha^2\lambda\eta\xi(\Delta-A)^2(13+5\epsilon)(1-\epsilon^2)\right]}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)\right]^2}.
\end{aligned}
$$

**Observation 7.2.3.** *Proposition 7.2.3 shows that the collection rate of used products for the retailer is twice that of the TPC. The reason is that the marginal profit of the retailer from collecting used products i.e.* $(B_r^{RT} - A)$ *is twice that of the TPC i.e.* $(B_t^{RT} - A)$.

#### 7.2.2.4 C-Model

Here, we consider the situation of integrated business scenario under manufacturer-retailer joint collection of used products. A centralized decision-making entity takes all decisions viz. basic retail price $p_0$, product quality $q$, CSR investments $\theta_m$ and $\theta_r$, collection rate of used products $\tau_m$ and $\tau_r$ through maximizing the total profit of the whole supply chain. Because of the centralized-decision making entity, the internal exchange prices $w$ and $B_r$ play no role in this scenario. The profit function of the centralized scenario is obtained by adding equations (7.2.1) and (7.2.2). The C-Model is presented as follows:

$$\max_{(p_0,q,\theta_m,\theta_r,\tau_m,\tau_r)} \Pi_w^C(p_0,q,\theta_m,\theta_r,\tau_m,\tau_r) = (p - c_m - \theta_m - \theta_r)D + (\Delta - A)\tau_m D + (\Delta - A)\tau_r D - \xi q^2 - \lambda\theta_m^2 - \eta\theta_r^2 - \frac{\mu(\tau_m^2 + \tau_r^2)}{1-\epsilon} \tag{7.2.10}$$

Tackling the first order necessary conditions for optimality, we can get optimal reactions of C-Model, which have been summed up in the following proposition:

**Proposition 7.2.4.** *If* $\mu > \frac{2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)}{\xi[\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\lambda\eta}$ *holds, then the retail price, product quality, CSR investments, collection rates of used products for C-Model are given respectively by*

$$p^C = \frac{\begin{pmatrix} D_0\xi\left[\mu\left(2\lambda\eta + \lambda(\gamma-\alpha) + \eta(\beta-\alpha)\right) - 2\alpha\lambda\eta(\Delta-A)^2(1-\epsilon)\right] \\ -c_m\mu\left[\xi\left(2\alpha\lambda\eta - \lambda\gamma(\gamma-\alpha) - \eta\beta(\beta-\alpha)\right) - \delta^2\lambda\eta\right] \end{pmatrix}}{\alpha\left[\mu\left[\xi\left(\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - 2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)\right]},$$

$$q^C = \frac{\delta\lambda\eta\mu(D_0 - c_m\alpha)}{\mu\left[\xi\left(\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - 2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)},$$

$$\theta_m^C = \frac{\eta\mu\xi(\beta-\alpha)(D_0 - c_m\alpha)}{\mu\left[\xi\left(\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - 2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)},$$

$$\theta_r^C = \frac{\lambda\mu\xi(\beta-\alpha)(D_0 - c_m\alpha)}{\mu\left[\xi\left(\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - 2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)},$$

$$\tau_m^C = \frac{\alpha\lambda\eta\xi(\Delta-A)(D_0 - c_m\alpha)(1-\epsilon)}{\mu\left[\xi\left(\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - 2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)},$$

$$\tau_r^C = \frac{\alpha\lambda\eta\xi(\Delta-A)(D_0 - c_m\alpha)(1-\epsilon)}{\mu\left[\xi\left(\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - 2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)}.$$

**Proof.** Now,
$\frac{\partial^2\Pi_w^C}{\partial p_0^2} = -2\alpha < 0$; $\frac{\partial^2\Pi_w^C}{\partial\theta_m^2} = -2(\lambda+\beta)$; $\frac{\partial^2\Pi_w^C}{\partial\theta_r^2} = -2\eta - 2(\gamma - d\alpha)(1-d) < 0$;

$\frac{\partial^2\Pi_w^C}{\partial q^2} = -2\xi;\ \frac{\partial^2\Pi_w^C}{\partial \tau_m^2} = \frac{\partial^2\Pi_w^C}{\partial \tau_r^2} = -\frac{2\mu}{1-\epsilon^2} < 0;$
$\frac{\partial^2\Pi_w^C}{\partial p_0\partial\theta_m} = \alpha+\beta;\ \frac{\partial^2\Pi_w^C}{\partial p_0\partial\theta_r} = \gamma+\alpha(1-2d);\ \frac{\partial^2\Pi_w^C}{\partial p_0\partial q} = \delta;\ \frac{\partial^2\Pi_w^C}{\partial p_0\partial\tau_m} = \frac{\partial^2\Pi_w^C}{\partial p_0\partial\tau_r} = -\alpha(\Delta-A);$
$\frac{\partial^2\Pi_w^C}{\partial\theta_m\partial\theta_r} = d\alpha-(1-d)\beta-\gamma;\ \frac{\partial^2\Pi_w^C}{\partial\theta_m\partial q} = -\delta;\ \frac{\partial^2\Pi_w^C}{\partial\theta_m\partial\tau_m} = \frac{\partial^2\Pi_w^C}{\partial\theta_m\partial\tau_r} = \beta(\Delta-A);$
$\frac{\partial^2\Pi_w^C}{\partial\theta_r\partial q} = -\delta(1-d);\ \frac{\partial^2\Pi_w^C}{\partial\theta_r\partial\tau_m} = \frac{\partial^2\Pi_w^C}{\partial\theta_r\partial\tau_r} = (\gamma-d\alpha)(\Delta-A);$
$\frac{\partial^2\Pi_w^C}{\partial q\partial\tau_m} = \frac{\partial^2\Pi_w^C}{\partial q\partial\tau_r} = \delta(\Delta-A);\ \frac{\partial^2\Pi_w^C}{\partial\tau_m\partial\tau_r} = 0.$

The Hessian matrix associated with $\Pi_w^C$ is given by

$$H_w^C = \begin{pmatrix} -2\alpha & \alpha+\beta & \alpha(1-2d)+\gamma & \delta & -\alpha(\Delta-A) & -\alpha(\Delta-A) \\ \alpha+\beta & -2(\lambda+\beta) & d\alpha-(1-d)\beta-\gamma & -\delta & \beta(\Delta-A) & \beta(\Delta-A) \\ \alpha(1-2d)+\gamma & d\alpha-(1-d)\beta-\gamma & -2\eta-2(\gamma-d\alpha)(1-d) & -\delta(1-d) & (\gamma-d\alpha)(\Delta-A) & (\gamma-d\alpha)(\Delta-A) \\ \delta & -\delta & -\delta(1-d) & -2\xi & \delta(\Delta-A) & \delta(\Delta-A) \\ -\alpha(\Delta-A) & \beta(\Delta-A) & (\gamma-d\alpha)(\Delta-A) & \delta(\Delta-A) & -\frac{2\mu}{1-\epsilon^2} & 0 \\ -\alpha(\Delta-A) & \beta(\Delta-A) & (\gamma-d\alpha)(\Delta-A) & \delta(\Delta-A) & 0 & -\frac{2\mu}{1-\epsilon^2} \end{pmatrix}$$

The principal minors are: $|M_1| = -2\alpha < 0$, $|M_2| = \Xi_1 > 0$, if $\eta > \frac{(\gamma-\alpha)^2}{4\alpha}$,
$|M_3| = -2\left[\lambda\Xi_1 - \eta(\beta-\alpha)^2\right] < 0$, if $\lambda > \frac{\eta(\beta-\alpha)^2}{\Xi_1}$,
$|M_4| = -4\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] > 0$, if $\xi > \frac{\delta^2\lambda\eta}{\lambda\Xi_1-\eta(\beta-\alpha)^2}$,
$|M_5| = -\frac{8\left[\mu\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha^2\lambda\eta(\Delta-A)^2(1-\epsilon)\right]}{1-\epsilon} < 0$, if $\mu > \frac{\alpha^2\lambda\eta(\Delta-A)^2(1-\epsilon)}{\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta}$,
and $|H_w^C| = \frac{16\mu\left[\mu\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)\right]}{(1-\epsilon)^2} > 0$,
if $\mu > \frac{2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)}{\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta}$. Therefore, if $\mu > \frac{2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)}{\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta}$ holds, then the Hessian matrix $H_w^C$ is negative definite and the profit function $\Pi_w^C$ is jointly concave in $p_0$, $\theta_m$, $\theta_r$, $q$, $\tau_m$, and $\tau_r$. So, solving the first order conditions of optimality, the optimal reactions of the C-Model can be obtained as given in Proposition 7.2.4. Hence, Proposition 7.2.4 is proved. ■

With these reactions, the optimal market demand, collection quantity and profits of the whole supply chain for C-Model are given by

$$D^C = \frac{2\alpha\lambda\eta\mu\xi(D_0-c_m\alpha)}{\left[\mu\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)\right]},$$
$$D_r^C = \frac{4\alpha^2\lambda^2\eta^2\xi^2\mu(\Delta-A)(D_0-c_m\alpha)^2(1-\epsilon)}{\left[\mu\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)\right]^2},$$
$$\Pi_w^C = \frac{\lambda\eta\mu\xi(D_0-c_m\alpha)^2}{\left[\mu\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)\right]^2}.$$

**Observation 7.2.4.** *From Proposition 7.2.4, we note that the total collection rate of used products in C-Model is* $\tau_m^C+\tau_r^C = \frac{2\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(1-\epsilon)}{\mu\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)}$. *It should lie in* $(0,1)$. *In order to satisfy this condition, the collection cost coefficient* $\mu$ *should be large* *enough such that* $\mu > \frac{2\alpha\lambda\eta\xi(\Delta-A)[(D_0-c_m\alpha)+\alpha(\Delta-A)](1-\epsilon)}{\xi[\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\eta\lambda}$.

#### 7.2.2.5 A Comparative analysis of optimal results

In this subsection, we compare optimal results of our proposed models to get the most ideal decentralized model and give a few suggestions to business managers.

**Proposition 7.2.5.** *(i) The optimal transfer prices to the retailer and the TPC follow the relationship* $B_r^{MR} = B_r^{RT}$ *and* $B_t^{RT} > B_t^{MT}$*, (ii) The optimal collection rate of used products for the manufacturer follows the sequence* $\tau_m^C > \tau_m^{MR} > \tau_m^{MT}$*, (iii) If* $\epsilon \leq 0.5$*, then the optimal collection rate of used products for the retailer follows the sequence* $\tau_r^C > \tau_r^{MR} \geq \tau_r^{RT}$*, (iv) The optimal collection rate of used products for the TPC follows the sequence* $\tau_t^{RT} > \tau_t^{MT}$ *(v) The optimal total collection rates of used products under different models follow the sequence* $\tau^{MR} > \tau^{RT} > \tau^{MT}$.

**Proof.** As Observation 7.2.4 shows that the collection cost coefficient $\mu$ should be large enough such that $\mu > \frac{2\alpha\lambda\eta\xi(\Delta-A)[(D_0-c_m\alpha)+\alpha(\Delta-A)](1-\epsilon)}{\xi[\lambda\Xi_1-\eta(\beta-\alpha)^2]-\delta^2\eta\lambda}$, for all the following proofs we assume this value of $\mu$.

(i) For the transfer price to the third-party collector

$B_t^{RT} - B_t^{MT} = \frac{\epsilon(\Delta-A)}{2(2+\epsilon)} > 0.$

(ii) For the manufacturer's collection rate of used products

$$\tau_m^{MR} - \tau_m^{MT} = \frac{\alpha^3\lambda^2\eta^2\xi^2(\Delta-A)^3(D_0-c_m\alpha)(3-\epsilon^2)(1-\epsilon^2)^2}{\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]\left[\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3+\epsilon)\right]} > 0.$$

$$\tau_m^C - \tau_m^{MR} = \frac{\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(1-\epsilon)\left[\mu\left[\xi\left((1-\epsilon)\lambda\Xi_1+\epsilon\eta(\beta-\alpha)^2\right)+\delta^2\lambda\eta\epsilon\right]-\alpha\Xi_7(1-\epsilon)\right]}{\alpha\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]\left[\mu\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-2\alpha\lambda\eta\xi(\Delta-A)^2(1-\epsilon)\right]} > 0.$$

(iii) For the retailer's collection rate of used products

$$\tau_r^{MR} - \tau_r^{RT} = \frac{\alpha^3\lambda^2\eta^2\xi^2(\Delta-A)^3(D_0-c_m\alpha)(1-2\epsilon)(1-\epsilon^2)^2}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]} \geq 0, \text{ if } \epsilon \leq 0.5.$$

$$\tau_r^C - \tau_r^{MR} = \frac{\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(1-\epsilon)\left[\mu\left[\xi\left((1-\epsilon)\lambda\Xi_1+\epsilon\eta(\beta-\alpha)^2\right)+\delta^2\lambda\eta\epsilon\right]-\alpha\Xi_7(1-\epsilon)\right]}{\alpha\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]\left[\mu\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-2\alpha\lambda\eta\xi(\Delta-A)^2(1-\epsilon)\right]} > 0.$$

(iv) For the third-party collector's collection rate of used products

$$\tau_t^{RT} - \tau_t^{MT} = \frac{\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(1-\epsilon)\left[\mu\epsilon\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]+\alpha\Xi_7(2-\epsilon)\right]}{\left[\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3+\epsilon)\right]\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]} > 0.$$

(v) For the total collection rate of used products

$$\tau^{MR}-\tau^{RT}=\frac{\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(1-\epsilon^2)\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(1+3\epsilon)\right]}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]}>0.$$

$$\tau^{RT}-\tau^{MT}=\frac{\alpha\lambda\eta\xi(\Delta-A)(D_0-c_m\alpha)(1-\epsilon^2)\left[\mu\epsilon\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-2\alpha\Xi_7(3+\epsilon)\right]}{\left[\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3+\epsilon)\right]\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]}>0, \text{ due}$$

to large value of $\mu$ as given in Observation 7.2.4. Where $\Xi_7=\alpha\lambda\eta\xi(\Delta-A)^2(1-\epsilon^2)$. ■

The transfer price acts as a stimulant to any collector to collect used products. The more the transfer price, the more the collection effort will be. It is observed that the profit of the manufacturer has a growing trend with $B_r$. That's why, the manufacturer pays the upper bound of $B_r$ to the retailer in both MR and RT-Models. The manufacturer may have some idea regarding the used products market when he is involved in collecting used products. But when he does not collect used products directly, he hesitates to confront any risk. That's why, he pays a higher transfer price to the TPC in RT-Model than MT-Model.

As the manufacturer needs to pay a higher transfer price in MR-Model than MT-Model, he wants to reduce this loss through collecting more used products. So, the manufacturer's collection rate of used products is higher in MR-Model than MT-Model. The retailer's collection rate depends on both the competition coefficient $\epsilon$ and collection options. If $\epsilon$ is less than 0.5, then the retailer puts more effort in the case of MR-Model. But with the increase of $\epsilon$, the retailer's enthusiasm for collecting used products shifts from MR-Model to RT-Model. The retailer may feel that a lower transfer price to the TPC may lessen her interest to collect used products under a highly competitive situation. As the TPC gets higher transfer price in RT-Model, s/he shows more endeavor in collecting used products under the said model.

It is noteworthy that although the individual collection rate of used products is affected by $\epsilon$, it has no impact on the positioning of the total collection rate of used products under different models. It is always higher in MR-Model and lower in MT-Model.

**Proposition 7.2.6.** *If $\epsilon\leq 0.5$, then (i) the optimal wholesale price follows the sequence $w^{RT}\geq w^{MR}>w^{MT}$, (ii) the optimal retail price follows the sequence $p^{MT}>p^{RT}\geq p^{MR}>p^{C}$, (iii) the optimal product quality follows the sequence $q^C>q^{MR}\geq q^{RT}>q^{MT}$, (iv) the optimal CSR investments follow the sequence $\theta_i^C>\theta_i^{MR}\geq\theta_i^{RT}>\theta_i^{MT},\ i=m,\ r$.*

**Proof.** (i) For the wholesale price

$$w^{RT} - w^{MR} = \frac{\Xi_7(D_0-c_m\alpha)(1-2\epsilon)\left[\mu\left[\xi\left(\lambda\Xi_1-\eta\beta(\beta-\alpha)\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7\right]}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]} \geq 0, \text{ if } \epsilon \leq 0.5.$$

$$w^{MR} - w^{MT} = \frac{\Xi_7(D_0-c_m\alpha)\left[\mu\left[\xi\left((1+\epsilon)^2[\lambda\Xi_1-\eta(\beta-\alpha)^2]+\eta(\beta-\alpha)[\alpha(1-\epsilon-\epsilon^2)+\beta(2+\epsilon)]\right)+\delta^2\lambda\eta(1-\epsilon-\epsilon^2)\right]-\alpha\Xi_7(3+\epsilon)\right]}{\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]\left[\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3+\epsilon)\right]} > 0.$$

(ii) For the retail price

$$p^{MT} - p^{RT} = \frac{\Xi_7\mu(D_0-c_m\alpha)(4+3\epsilon)\left[\xi\left(2\alpha\lambda\eta-\lambda\gamma(\gamma-\alpha)-\eta\beta(\beta-\alpha)\right)-\delta^2\lambda\eta\right]}{\left[\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3+\epsilon)\right]\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]} > 0.$$

$$p^{RT} - p^{MR} = \frac{\Xi_7\mu(D_0-c_m\alpha)(1-2\epsilon)\left[\xi\left(2\alpha\lambda\eta-\lambda\gamma(\gamma-\alpha)-\eta\beta(\beta-\alpha)\right)-\delta^2\lambda\eta\right]}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]} \geq 0, \text{ if } \epsilon \leq 0.5.$$

$$p^{MR} - p^{C} = \frac{\lambda\xi\mu(D_0-c_m\alpha)\left[\xi\left(2\alpha\lambda\eta-\lambda\gamma(\gamma-\alpha)-\eta\beta(\beta-\alpha)\right)-\delta^2\lambda\eta\right]\left[\mu\Xi_1-\alpha^2\eta(\Delta-A)^2(1+\epsilon-3\epsilon^2+\epsilon^3)\right]}{\alpha\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]\left[\mu\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-2\alpha\lambda\eta\xi(\Delta-A)^2(1-\epsilon)\right]} > 0.$$

(iii) For the product quality

$$q^{RT} - q^{MT} = \frac{\alpha\lambda\eta\delta\Xi_7\mu(D_0-c_m\alpha)(4+3\epsilon)}{\left[\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3+\epsilon)\right]\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]} > 0.$$

$$q^{MR} - q^{RT} = \frac{\alpha\lambda\eta\delta\Xi_7\mu(D_0-c_m\alpha)(1-2\epsilon)}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]} \geq 0, \text{ if } \epsilon \leq 0.5.$$

$$q^{C} - q^{MR} = \frac{\lambda^2\eta\delta\xi\mu(D_0-c_m\alpha)\left[\mu\Xi_1-\alpha^2\eta(\Delta-A)^2(1+\epsilon-3\epsilon^2+\epsilon^3)\right]}{\alpha\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]\left[\mu\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-2\alpha\lambda\eta\xi(\Delta-A)^2(1-\epsilon)\right]} > 0.$$

(iv) For the CSR investments

$$\theta_m^{RT} - \theta_m^{MT} = \frac{\alpha\eta\xi\Xi_7\mu(\beta-\alpha)(D_0-c_m\alpha)(4+3\epsilon)}{\left[\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3+\epsilon)\right]\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]} > 0.$$

$$\theta_m^{MR} - \theta_m^{RT} = \frac{\alpha\eta\xi\Xi_7\mu(\beta-\alpha)(D_0-c_m\alpha)(1-2\epsilon)}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]} \geq 0, \text{ if } \epsilon \leq 0.5.$$

$$\theta_m^{C} - \theta_m^{MR} = \frac{\lambda\eta\xi^2\mu(\beta-\alpha)(D_0-c_m\alpha)\left[\mu\Xi_1-\alpha^2\eta(\Delta-A)^2(1+\epsilon-3\epsilon^2+\epsilon^3)\right]}{\alpha\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]\left[\mu\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-2\alpha\lambda\eta\xi(\Delta-A)^2(1-\epsilon)\right]} > 0.$$

$$\theta_r^{RT} - \theta_r^{MT} = \frac{\alpha\lambda\xi\Xi_7\mu(\gamma-\alpha)(D_0-c_m\alpha)(4+3\epsilon)}{\left[\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3+\epsilon)\right]\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]} > 0.$$

$$\theta_r^{MR} - \theta_r^{RT} = \frac{\alpha\lambda\xi\Xi_7\mu(\gamma-\alpha)(D_0-c_m\alpha)(1-2\epsilon)}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]} \geq 0, \text{ if } \epsilon \leq 0.5.$$

$\theta_r^C - \theta_r^{MR} = \frac{\lambda^2\xi^2\mu(\gamma-\alpha)(D_0-c_m\alpha)\left[\mu\Xi_1-\alpha^2\eta(\Delta-A)^2(1+\epsilon-3\epsilon^2+\epsilon^3)\right]}{\alpha\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]\left[\mu\left[\xi\left(\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-2\alpha\lambda\eta\xi(\Delta-A)^2(1-\epsilon)\right]} > 0.$ ■

Proposition 7.2.6 demonstrates that the manufacturer charges a lower wholesale price in MT-Model. The reason is that, in MT-Model, the retailer can gain profit from selling new product ($(p-w)D$), but in other two models, the retailer can gain from both selling new product ($(p-w)D$) and collecting used products ($(B_r - A)\tau_r D$). The wholesale prices in MR and RT-Models depend on the competition coefficient. If it is less than 0.5, then the manufacturer charges a higher wholesale price in RT-Model. With the increase of $\epsilon$, the manufacturer reduces the wholesale price in RT-Model. Although the manufacturer charges a lower wholesale price in MT-Model, due to a single earning option, the retailer sets a higher retail price. In MR and RT-Models, the retail price follows the similar trend of the wholesale price. It is directly affected by the wholesale price and indirectly by the transfer price. C-Model offers a lower retail price as it is liberated from the double-marginalization impact.

As the collection rate in MT-Model is lower than other two decentralized models, the manufacturer needs to utilize more raw materials for producing new product which incurs an additional expense. As a result, the manufacturer reduces quality improvement effort and CSR investment. The retailer also diminishes her CSR investment. For a lower estimation of $\epsilon$, these reactions are higher in MR-Model. However, with the increase of $\epsilon$, these reactions become higher in RT-Model. Therefore, for lower $\epsilon$, the market demand is higher in MR-Model while for higher $\epsilon$, it is higher in RT-Model. It reveals that the competition between two competing collectors influences optimal reactions and market demand only when one of the competing collector is the retailer. In the case of C-Model, customers can get a higher quality product at a lower price. CSR investments are also higher in C-Model.

**Proposition 7.2.7.** *(i)If $\epsilon \leq 0.5$ then the optimal profit of the manufacturer follows the sequence $\Pi_m^{MR} \geq \Pi_m^{RT} > \Pi_m^{MT}$, and (ii) the optimal profit of the TPC follows the sequence $\Pi_t^{RT} > \Pi_t^{MT}$.*

**Proof.** (i) For the manufacturer's profit

$\Pi_m^{RT} - \Pi_m^{MT} = \frac{\alpha\lambda\eta\xi\Xi_7\mu(D_0-c_m\alpha)^2(4+3\epsilon)}{\left[\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3+\epsilon)\right]\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]} > 0.$

$\Pi_m^{MR} - \Pi_m^{RT} = \frac{\alpha\lambda\eta\xi\Xi_7\mu(D_0-c_m\alpha)^2(1-2\epsilon)}{\left[2\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-5\alpha\Xi_7\right]\left[\mu\left[\xi\left(2\lambda\Xi_1-\eta(\beta-\alpha)^2\right)-\delta^2\lambda\eta\right]-\alpha\Xi_7(3-\epsilon)\right]} \geq 0$, if $\epsilon \leq 0.5$.

(ii) For the third-party collector's profit

$$\Pi_t^{RT} - \Pi_t^{MT} = \frac{\alpha\lambda\eta\xi\Xi_7\mu(D_0 - c_m\alpha)^2\left[\Xi_8^2\epsilon(4+\epsilon) + 8\alpha\Xi_7(\Xi_8 - 2\alpha\Xi_7) + 7\alpha^2\Xi_7^2\epsilon(2+\epsilon)(5+3\epsilon) - 6\alpha\Xi_7\Xi_8[7+\epsilon(7+2\epsilon)]\right]}{\left[\mu(2+\epsilon)\left[\xi\left(2\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - \alpha\Xi_7(3+\epsilon)\right]\left[2\mu\left[\xi\left(2\lambda\Xi_1 - \eta(\beta-\alpha)^2\right) - \delta^2\lambda\eta\right] - 5\alpha\Xi_7\right]} > 0$$

as $\Xi_8 > 2\alpha\Xi_7$ and $0 < \epsilon < 1$, where $\Xi_8 = \mu\left[\xi\left(2\lambda\Xi_1 - \eta(\beta - \alpha)^2\right) - \delta^2\lambda\eta\right]$. ■

Proposition 7.2.7 indicates that market demand and overall collection rate of used products in MT-Model being lower compared to the other two models, the profit of the manufacturer is also lower in that model. Similar to other decisions, profits of the manufacturer in MR and RT-Model are also influenced by $\epsilon$. Since for a lower $\epsilon$, the market demand is higher in MR-Model, the profit of the manufacturer also becomes higher. But for higher $\epsilon$, it becomes higher in RT-Model. While comparing the profit of the TPC, we note that it is lower in MT-Model. This is because of the lower market demand and a lower amount of transfer price in MT-Model. Due to algebraic complexity, we avoid the comparison of profits of the retailer and the whole supply chain analytically, which will be compared numerically in the next section.

#### 7.2.2.6 *Joint revenue-and-cost sharing contract (CO-Model)*

Revenue sharing and cost sharing contracts are two notable techniques to coordinate multi-tier CLSC framework. However, a straightforward contract will most likely be unable to coordinate CLSC. It can provide at most a win-win situation for channel individuals. To beat this inadequacy, we propose a joint revenue-and-cost sharing contract which instigates channel individuals to settle the reactions indistinguishable from the centralized model. Under the proposed contract, the retailer agrees to share some portion $(1-x) \in (0,1)$ of her revenue to the manufacturer and in return, the manufacturer sells the product with comparatively lower wholesale price $w^{CO}$. But this may not encourage the manufacturer to improve the quality of the product as quality improvement needs some additional cost. Therefore, the retailer shares some portion $\phi \in (0,1)$ of quality improvement cost which motivates the manufacturer in enhancing the product quality. Under the proposed contract, the profit functions of the manufacturer and the retailer will take the form as given in the following:

$$\begin{aligned} \Pi_m^{CO}(w_0^{CO}, \theta_m, q, \tau_m, B_r) &= (w^{CO} - c_m - \theta_m)D + (\Delta - A)\tau_m D + (\Delta - B_r)\tau_r D \\ &\quad -\lambda\theta_m^2 - \frac{\mu(\tau_m^2 + \epsilon\tau_r^2)}{1-\epsilon^2} - (1-\phi)\xi q^2 + (1-x)pD, \quad (7.2.11) \\ \Pi_r^{CO}(p_0, \theta_r, \tau_r) &= (xp - w^{CO} - \theta_r)D + (B_r - A)\tau_r D \\ &\quad -\eta\theta_r^2 - \frac{\mu(\tau_r^2 + \epsilon\tau_m^2)}{1-\epsilon^2} - \phi\xi q^2 \quad (7.2.12) \end{aligned}$$

Hence, CO-Model is presented as follows:

$$\begin{cases} \max\limits_{(w_0^{CO},\theta_m,q,\tau_m,B_r)} \Pi_m^{CO}(w_0^{CO},\theta_m,q,\tau_m,B_r) \text{ and} \\ \max\limits_{(p_0,\theta_r,\tau_r)} \Pi_r^{CO}(p_0,\theta_r,\tau_r) \\ \text{such that } p^{CO}=p^C; q^{CO}=q^C; \theta_m^{CO}=\theta_m^C; \theta_r^{CO}=\theta_r^C; \tau_m^{CO}=\tau_m^C \text{ and } \tau_r^{CO}=\tau_r^C. \end{cases}$$

We first calculate the retailer's best reactions by tackling the first order necessary conditions for optimality, and those reactions are given by

$$\begin{aligned} p_0^{CO}(w_0^{CO},\theta_m,q,\tau_m,B_r) &= \frac{\begin{pmatrix} \mu\big[(x\gamma-\alpha)\big((1-dx)(D_0+\beta\theta_m+\delta q)-(\gamma-d\alpha)(w_0+b\theta_m)\big) \\ +2\eta\big(x(D_0+\alpha w_0+\beta\theta_m+\delta q)+b\alpha\theta_m\big)\big] \\ -\alpha\eta(D_0+\beta\theta_m+\delta q)(B_r-A)^2(1-\epsilon^2) \end{pmatrix}}{\mu[4\alpha\eta x-(x\gamma-\alpha)^2]-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)}, \\ \theta_r^{CO}(w_0^{CO},\theta_m,q,\tau_m,B_r) &= \frac{\mu(x\gamma-\alpha)[x(D_0+\beta\theta_m+\delta q)-\alpha(w_0^{CO}+b\theta_m)]}{\mu[4\alpha\eta x-(x\gamma-\alpha)^2]-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)}, \\ \tau_r^{CO}(w_0^{CO},\theta_m,q,\tau_m,B_r) &= \frac{\alpha\eta(B_r-A)[x(D_0+\beta\theta_m+\delta q)-\alpha(w_0^{CO}+b\theta_m)](1-\epsilon^2)}{\mu[4\alpha\eta x-(x\gamma-\alpha)^2]-\alpha^2\eta(B_r-A)^2(1-\epsilon^2)}. \end{aligned}$$

Now, equating $p_0^{CO}$ and $p_0^C$ under consideration of all other reactions same as those of C-Model, one can get $w_0^{CO}$ in terms of $\phi$ and $x$ as follows:

$$w_0^{CO}(\phi,x) = \frac{\begin{pmatrix} D_0\xi\Big[\mu\big[(1-x)\lambda\big(\alpha\Theta_1+\gamma[(\gamma-d\alpha)(x\gamma-\alpha)+2\eta x(2+\gamma)]\big) \\ +\eta(\beta-\alpha)(b-x)\Theta_1\big]+\alpha\lambda\eta(1-\epsilon)\big[(1+\epsilon-2x)\big(2\alpha\eta-(\gamma-\alpha)^2\big) \\ -2x\gamma(\gamma-\alpha)(1-x)\big]\Big]+c\Big[\lambda\xi\big(\Theta_1-x\gamma(\gamma-d\alpha)\big)\big[\mu\big(4\alpha\eta x-(x\gamma-\alpha)^2\big) \\ -\alpha^2\eta(\Delta-A)^2(1-\epsilon^2)\big]+\mu\Theta_1\big(\eta\xi(\beta-\alpha)(b\alpha-x\beta)-x\delta^2\lambda\eta\big)\Big] \end{pmatrix}}{\Big[\mu\big[\xi\big(\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\delta^2\lambda\eta\big]-2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)\Big]\Theta_1} \quad (7.2.13)$$

where $\Theta_1 = 2\alpha\eta-(\gamma-d\alpha)(x\gamma-\alpha)$.

Again, considering retailer's reactions are same as those of C-Model, from $\frac{\partial \Pi_m^{CO}}{\partial q} = 0$, we get

$$q^{CO}(w_0^{CO},\theta_m,\tau_m,B_r) = \frac{\delta\big[w_0^{CO}-c_m-(1-b)\theta_m+(\Delta-A)\tau_m+(\Delta-B_r)\tau_r^C+(1-x)p_0^C\big]}{2\xi(1-\phi)}$$

Now, equating $q^{CO}$ and $q^C$ under consideration of all other reactions same as those of C-Model, one can get $w_0^{CO}$ in terms of $\phi$ and $x$ as follows:

$$w_0^{CO}(\phi,x) = \frac{\begin{pmatrix} (D_0-c_m\alpha)\xi\big[\alpha\lambda\eta(\Delta-A)^2(1-\epsilon)-\mu\big(2\lambda\eta\phi+\lambda(\gamma-\alpha)+b\eta(\beta-\alpha)\big)\big] \\ +x\Big[D_0\xi\big[\mu\big(2\eta\phi+\lambda(\gamma-\alpha)+\eta(\beta-\alpha)\big)\big] \\ +c_m\mu\big[\xi\big(2\alpha\lambda\eta-\lambda\gamma(\gamma-\alpha)-\eta\beta(\beta-\alpha)\big)-\delta^2\lambda\eta\big]\Big] \end{pmatrix}}{\mu\big[\xi\big(\lambda\Xi_1-\eta(\beta-\alpha)^2\big)-\delta^2\lambda\eta\big]-2\alpha^2\lambda\eta\xi(\Delta-A)^2(1-\epsilon)} \quad (7.2.14)$$

Equating these two values of $w_0^{CO}$ given in Eqs. (7.2.13) and (7.2.14), we get a quadratic equation in $x$ as $Rx^2+Sx+T=0$, where $R = 2d\alpha\gamma\mu > 0$,

$S = -2\mu\big(2\alpha\eta + d\alpha(\gamma+\alpha) - (\gamma - d\alpha)(\gamma - \gamma\phi - 2\alpha)\big) + \alpha\gamma(\gamma - d\alpha)(\Delta - A)^2(1-\epsilon) < 0$,
$T = \alpha\big[2\mu\big(\gamma + \phi[2\eta + (\gamma - d\alpha)]\big) + (\Delta - A)^2\big(2\alpha\eta\epsilon - (\gamma - d\alpha)[\gamma + \epsilon(\gamma - \alpha)]\big)(1-\epsilon)\big] > 0$.
Let us consider the equation $f(x) = Rx^2 + Sx + T = 0$. As, $R > 0,\ S < 0$ and $T > 0$, therefore, the number of changes in sign is 2. Hence the equation $f(x) = 0$ has two positive roots. Again, $f(0) = T > 0$, $f(1) = R + S + T = -[2\alpha\eta + (\gamma - \alpha)(\gamma - d\alpha)][2\mu(1-\phi) - \alpha(\Delta - A)^2\epsilon(1-\epsilon)] < 0$ and it can be shown that $S^2 - 4RT > 0$. So, by Descartes' rule of signs, it has at least one real root in $(0,1)$. Let it be $x^* \in (0,1)$. The roots of the equation $f(x) = 0$ are given by $x = \frac{-S \pm \sqrt{S^2 - 4RT}}{2R}$. With $x = x^*$, the optimal value of $w_0^{CO}$ is given by

$$w_0^{CO}(\phi) = \frac{\begin{pmatrix} (D_0 - c_m\alpha)\xi\big[\alpha\lambda\eta(\Delta - A)^2(1-\epsilon) - \mu\big(2\lambda\eta\phi + \lambda(\gamma-\alpha) + b\eta(\beta-\alpha)\big)\big] \\ +x^*\Big[D_0\xi\big[\mu\big(2\eta\phi + \lambda(\gamma-\alpha) + \eta(\beta-\alpha)\big)\big] \\ +c_m\mu\big[\xi\big(2\alpha\lambda\eta - \lambda\gamma(\gamma-\alpha) - \eta\beta(\beta-\alpha)\big) - \delta^2\lambda\eta\big]\Big] \end{pmatrix}}{\mu\big[\xi\big(\lambda\Xi_1 - \eta(\beta-\alpha)^2\big) - \delta^2\lambda\eta\big] - 2\alpha^2\lambda\eta\xi(\Delta - A)^2(1-\epsilon)} \tag{7.2.15}$$

The estimation of the other parameter $\phi$ can be obtained from the condition that both channel individuals will show enthusiasm in participating this contract *i.e.* their profits after contract surpass or equivalent to those of MR-Model. From the manufacturer's condition, we get

$$\begin{aligned} \Pi_m^{CO} &\geq \Pi_m^{MR} \\ \Rightarrow \phi &\geq \frac{\begin{pmatrix} [w_0^{MR} - c_m - (1-b)\theta_m^{MR} + (\Delta - A)\tau_m^{MR}]D^{MR} - [w_0^{CO} - c_m - (1-b)\theta_m^C \\ +(\Delta - A)\tau_m^C]D^C + \lambda[(\theta_m^C)^2 - (\theta_m^{MR})^2] + \xi[(q^C)^2 - (q^{MR})^2] \\ +\frac{\mu}{1-\epsilon^2}[(\tau_m^C)^2 - (\tau_m^{MR})^2 + \epsilon(\tau_r^C)^2 - (\tau_r^{MR})^2] - (1-x^*)p^C D^C \end{pmatrix}}{\xi(q^C)^2} \\ &= \phi_{min} \end{aligned} \tag{7.2.16}$$

From the retailer's condition, we get

$$\begin{aligned} \Pi_r^{CO} &\geq \Pi_r^{MR} \\ \Rightarrow \phi &\leq \frac{\begin{pmatrix} [x^* p^C - w_0^{CO} - \theta_r^C + (\Delta - A)\tau_r^C]D^C - [p^{MR} - w_0^{MR} - \theta_m^{MR} + (\Delta - A)\tau_r^{MR}]D^{MR} \\ -\eta[(\theta_r^C)^2 - (\theta_r^{MR})^2] - \frac{\mu}{1-\epsilon^2}[(\tau_r^C)^2 - (\tau_r^{MR})^2 + \epsilon(\tau_m^C)^2 - (\tau_m^{MR})^2] \end{pmatrix}}{\xi(q^C)^2} \\ &= \phi_{max} \end{aligned} \tag{7.2.17}$$

So, the profit of the whole supply chain under contract is $\Pi_w^{CO} = \Pi_m^{CO} + \Pi_r^{CO} = \Pi_w^C$. We already have $x^* \in (0,1)$, and if there exists a $\phi$ such that $\phi \in (0,1)$, then we have the following proposition.

**Proposition 7.2.8.** *If the manufacturer sets the wholesale price $w^{CO}$ and $\phi \in [\phi_{min}, \phi_{max}]$, then the proposed joint revenue-and-cost sharing contract can coordinate the supply chain and help channel individuals to achieve win-win situation.*

### 7.2.3 Numerical analysis

In order to exhibit the outcomes of the proposed models and inspect the adequacy of the proposed coordination contract, this section performs a real case study for a CLSC that deals with printer cartridges and provides some significant managerial insights. We suppose the hypothetical parameter-values those are consistent with parameter-values used in the literature e.g., Huang et al. (2013); Zhao et al. (2017), with some legitimate change in accordance with the suppositions of our study, and use the artificial names – 'MCL' for the manufacturer, 'RCL' for the retailer and 'TCL' for the TPC. In the proposed supply chain, besides producing new printer cartridges from fresh raw material, MCL remanufactures the used cartridges that were previously collected. The collection of used cartridges can be performed under three competing structures – collection through MCL and RCL, collection through MCL and TCL, and collection through RCL and TCL. To gain competitive advantage, MCL focuses on maintaining the quality of the cartridges. Both MCL and RCL contribute some amount in CSR, such as labor safety, education (distribute mobile phones, tabs, etc. for online classes), health care (distribute face masks, sanitizer, PPE kits, etc.), for each unit of sales and so, the selling prices are affected by their respective CSR investments with the elasticity parameter equal to $b = 0.7$ and $d = 0.5$, respectively. The basic market demand of the cartridges is $D_0 = 100$ unit/week. The market demand for the cartridges is affected by four factors – price, CSR investments of MCL and RCL, quality with the elasticity parameters equal to $\alpha = 0.3; \beta = 2.0; \gamma = 1.5$, and $\delta = 0.28$. MCL produces new cartridges at a manufacturing cost of $c_m = \$20$ per unit and remanufactures the used cartridges at a remanufacturing cost of $c_r = \$5$ per unit. So, cost saving from remanufacturing used cartridges is $\Delta = \$15$ per unit. Each collector pays $A = \$5$ as an acquisition price for each unit of used cartridges. Competition and collection cost coefficients are taken as $\epsilon = 0.2$ and $\mu = 600$. MCL and RCL have to incur some cost for improving product quality and investing in CSR with coefficient equal to $\xi = 35; \lambda = 15$, and $\eta = 12$. For better understanding, the parameter-values are summed up in Table 7.2.2.

**Table 7.2.2:** Parameter-values.

| Parameters | $D_0$ | $\alpha$ | $\beta$ | $\gamma$ | $\delta$ | $b$ | $d$ | $\epsilon$ | $\mu$ | $\lambda$ | $\eta$ | $\xi$ | $c_m$ | $c_r$ | A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Values | 100 | 0.3 | 2.0 | 1.5 | 0.28 | 0.7 | 0.5 | 0.2 | 600 | 15 | 12 | 35 | 20 | 5 | 5 |

#### 7.2.3.1 Optimal results of different models

Optimal results of different models are presented in Table 7.2.3. From Table 7.2.3, it is observed that the presence of RCL as a collector of used cartridges has great impact

**Table 7.2.3:** Optimal results of the proposed models.

| Optimal results | MR-Model | MT-Model | RT-Model | C-Model | CO-Model |
|---|---|---|---|---|---|
| $w_0$ | 193.254 | 192.329 | 193.568 | - | 23.0631 |
| $w$ | 197.128 | 196.165 | 197.433 | - | **31.7234** |
| $p_0$ | 294.900 | 295.283 | 294.986 | 247.424 | 247.424 |
| $p$ | **297.342** | 297.700 | 297.422 | 252.882 | 252.882 |
| $q$ | **0.39070** | 0.38680 | 0.38982 | 0.87331 | 0.87331 |
| $\theta_m$ | **5.53485** | 5.47969 | 5.52246 | 12.3719 | 12.3719 |
| $\theta_r$ | **4.88369** | 4.83502 | 4.87276 | 10.9164 | 10.9164 |
| $\tau_m$ | **0.23442** | 0.23208 | - | 0.43665 | 0.43665 |
| $\tau_r$ | **0.23442** | - | 0.23389 | 0.43665 | 0.43665 |
| $\tau_t$ | - | 0.10549 | **0.11695** | - | - |
| $\tau$ | **0.46884** | 0.33757 | 0.35881 | 0.87330 | 0.87330 |
| $B_r$ | 15 | - | 15 | - | 15 |
| $B_t$ | - | 9.54545 | **10** | - | - |
| $\Pi_m$ | **4590.67** | 4544.92 | 4580.39 | - | 6838.71 |
| $\Pi_r$ | **2534.63** | 2524.76 | 2528.42 | - | 3422.66 |
| $\Pi_t$ | - | 0.22257 | **1.70955** | - | - |
| $\Pi_w$ | **7125.30** | 7069.91 | 7110.52 | 10261.4 | 10261.4 |

on optimal reactions of RCL as well as other members of the supply chain. Under MR and RT-Models, RCL has two-fold occupations – one in the forward channel where she can influence market through dealing with the retail price, and other in the reverse channel where she can affect the market through managing the collection effort. However, in MT-Model, RCL impacts the market only through managing the retail price. As described in Propositions 7.2.5-7.2.7, MR-Model provides the product with higher quality at comparatively lower retail price and more CSR investments. Due to lower retail price, and higher product quality and CSR investments, the market demand is higher in this model. Both MCL and RCL exert more effort in collecting used cartridges. Higher market demand and higher collection rate improve profits of MCL, RCL, and the whole supply chain. As TCL gets more transfer price (\$10/used cartridge) in RT-Model, s/he puts more effort to collect used cartridges which in turn enhances his/her profit (from \$0.22257 in MT-Model to \$1.70995 in RT-Model). It can be seen that if MCL has to contract with TCL to collect used cartridges, he prefers to outsource the collection activity to RCL instead of handling it by himself. While comparing MR-Model with C-Model, we note that the product quality and CSR investments are more than double in C-Model. Customers also get the product at a comparatively lower price. Due to combined decision-making, the collection rate is about 86% higher in C-Model which helps in expanding the total profit of the supply chain. The centralized profit of the supply chain is \$10261.4, which is improved about 44% compared to MR-Model.

For CO-Model, we first calculate the optimal value of $\phi$ following Eqs. (7.2.16) and (7.2.17), which indicates $\phi \in [0.2878, 0.5075]$. So, we consider a particular value of $\phi$ as 0.35. With this value of $\phi$, the value of $x^*$ becomes 0.45352. After that, the optimal value of basic wholesale price is calculated following Eq. (7.2.15).

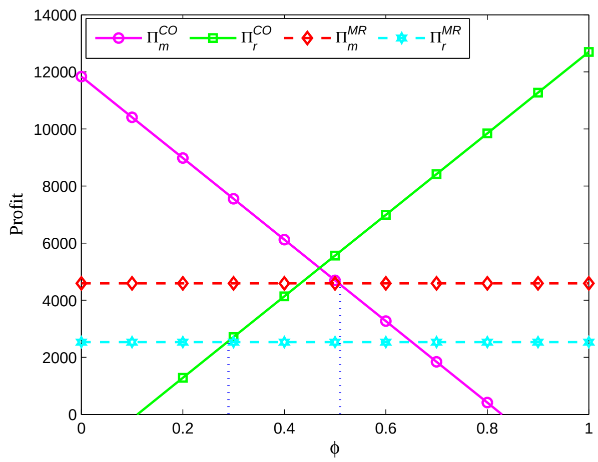



**Fig. 7.2.2:** Win-win situation for both members.

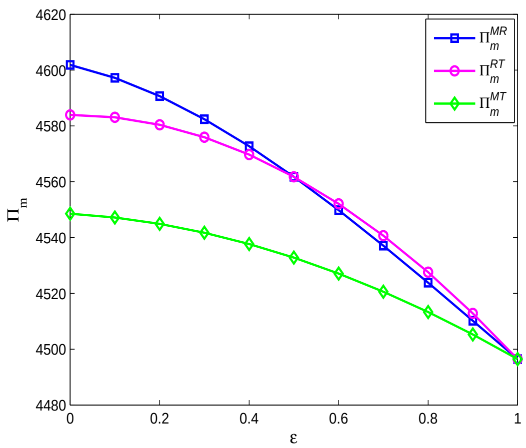
We obtain that, in CO-Model, MCL sells the cartridge at a wholesale price of \$31.7234/cartridge which is about 84% lower than that of MR-Model and other reactions are the same as those of C-Model. CO-Model guarantees both MCL and RCL to gain more profit than their decentralized (MR-Model) profits. Under this setting, MCL and RCL obtain respectively almost 49% and 35% higher profits compared to MR-Model. So, both MCL and RCL can achieve win-win situation using the proposed contract (see Fig. 7.2.2). The total profit of the whole supply chain is also equal to that of C-Model. Hence, the proposed contract can perfectly coordinate the supply chain. In this manner, CO-Model is not only beneficial to all channel individuals and the entire supply chain from economic perspective, but also beneficial from the viewpoint of environment (due to higher collection rate) and the society (due to higher CSR investments), in comparison with other models. As consumers obtain higher quality product in comparatively lower price, the proposed contract is also beneficial from consumers' viewpoint.

### 7.2.3.2 Sensitivity analysis

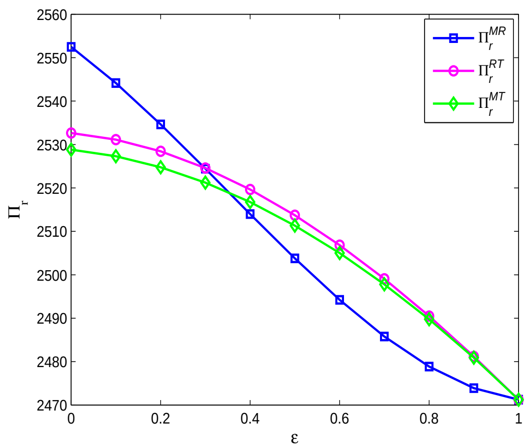
In this subsection, we look into the impact of some key model-parameters on optimal profits of channel individuals and the whole supply chain.

#### A. Effect of competition coefficient ($\epsilon$)

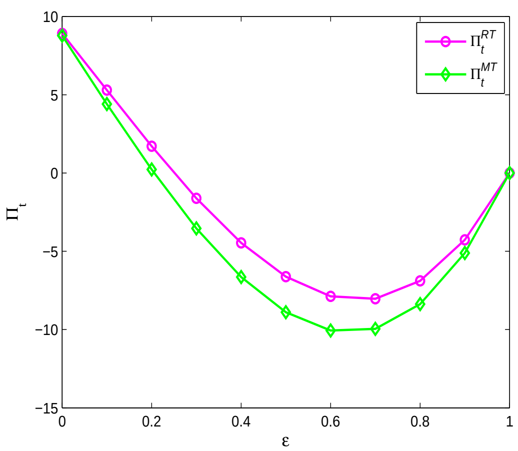
Fig. 7.2.3(a) illustrates that the profit of MCL tends to decline with the competition coefficient $\epsilon$. It has no effect on the positioning of MCL's profit in MT-Model. But, it affects MCL's profit in MR and RT-Models. MCL's profit is always lower in MT-Model. It is higher in MR-Model if $\epsilon$ is less than 0.5, but for a higher estimation of $\epsilon$, RT-Model provides the best outcome to MCL. This outcome is actually the same what we have seen in Proposition 7.2.7.



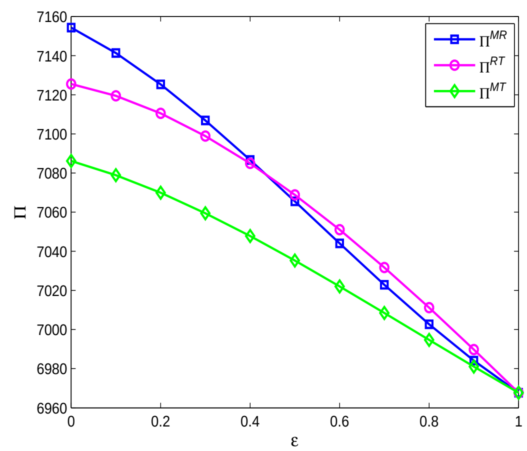

(a) $\epsilon$ vs $\Pi_m$.




(b) $\epsilon$ vs $\Pi_r$.




(c) $\epsilon$ vs $\Pi_t$.




(d) $\epsilon$ vs $\Pi$.

**Fig. 7.2.3:** Sensitivity of optimal profits w.r.t. $\epsilon$.

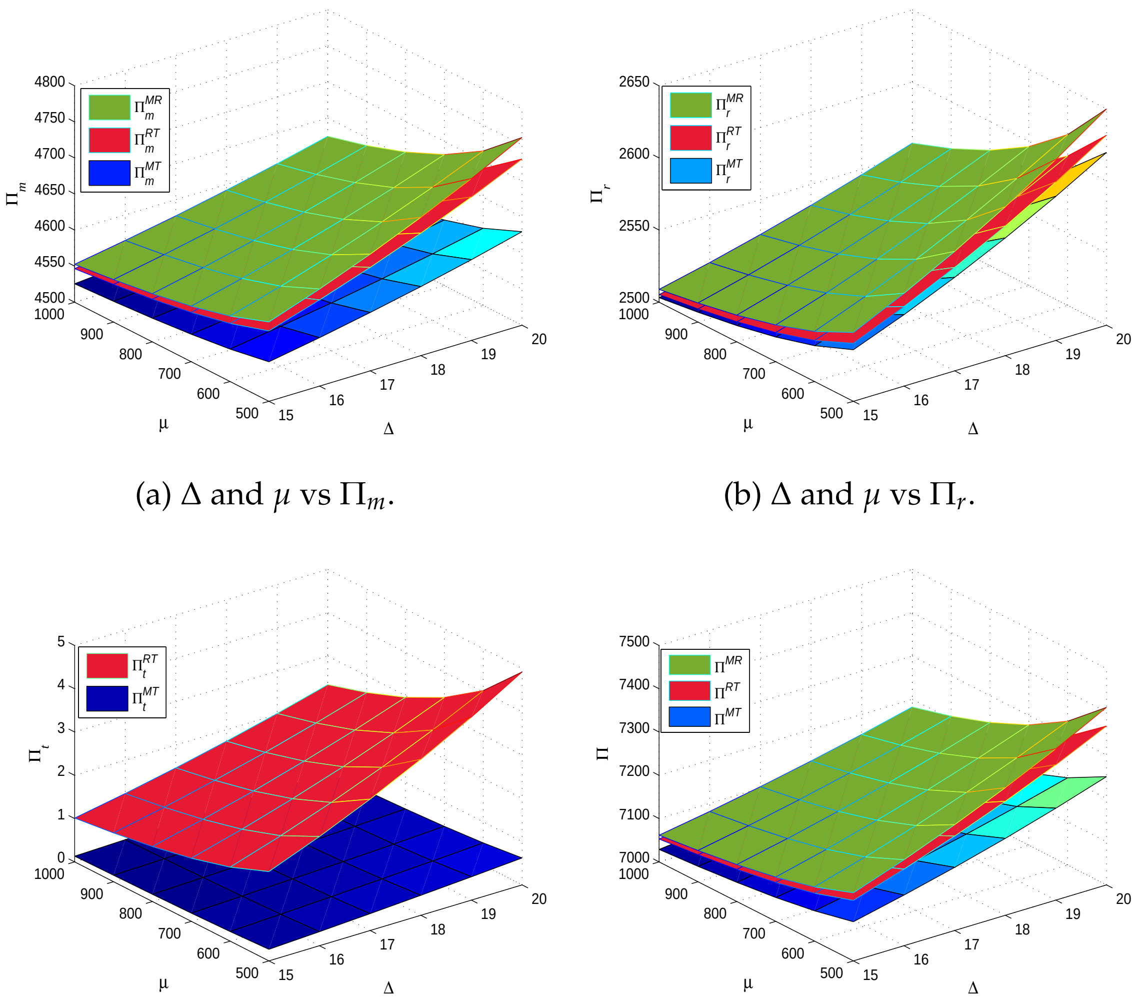
Similar to MCL's profit, RCL's profit also decreases with $\epsilon$. With the increasing competition between two collectors, RCL's profit diminishes sharply in MR model. When $\epsilon$ is less than 0.3, RCL's profit follows the sequence $\Pi_r^{MR} > \Pi_r^{RT} > \Pi_r^{MT}$, when $\epsilon \in [0.3, 0.36]$, RCL's profit follows the sequence $\Pi_r^{RT} > \Pi_r^{MR} > \Pi_r^{MT}$, when $\epsilon$ is greater than 0.36, the sequence becomes $\Pi_r^{RT} > \Pi_r^{MT} > \Pi_r^{MR}$ (Fig. 7.2.3(b)). Hence, from Fig. 7.2.3(b) one can observe that under mild competition, RCL wants to collect used products with MCL while under strong competition, she prefers to perform the collection activity with TCL. This is because the collection related cost increases as the competition between the two collectors increases. MCL being the leader of the supply chain, will not prefer to collect used products under strong competition. Again, RCL gets more transfer price than the TCL. Thus, she has the responsibility to work with the TCL.

TCL gets a higher transfer price in RT-Model than MT-Model which can produce a higher profit. So, TCL has more enthusiasm for collecting used products in RT-Model. The competition coefficient $\epsilon$ has a significant effect on TCL's profit. Fig. 7.2.3(c) displays that TCL shows enthusiasm in collecting used products only when $\epsilon$ is sufficiently small. More specifically, TCL wants to take part in the collection of used products when $\epsilon$ is less than 0.2. Actually, under strong competition between two collectors, TCL cannot gain profit. This is because of the higher collection cost.

In the proposed models, the profit of the whole supply chain follows a pattern similar to MCL's profit. It is always lower in MT-Model. If $\epsilon$ is less than 0.4, then it is higher in MR-Model; otherwise, it is higher in RT-Model (Fig. 7.2.3(d)).

### B. Effect of cost saving from remanufacturing ($\Delta$)

The performance of any CLSC depends on how much the manufacturer earns from product remanufacturing, or in other words, the amount of cost savings from remanufacturing ($\Delta$). A higher estimation of $\Delta$ encourages MCL to collect more used products for remanufacturing. Again, as $\Delta$ increases, MCL offers a higher transfer price to both RCL and TCL. A higher transfer price motivates them in collecting used products. So, the collection rate increases. Moreover, due to higher cost saving, MCL reduces the wholesale price and RCL lessens the retail price of the product. As a result, profits of all channel individuals tend to increase. Figures 7.2.4(a), 7.2.4(b), and 7.2.4(d) exhibit that the profits of MCL, RCL and the whole supply chain are higher in MR-Model followed by RT-Model and MT-Model. As TCL gets a higher transfer price in RT-Model, so its profit is higher in RT-Model and lower in MT-Model (Fig. 7.2.4(c)). This finding suggests that the manufacturer should use modern technologies to maximize profit through higher cost saving from remanufacturing.




(a) Δ and $\mu$ vs $\Pi_m$.

(b) Δ and $\mu$ vs $\Pi_r$.

(c) Δ and $\mu$ vs $\Pi_t$.

(d) Δ and $\mu$ vs Π.

**Fig. 7.2.4:** Sensitivity of optimal profits w.r.t. Δ and $\mu$.

## *C. Effect of collection cost coefficient* ($\mu$)

An increase in the collection cost coefficient ($\mu$) leads to increase in collection cost. So, when $\mu$ increases, profits of channel individuals decrease in all models (Fig. 7.2.4). The rate of decrement is almost similar for MCL, RCL, and the whole supply chain in all three models. The rate of decrement of TCL's profit is slightly higher in RT-Model than that in MT-Model. This analysis demonstrates that the collection cost coefficient should not be expanded aimlessly by expanding investments related to collection activities for profit maximization.

## 7.3
# *Conclusions*

The comparative analysis of optimal results of Section 7.1 provides some managerial insights. First, the pricing behavior of channel members is highly affected by various collection options. A comparatively lower wholesale price is enjoyed by the retailer only when the manufacturer himself collects used products directly from customers, whereas when the manufacturer contracts with the third-party collector, he will have to set a higher wholesale price to reduce the losses induced from transfer price. Second, the collection rate depends on who is in charge of collecting used products from customers and how much transfer price the manufacturer agrees to pay. When the manufacturer contracts with the retailer or the third-party collector for collecting used products, he needs to invest some transfer price. The manufacturer never contracts with the third-party collector for collecting used products. If the manufacturer denies to pay much transfer price, instead of contracting with the retailer or collector, he should collect used products directly. Third, the higher the CSR investment done by the retailer, the higher the level of CSR effort will be. A higher CSR effort increases the market demand, which improves the profitability of channel members, consumer surplus and total social welfare. Therefore, the leader of the channel or the government ought to encourage the retailer to involve in CSR to create a good corporate image. Fourth, the governmental intervention seems to be advantageous for both channel members and environment, since it can improve CSR effort. An increased CSR effort increases the market demand and boosts the collection rate of used products. A higher collection rate of used products shows the channel members' environmental awareness, and a higher market demand enhances the profits of the channel members. Fifth, the adjustment factor and CSR level floor have positive impacts on optimal decisions and the profit of the manufacturer but the retailer's profit decreases with CSR level floor. This is probably because of the investment cost. A higher CSR effort needs higher investment cost resulting a decrease in the retailer's profit. So, the government should set a suitable CSR level floor. Finally, among the three different decentralized models, Model C gives the worst possible outcome whereas Model M gives the best possible outcome if the manufacturer wants to spend less amount of transfer price. Although Model M provides better performance, it fails to compete with the integrated model because of double-marginalization effect. That's why, channel coordination is necessary for better performance. The proposed TPT contract can coordinate the supply chain and helps channel members to achieve the win-win situation.

The analytical and numerical comparison of optimal results of Section 7.2 give the following outcomes: (1) MT-Model is not beneficial to any supply chain individual. Between MR-Model and RT-Model, which one is preferable to channel individuals depends on the competition coefficient. The TPC prefers to collect used products with the retailer competitively. (2) A higher competition coefficient has an adverse effect on optimal reactions and the profitability of channel individuals. This means that the competition between two collectors is detrimental to channel individuals. This is the reason why channel individuals favor continuing collection activities in the isolated market despite of higher transportation costs, operating costs, etc. in the said market. (3) Cost saving from remanufacturing has a positive effect while the collection cost coefficient has a negative effect on optimal reactions and the profits of channel individuals. (4) The manufacturer can enhance the channel performance by either improving product quality or investing in CSR or both. The retailer's CSR investment has also a positive impact on the channel performance. (5) The proposed contract helps the manufacturer to sell high quality product at relatively lower wholesale price. As a result, the retailer sells it at lower retail price. It also helps both the manufacturer and the retailer to contribute more in CSR. From an economic perspective, besides improving the profit of the whole supply chain, the proposed contract also enhances the profits of all channel individuals. Moreover, the proposed contract is capable of rising the collection rate of used products. Accordingly, it is effective from an environmental perspective. Furthermore, it encourages both the manufacturer and the retailer to contribute more in CSR. Consequently, it is effective with respect to social sustainability. Therefore, it helps supply chain managers in elevating all three dimensions of sustainability.

# 8

# Conclusions and future research avenues

*"Ends are not bad things, they just mean that something else is about to begin"*

– C. JoyBell C.

This final chapter concludes the thesis by means of recalling the objectives of this study, recapturing the main findings as well as the managerial implications for the government and policy-makers based on those findings, and highlighting the limitations and recommendations for further research aspects. GSCM is a topic that has evolved over the last couple of decades as a flourishing sub-region of SCM and getting a rising consideration from both academics and practitioners. During this time, GSCM has become a famous methodology for few manufacturing companies to acquire financial advantages by lessening environmental contamination and risks while controlling environmental damages. For lessening environmental risks, manufacturing companies have to utilize modern advanced technologies that desire additional investments. Again, for moderating environmental damages, appropriate reverse channels need to be selected to acquire enough end-of-life products. So, a tremendous number of intricacies have been seen in the implementation of this methodology and various new controversies have been uncovered, which raises doubts as to whether adopting the GSCM planning will upgrade environmental safety and finally lead to progressed profitability. Endeavoring to comprehend these intricacies is vital and of importance from both empirical and academic viewpoints.

In light of the above objectives, the third chapter considers the manufacturer's green innovation under warranty period as a first stepping stone in investigating whether execution of GSCM practices positively affects the profitability of channel individuals. Although additional investment is required for green innovation, surprisingly, it leads the supply chain to improved environmental progress and economic prosperity. Consequently, in all subsequent chapters, the manufacturer's green innovation is incorporated. In addition to green innovation, since the collection of used products also improves the environmental performance, various strategies utilized in used products collection is discussed in the next chapter. In the first part of the fourth chapter, the manufacturer and the retailer are considered as used product collector while in the second part, the third-party is included as a used product collector under the retailer's fairness behavior. Results indicate that the fairness behavior and transfer price play important role in deciding which reverse channel should be selected for collecting used products.

Product sale through the retailer is affected by double-marginalization effect which increases the product price, resulting in the loss in the channel members' income. Due to rapid growth of online business, both the product sale and used product collection through the online channel is an excellent decision to adapt up to the channel individuals' trepidation of losing profits due to green innovation. The fifth chapter deals with this issue and reveals that the inclusion of e-tail channel together with the retail channel improves channel performance; selling price in the retail and e-tail channel depends on customers' loyalty to those channels. In addition, when a manufacturer starts producing green product, its competition with traditional non-green product is inevitable. Again, when more than one retailer sells those products, there is also a competition between them. So, an immediate question may arise – how do competing manufacturers and competing retailers behave while making their decisions? In seeking an answer to this question, the sixth chapter assesses cooperative and non-cooperative behaviors of same level players. Results illustrate that the cooperative behavior (Collusion) can provide better outcome to any one of the individuals only but their competing behavior (Nash) is profitable for the majority of the individuals.

So far we have focused on economic performance as well as environmental sustainability, but the global covid epidemic and lockdown have shown us how important it is to emphasize social performance. In this regard, Chapter 7 extends the boundaries of GSCM to a sustainable supply chain management by integrating

CSR. The first part of this chapter discusses various used product collection options through single channel with retailer's CSR effort and government sponsorship whilst the second part deals with recycling competition and CSR investments of both the manufacturer and the retailer. Analytical and numerical comparison indicate that CSR effort and government intervention are able to improve channel efficiency significantly; the manufacturer prefers to collect used product and never contracts with the TPC for this purpose in case of single collection but in case of collection competition, the competition coefficient determines whether the manufacturer himself procures with the retailer or outsource it to the TPC.

## 8.1 Managerial implications

In view of the key findings of this thesis, the accompanying managerial implications may be furnished to the government, policy-makers, and practitioners. It developed various models under different practical assumptions and provided the best possible outcomes of those models. With the assistance of those consequences, business administrators are able to better understand the relationships between various GSCM factors, how to make the appropriate decisions and find out which model offers better potential results for advancing their financial and environmental goals.

Since the green innovation desires greater funding, the manufacturing managers may have in a dilemma whether to invest in green production or not. It is suggested not to run behind the green innovation during production; alternatively they are able to make use of modern innovative technologies, modified equipments beforehand. Beside green innovation, the concept of product remanufacturing is another important learning to guide manufacturing managers. Proper inspection of used products at the time of collection is recommended for full recovery. In addition, manufacturers may make use of e-tail channel for further improving their profitability. Again, in case of competition among multi-manufacturers and multi-retailers, they should make their decisions non-cooperatively. The retailer, being the bridge between the manufacturer and customers, should exert effort in marketing those products and put resources into CSR.

Governments with prominent and strong role in society, can persuade green manufacturers to apply more exertion in green innovation and the buyers to purchase more eco-friendly products. They can also inspire the small & medium companies to produce pottery, sal leaf plates, jute bags, etc. Government support for those companies can empower the production of these products. Different exciting packages like subsidy, tax reduction can encourage various firms in endeavor GSCM approaches. They should fortify environment-related rules and regulations, such as cap-and-trade policies, as it is claimed that the recognition of these regulations by organizations may be a step towards growing the reliance on environmental voluntary initiatives (Karra and Affes, 2014). Researchers and practitioners should share their innovative ideas regarding the implementation of GSCM practices and articulate the particular advantages gained through such practices.

In essence, developing mutual trust, high level of information sharing between channel members, strict government regulations, environmental training programs for firms' personnel, and the presence of environmentally-conscious customers are beneficial in terms of both financial and environmental viewpoint.

## 8.2 Limitations and further research

As with any research, this thesis also associates with a few restrictions that can be loose to open the way for future research and provide opportunities for further research. First of all, the consideration of deterministic demand is one of the major limitations of this thesis. While the actual business is quite complicated and the market faces some uncertainties. Thus, a model that considers a lot of uncertainty (possibly during product sale or collection of used products) may be a regular extension of the present study. This thesis only thinks about single objective problem such as maximization of profit which can be reached out to a multi-objective problem by including multiple objectives like cost minimization, emission reduction, etc. In addition, it considers single item and single-period or two-period situations which may be prolonged to a multi-item, multi-period situation in future investigations. Moreover, various costs of the supply chain are summed up as a single cost, and in most models, these costs are considered fixed. It is possible to extend these models to include several variable costs. Furthermore, members of each channel may have some private information. In light of these information asymmetry, development of some composite contracts aimed at asymmetric information sharing can be another direction worth looking at. Last but not the least, the numerical studies and sensitivity analysis of this thesis are carried out by considering fictitious parameter-values. Consideration of real industry data and investigation of its impact on GSCM performance can be a new avenue for future research.

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# List of Publications

1. **Analysing a closed-loop supply chain with selling price, warranty period and green sensitive consumer demand under revenue sharing contract**. *Journal of Cleaner Production*, (Elsevier; *2021 Impact factor: 11.072*) (2018) 190, 822-837. (*SCIE Journal*).

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3. **Pricing and greening strategies for a dual-channel closed-loop green supply chain**. *Flexible Services and Manufacturing Journal*, (Springer; *2021 Impact factor: 2.209*) (2020) 32(3), 724-761. (*SCIE Journal*).

4. **Pricing and used product collection strategies in a two-period closed-loop supply chain under greening level and effort dependent demand**. *Journal of Cleaner Production*, (Elsevier; *2021 Impact factor: 11.072*)(2020) 265, 121335. (*SCIE Journal*).

5. **Optimizing price, quality and CSR investment under competing dual recycling channels in a sustainable closed-loop supply chain**. *CIRP Journal of Manufacturing Science and Technology*, (Elsevier; *2021 Impact factor: 3.56*) (2021) 35, 193-208. (*SCIE Journal*).

6. **Coordinating a closed-loop green supply chain for remanufactured product under competition**. *Scientia Iranica*, (Sharif University of Technology; *2021 Impact factor: 1.416*) (2021). (In Press). (*SCIE Journal*).

7. **A comparative analysis of greening policies and CSR efforts in a government-led sustainable supply chain across different channel powers**. *International Journal of Business and Globalisation*, (Inderscience) (2021). (In Press). (*SCOPUS Journal*).

8. **Investigating a green supply chain with product recycling under retailer's fairness behavior**. *Journal of Industrial and Management Optimization*, (AIMS; *2021 Impact factor: 1.411*) (2022) 18(5), 3641-3677. (*SCIE Journal*).

9. **Retailers' competition and cooperation in a closed-loop green supply chain under governmental intervention and cap-and-trade policy**. *Operational Research*, (Springer; *2021 Impact factor: 2.708*) (2022) 22, 859-894. (*SCIE Journal*).

10. **Integrating Corporate Social Responsibility in a two-echelon closed-loop supply chain under government subsidy and used products collection**. *Flexible Services and Manufacturing Journal*, (Springer; *2021 Impact factor: 2.209*) (2022) 34, 65-100. (*SCIE Journal*).

11. **Analyzing a manufacturer-retailer sustainable supply chain under cap-and-trade policy and revenue sharing contract**. *Operational Research*, (Springer; *2021 Impact factor: 2.708*) (2022) 22, 4057-4092. (*SCIE Journal*).

12. **Investigating strategies of a green closed-loop supply chain for substitutable products under government subsidy** by Chirantan Mondal & Bibhas C. Giri. *Journal of Industrial and Production Engineering*, (Taylor & Francis) (2022) 39(4), 253-276. (*ESCI Journal*).

13. **Analyzing strategies in a green e-commerce supply chain with return policy and exchange offer**. *Computers & Industrial Engineering*, (Elsevier; *2021 Impact factor: 7.180*) (2022) 171, 108492. (*SCI Journal*).

14. **Tax-subsidy or reward-penalty? Determining optimal strategy in sustainable closed-loop supply chain under quality-dependent return**. *International Journal of Systems Science: Operations & Logistics*, (Taylor & Francis; *2021 Impact factor: 9.040*) (2022) 1-26. (*SCIE Journal*).

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# Analysing a closed-loop supply chain with selling price, warranty period and green sensitive consumer demand under revenue sharing contract

B.C. Giri [a, *], C. Mondal [a], T. Maiti [b]

[a] Department of Mathematics, Jadavpur University, Kolkata, 700 032, India
[b] Department of Mathematics, Gurudas College, Kolkata, 700 054, India

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ABSTRACT

In this paper, a two-echelon closed-loop supply chain with one manufacturer and one retailer is considered, and two game theoretic models are presented in which the first model (Model I) considers demand dependent on selling price and warranty period while the second model (Model II) considers demand dependent on greening level in addition to the selling price and warranty period. During the warranty period offered by the manufacturer, a portion of the returned items is refurbished and sent back to the customer while the remaining portion is remanufactured and sold in the secondary market, and the same portion is replaced by the new products in the market. Both the models are solved under centralized, decentralized, and revenue sharing contract scenarios. In the decentralized scenario, a Stackelberg game is considered between the manufacturer and the retailer in which the manufacturer is assumed to be the leader and the retailer as the follower. Through analytic and numerical analyses, it is seen that Model II gives better response on all the key decisions of the supply chain than Model I. The centralized scenario achieves higher greening level and warranty period compared to the decentralized scenario. Sensitivity analysis is performed to investigate the effect of key-model parameters on optimal decisions.



## 1. Introduction

In recent era, public concerns about saving energy and environmental protection have been increased in most developed countries. Manufacturers are directed to take back used products at the end of their life period to prevent carbon emission. In a closed-loop supply chain (CLSC), the used product collection and remanufacturing can not only reduce the manufacturing cost but also reduce carbon emissions and environmental pollution. CLSC management in fact could be used to gain competitive advantage and achieve sustainable development (Savaskan and Van Wassenhove, 2006; Abbey et al., 2014). In practice, some industries choose the appropriate reverse channel at the time of remanufacturing to obtain more profit. For example, Xerox has been a leader in reusing high-value end-of-life copiers in the manufacturing of new copiers. Hewlett Packard Corporation for computers and peripherals, and Canon for print and copy cartridges undertake the similar activities (Savaskan and Van Wassenhove, 2006). Some manufacturers also make use of collection efforts such as product design, process modification to smooth the progress of recycling, reverse logistics services, employee-training programs, etc. to enhance their reputation, satisfying the environmental concerns of consumers and simplify their disposal process. In addition, the manufacturers also concern about reduction of carbon emission, air pollution, water pollution and green house gas emission during their economic remanufacturing processes. In a closed-loop supply chain, intends are not only the forward supply chain's pricing strategy, promotion of product and selling the product but also the reverse supply chain's recycling strategy. Retailers can successfully guide customers towards a low-carbon (green) consumption mindset, and encourage the renovation of consumers from non-environment friendly to environment-friendly by promoting low-carbon (green) products by explaining their benefits, advise them to customers and setting up outstanding display showcases, etc., (Li et al., 2016). Over the last few years, the concept of sustainable

* Corresponding author.
*E-mail addresses:* bcgiri.jumath@gmail.com (B.C. Giri), chirantan.mondal94@gmail.com (C. Mondal), tarun.ju@gmail.com (T. Maiti).

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# OPTIMAL PRODUCT QUALITY AND PRICING STRATEGY FOR A TWO-PERIOD CLOSED-LOOP SUPPLY CHAIN WITH RETAILER VARIABLE MARKUP

B.C. Giri[1], C. Mondal[1] and T. Maiti[2,*]

**Abstract.** In this paper, we consider a two-period closed-loop supply chain which is comprised of a single manufacturer and a single retailer for trading a single product. At the retailer, the demand in the first period depends on the selling price, product quality and refund price, whereas in the second period, it depends on the selling price and the product quality. The retailer sets the selling prices with variable markups on the wholesale prices of the manufacturer and offers a return policy (immediate return and used product return) limited to the first period only. The immediate return is dependent on the refund price and the product quality, and the amount of returned used items is a fraction of the first period's demand. The retailer sends the returned items to the manufacturer who reproduces/repairs those items and sells in the second period. We assume that the manufacturer acts as the Stackelberg leader and the retailer as the follower. We study the impacts of return policy, product quality and pricing strategy on the optimal decisions under two decision strategies (I and II). In the decision strategy I, both the players optimize their total profits over the entire selling season, whereas in the decision strategy II, they optimize each period's profit sequentially. With the help of a numerical example we explore that the decision strategy I gives better result than the decision strategy II in terms of all decision variables except the product quality. We also investigate the effects of key model-parameters on the optimal decisions.

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## 1. Introduction

With the rapid development of economy and society, people's appeal of saving energy and sustainable development is increasing. As a research hotspot, the study of closed-loop supply chain management, which explicitly takes account of product returns, in addition to the downstream flow of materials, plays an increasing prominent role in sustainable development and environment protection. The economical and environmental benefits of product remanufacturing have been widely recognized during the past fifteen years [6, 18, 37]. A closed-loop supply chain (CLSC) consists of both forward and reverse activities. Forward activities include new product development, product design and engineering, procurement and production, marketing, sales, distribution, and

*Keywords.* Closed-loop supply chain, retailer variable markup, two-period model, remanufacturing, return policy, product quality, pricing strategy.

[1] Department of Mathematics, Jadavpur University, Kolkata 700 032, India.
[2] Department of Mathematics, Gurudas College, Kolkata 700 054, India.
*Corresponding author: tarun.ju@gmail.com

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# Pricing and greening strategies for a dual-channel closed-loop green supply chain

C. Mondal[1] · B. C. Giri[1] · T. Maiti[2]

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**Abstract**

This article considers a closed-loop green supply chain with both forward and reverse dual-channels, where a manufacturer produces and sells a single green product to the potential customers through both the direct online channel (e-tail/internet) and the traditional retail channel in the forward dual-channel, and collects the used products for remanufacturing from the customers through both the retail and the direct online channels in the reverse dual-channel (Model II). The pricing and greening strategies for the channel members and the whole supply chain are derived both analytically and numerically under centralized and three decentralized scenarios viz. manufacturer-led and retailer-led decentralized scenarios and Nash game. These results are compared with those in the case when reverse logistic does not exist (Model I). Two special cases are examined when the products are returned through only online channel and only retail channel. Sensitivity analysis is performed to explore the effect of key model-parameters on optimal decisions. From numerical analysis, it is observed that the retail price in the centralized scenario is higher than that in the decentralized scenario, which contradicts the result due to double marginalization, and the retailer-led decentralized policy provides higher profit than the other decentralized policies. Model II gives better result in terms of profit of the whole supply chain, whereas Model I suggests a more environment-friendly product. It is also observed that the channel members gain more profit when the retailer only collects the used products.

**Keywords** Supply chain management · Dual-channel · Greening level · Pricing policies · Remanufacturing

✉ C. Mondal
chirantan.mondal94@gmail.com

Extended author information available on the last page of the article

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# Pricing and used product collection strategies in a two-period closed-loop supply chain under greening level and effort dependent demand

Chirantan Mondal *, Bibhas C. Giri

*Department of Mathematics, Jadavpur University, Kolkata, 700 032, India*

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A B S T R A C T

This article presents a two-period closed-loop green supply chain model with a single manufacturer and a single retailer to investigate the impact of green innovation, marketing effort and collection rate of used products on the supply chain decisions. The market demand of the green product is assumed to be dependent on the selling price, greening level and marketing effort. In the first period, the manufacturer produces new product from fresh raw materials while in the second period, besides manufacturing new products, he also collects and remanufactures used products. The centralized model and three decentralized models (depending on the manufacturer's collection option of used products) are considered. A cost sharing contract is also employed to address the coordination issue. The optimal results are obtained, and the effect of key model-parameters on the optimal decisions are investigated through sensitivity analysis. It is observed that the supply chain gives better response when both the manufacturer and the retailer collect used products simultaneously, and the performance of the supply chain can be improved by instigating either green innovation or marketing effort or both.



## 1. Introduction

In the recent era, due to environmental degradation, natural resource shortage, fast improvement of society and globalization of economy, a large number of customers are focusing on environment-friendly (green) product even for paying higher price. The government is also implementing rules and regulations to diminish the negative effects of used products on the environment. The rising environmental awareness of the customers and more pressure from the government have forced many manufacturers (e.g. Xerox, Caterpillar, Boeing, Deere, and Pitney Bowes) to involve themselves in product remanufacturing. Besides lowering the manufacturing cost, remanufacturing of end-of-life products helps to reduce carbon emission and environment pollution. In fact, closed-loop supply chain (CLSC) management can be used to achieve competitive advantage and attain sustainable development (Savaskan and Van Wassenhove, 2006). Giuntini and Gaudette (2003) showed that remanufacturing an end-of-life product is 40–60% less expensive compared to manufacturing a brand-new product. To reduce carbon footprints, Coca-Cola has tied up with third party recycler, and Dell and Adidas have started greening their products through advanced technologies (Giri et al., 2018). In a CLSC, as the manufacturer employs environment-friendly technologies for green innovation and pollution reduction, the retailers should also encourage the customers for buying environment-friendly products by explaining their benefits, and setting up outstanding display platforms. Some retailers such as Tesco, Casino, etc. have begun to attach the carbon footprint label with the products to attract the customers. Due to these collective efforts of the manufacturer and the retailer, green vegetables and organic foods, energy star certified home appliances (Best Buy), green cars and buses (in India, Tata Motors launched environment-friendly bus named 'Marcopolo') etc. are gaining attractiveness among the customers, and green supply chain management (GSCM) has become a hot topic to the researchers. This article considers remanufacturing of used products in a closed-loop green supply chain using green innovation effort and marketing effort.

In CLSC, it is necessary for the manufacturer[1] and the retailer to find a suitable reverse channel for the collection of used products

* Corresponding author.
*E-mail addresses:* chirantan.mondal94@gmail.com, chirantan.jumath@gmail.com (C. Mondal), bcgiri.jumath@gmail.com (B.C. Giri).

[1] For the rest of the paper, the manufacturer will be treated as 'he' and the retailer as 'she'.

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# Optimizing price, quality and CSR investment under competing dual recycling channels in a sustainable closed-loop supply chain

Chirantan Mondal*, Bibhas C. Giri

*Department of Mathematics, Jadavpur University, Kolkata 700 032, India*

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Supply chain coordination

A B S T R A C T

This paper deals with pricing, product quality, Corporate Social Responsibility (CSR) investment, and used products collection strategy in a closed-loop supply chain (CLSC) in which both the manufacturer and the retailer contribute to CSR. The market demand is affected by the retail price, product quality and CSR investments. We develop the centralized model (C-Model) and three decentralized models viz. MR-Model, MT-Model, and RT-Model depending on competition between any two of the manufacturer, the retailer and the third-party collector for collecting used products in the reverse channel. A joint revenue-and-cost sharing contract is proposed to address the channel coordination issue. Optimal decisions are derived and compared analytically to determine the most efficient decentralized model, and verified with the help of a real case study. Our study reveals that due to lower product quality, CSR investments, collection rate of used products and higher selling price, the MT-Model is disadvantageous to all channel individuals while the MR-Model gives the best performance under comparatively less competition. The proposed contract can coordinate the supply chain and provide more profit to both the manufacturer and the retailer than their decentralized profits. It is additionally noticed that higher CSR investment, cost savings and collection rate of used products lead to sustainable development.



## Introduction

Over the past few years, due to the widespread attention of consumers towards social and environmental responsibilities, the study of closed-loop supply chain (CLSC) management in the light of Corporate Social Responsibility (CSR) investments turns into a significant area of exploration among academicians and practitioners. For environmental responsibility, one of the major tasks of any supply chain is to monitor the effectiveness of used products. By observing the life-cycle execution of products, organizations formulate an important strategic decision that is remanufacturing. It stems from organizations' intention to get exposure to positive environmental and moral effects which in turn include economic value as well [2,46,13]. The return of used products helps organizations in many ways such as preserving resources for future use, reducing environmental hazards, understanding the gap between expected and actual performances, nature of the usage of products in practice, and establishing a proactive relationship with consumers. Due to several importance of product remanufacturing, in practice, many manufacturing companies such as HP, Dell, Kodak, Canon, Apple, Boeing, Caterpillar, Xerox, etc. have implemented the product remanufacturing strategy into their traditional manufacturing processes [35,45,27]. Previous studies have demonstrated that companies can save up to 40–65% of the cost by managing product remanufacturing activities, which cannot only conserve raw materials economically but also avoid wastage of resources [21,50]. For example, Volkswagen saves 70% from the reuse of used car engines and parts; Xerox saves 40–65% by reusing parts of returned products; Kodak saves 40–60% by using parts of returned cameras, etc. [10]. Since the quality of products made from used products is an important issue, nowadays, in order to ensure the consistent quality of remanufactured products and create an environment-friendly brand image, manufacturers[1] eagerly want to advertise the quality levels of their products. For instance, Samsung Electronics claims that its latest smartphone Galaxy S10 is made by using bio-plastic (for earphone jack,

* Corresponding author.
*E-mail addresses:* chirantanm.math.rs@jadavpuruniversity.in (C. Mondal), bibhasc.giri@jadavpuruniversity.in (B.C. Giri).

[1] For the rest of the article, the manufacturer and the retailer will be treated as 'he' and 'she', respectively.

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Chirantan Mondal
Department of Mathematics
Jadavpur University
Kolkata - 700 032, India

Dear Mr. Mondal,

I am pleased to inform you that your paper co-authored with Bibhas C. Giri entitled, "Coordinating a closed-loop green supply chain for remanufactured product under competition" (Ref. No: SCI-2104-5598), has been accepted as an "Article" for publication in one of the issues of *Scientia Iranica*, Transactions E: Industrial Engineering.

Sincerely Yours,

S. T. A. Niaki

Seyed A. Niaki

**Editor-in-Chief:**
S.T.A. Niaki, Professor
Sharif University of Technology
niaki@sharif.edu

**Sharif University of Technology,** Tehran, Iran
P.O. Box: 11155-8639 | Tel.: (98-21) 66005419 | Fax: (98-21) 66012983
E-mail: scientia@sharif.edu | scientiairanica.sharif.edu

# A comparative analysis of greening policies and CSR efforts in a government-led sustainable supply chain across different channel powers

Chirantan Mondal* and Bibhas C. Giri

Department of Mathematics,
Jadavpur University,
Kolkata – 700032, India
Email: chirantan.mondal94@gmail.com
Email: chirantan.jumath@gmail.com
Email: bcgiri.jumath@gmail.com
*Corresponding author

**Abstract:** This article considers a government-led sustainable supply chain consisting of a manufacturer and a retailer under selling price, greening level and CSR effort dependent market demand. The manufacturer and the retailer are responsible for product greening and CSR, respectively. To stimulate product greening and CSR effort, the government subsidises both of them. The optimal decisions are obtained both analytically and numerically under four game-theoretic policies viz. centralised policy (model C), manufacturer-led decentralised policy (model M), retailer-led decentralised policy (model R) and Nash game (model N). Three special cases are examined by considering that the manufacturer does not produce green products, the retailer does not give any effort in CSR, and both of them do not provide any effort. Our results show that model N provides comparatively better outcome, and each member prefers to lead the channel as it helps to gain higher profit.

**Keywords:** sustainable supply chain; greening level; corporate social responsibility; CSR; government subsidy; game theory.

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**Biographical notes:** Chirantan Mondal is a research scholar in the Department of Mathematics, Jadavpur University, Kolkata, India. He obtained his BS and MS in Mathematics both from University of Calcutta. His area of interest is green supply chain management. He has published papers in *Journal of Cleaner Production*, *Operational Research*, *Flexible Services and Manufacturing Journal* and *RAIRO Operations Research*.

Bibhas C. Giri is a Professor in the Department of Mathematics, Jadavpur University, Kolkata, India. He obtained his MS in Mathematics and PhD in Operations Research both from Jadavpur University, Kolkata, India. His research interests include inventory/supply chain management, production planning and scheduling, reliability and maintenance. He has published more than 100 research papers in the journal of international repute. His papers have appeared in journals such as *Naval Research Logistics*, *International Journal of Production Research*, *OMEGA*, *Journal of the Operational Research Society*, *European Journal of Operational Research*, *International Journal of*

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# INVESTIGATING A GREEN SUPPLY CHAIN WITH PRODUCT RECYCLING UNDER RETAILER'S FAIRNESS BEHAVIOR

Chirantan Mondal* and Bibhas C. Giri

Department of Mathematics
Jadavpur University, Kolkata - 700 032, India

(Communicated by Daniel Oron)

Abstract. Due to the rapid increment of environmental pollution and advancement of society, recently many manufacturing firms have started greening their products and focusing on product remanufacturing. The retailing firms are also taking several efforts for marketing those products and thinking more about the fairness of the business. Keeping this in mind, this study investigates the effect of recycling activity and the retailer's fairness behavior on pricing, green improvement, and marketing effort in a closed-loop green supply chain. In the forward channel, the manufacturer sells the green product through the retailer while in the reverse channel, either the manufacturer or the retailer or an independent third-party collects used products. The centralized model and six decentralized models are developed depending on the retailer's fairness behavior and/or product recycling. The optimal results are derived and compared analytically. The analytical results are verified by exemplifying a numerical example. A restitution-based wholesale price contract is developed to resolve the channel conflicts and coordinate the supply chain. Our results reveal that (i) the manufacturer never selects the third-party as a collector of used products under fair-neutral retailer, (ii) the fairness behavior of the retailer improves her profitability but it diminishes the manufacturer's profit, and (iii) if the manufacturer does not pay much transfer price, then the collection through the third-party is preferable to the fair-minded retailer.

1. **Introduction.** In recent years, rising environmental pollution, government legislations, changes in consumers' purchasing and returning practices, and a competitive business environment are compelling more and more manufacturers to employ in product remanufacturing. Remanufacturing is a large-scale industrial process of collecting used products and reusing them to generate extra qualities (Huang et al. [17]). It not only lessens environmental pollution but also improves the profit of the manufacturer[1] by lowering the utilization of fresh raw materials and saving the production cost. Cost-saving goals may vary from industry to industry. For example, Volkswagen saves 70% from the reuse of used car engines and parts; Xerox saves 40-65% by reusing parts of returned products; Kodak saves 40-60% by using parts of returned cameras, etc. (Genc and De Giovanni [10]). Now, one question may arise - who should collect used products from customers? Generally, manufacturers

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* Corresponding author: Chirantan Mondal.
[1]For the rest of the paper, the manufacturer will be treated as 'he' and the retailer as 'she'.

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ORIGINAL PAPER

# Retailers' competition and cooperation in a closed-loop green supply chain under governmental intervention and cap-and-trade policy

**Chirantan Mondal**[1] · **Bibhas C. Giri**[1]

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## Abstract

This paper investigates retailers' competition and cooperation in a closed-loop green supply chain consisting of one common manufacturer and two competing retailers under governmental intervention and cap-and-trade policy. Considering a consistent pricing strategy of the manufacturer, this study develops one centralized policy and three manufacturer-led decentralized policies viz. Collusion, Cournot (Nash), and Stackelberg depending on different competitive behaviors of the retailers. Optimal decisions are compared analytically through a special case where the retailers face the same basic market, and numerically where they face both the same basic market and different basic markets. A transfer payment mechanism is developed so that all the channel members achieve Pareto improvement. Numerical results indicate that (1) among the three decentralized scenarios, Nash behavior is profitable to the manufacturer, customers, and the whole supply chain, but Collusion behavior is profitable to the retailers only when the difference of their basic markets is small, (2) when the retailers face the same basic market and play Stackelberg game, it is beneficial for the retailers to be follower rather than leader, and (3) occurrence of both the government subsidy and cap-and-trade policy is profitable to all the channel members.

**Keywords** Closed-loop supply chain · Greening level · Pricing policies · Cap-and-trade policy · Governmental intervention

✉ Chirantan Mondal
chirantan.mondal94@gmail.com; chirantan.jumath@gmail.com

Bibhas C. Giri
bcgiri.jumath@gmail.com

[1] Department of Mathematics, Jadavpur University, Kolkata 700 032, India

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# Integrating Corporate Social Responsibility in a closed-loop supply chain under government subsidy and used products collection strategies

**Chirantan Mondal**[1] · **Bibhas C. Giri**[1] · **Sanjib Biswas**[2]

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## Abstract

Due to rapid advancement of the society, recently many manufacturing and retailing companies are showing their interests in Corporate Social Responsibility (CSR) in addition to maximizing their profits. This study introduces CSR activity of the retailer, and develops an integrated model (Model I) and three manufacturer-led decentralized models (Model M, R, and C) depending on different collection options of used products under selling price and CSR effort dependent market demand. The aim of this study is to explore how CSR effort of the retailer can influence the optimal decisions of the supply chain members. In order to stimulate the CSR effort, the government provides CSR dependent subsidy to the retailer. Besides deriving closed-form optimal solutions, this research also determines optimal consumer surplus, environmental damage and social welfare for the proposed models. A comparative study is performed to determine the best sustainable decentralized model. The numerical results show that among the three decentralized models, Model M gives the best performance but fails to challenge with Model I, and government subsidy plays a key role in improving channel performance. A two-part tariff contract is considered to address channel coordination issue. The effects of some key model-parameters on the optimal profitability and the social welfare are investigated through sensitivity analysis, which can help managers to implement CSR activity as well as improve channel performance.

**Keywords** Closed-loop supply chain · Corporate Social Responsibility (CSR) · Government subsidy · Social welfare · Collection rate of used products · Two-part tariff contract

✉ Chirantan Mondal
chirantan.mondal94@gmail.com; chirantan.jumath@gmail.com

Extended author information available on the last page of the article

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ORIGINAL PAPER

# Analyzing a manufacturer-retailer sustainable supply chain under cap-and-trade policy and revenue sharing contract

**Chirantan Mondal**[1] · **Bibhas C. Giri**[1]

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## Abstract

Due to growing public awareness about environment-friendly (green) products, green improvement has become an important factor in supply chain management. This paper deals with a two-echelon sustainable supply chain where both the manufacturer and the retailer are environmentally conscious. Market demand is assumed to be dependent on the selling price and green activities of both the channel members, while the carbon emissions are affected by the greening level of the product. In a make-to-order setting, this paper develops four models, viz. centralized, decentralized, retailer-led revenue sharing and bargaining revenue sharing under the cap-and-trade policy, and compares the optimal outcomes analytically. Numerical examples are taken to investigate the influence of some key model-parameters on optimal decisions. Our results demonstrate that besides improving the greening level of the product, the retailer-led revenue sharing can achieve a win-win situation for both the manufacturer and the retailer. Although the bargaining revenue sharing results in lower profit for the retailer, through promoting the greening level of the product effectively and diminishing the selling price it appears favorable for consumers, the manufacturer and the entire supply chain. Sensitivity analysis illustrates that a higher value of carbon trading cost encourages the manufacturer in improving the greening level and so, reducing the carbon emissions.


**Keywords** Sustainable supply chain · Greening level · Pricing policy · Cap-and-trade policy · Revenue sharing contract

✉ Chirantan Mondal
chirantan.mondal94@gmail.com; chirantan.jumath@gmail.com

Bibhas C. Giri
bcgiri.jumath@gmail.com

[1] Department of Mathematics, Jadavpur University, Kolkata 700 032, India

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ARTICLE



# Investigating strategies of a green closed-loop supply chain for substitutable products under government subsidy

Chirantan Mondal and Bibhas C. Giri

Department of Mathematics, Jadavpur University, Kolkata, India

**ABSTRACT**

This article describes a two-level green closed-loop supply chain including two competing manufacturers and a common retailer for marketing substitutable products under government sponsorship. The primary aim is to explore how the manufacturers set strategies for better outcomes, how the government intervention affects the optimal results and how to enhance supply chain efficiency. It considers various problem scenarios, namely, centralized, Nash game, and manufacturer-led Stackelberg game. Cost sharing (CS) and revenue sharing under cost sharing (RCS) contracts are executed to expand the greening level and execution of the supply chain. Numerical analyses show that (i) Stackelberg game is profitable for the manufacturers while Nash game is favorable for the retailer and the entire supply chain; (ii) CS contract cannot give a win-win outcome but RCS contract assists with accomplishing it; and (iii) the government subsidy can effectively expand the sales volume by enhancing product's greening level.

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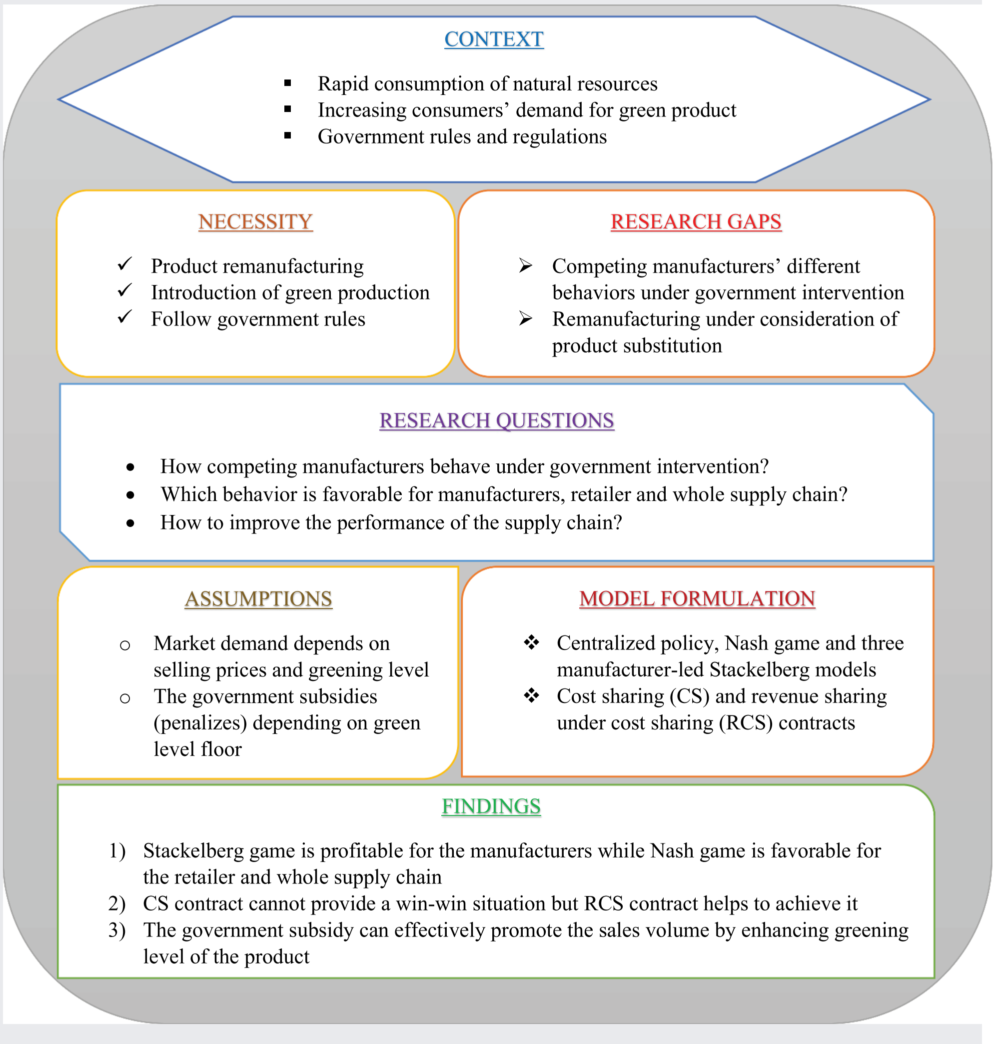


**CONTACT** Chirantan Mondal chirantan.mondal94@gmail.com

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# Analyzing strategies in a green e-commerce supply chain with return policy and exchange offer

Chirantan Mondal *, Bibhas C. Giri

*Department of Mathematics, Jadavpur University, Kolkata 700 032, India*

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ABSTRACT

Due to groundbreaking rise of e-commerce and growing trends of customers' environmental mindfulness, recently, more and more manufacturers are willing to produce eco-friendly products and deliver them through e-commerce platform (EP). Taking into account the product's selling price, greening level, and the EP's service level, this article investigates two types of return policies, viz. refund and replacement policies for defective products and EP's exchange offer in a green e-commerce supply chain. It constructs four decentralized models and determines optimal decisions by using the manufacturer-led Stackelberg gaming approach. Subsequently, a compensation-based profit-sharing contract is designed to investigate channel coordination. Analytical and numerical studies are used to compare and verify optimal decisions. The results show that (a) the replacement policy provides better outcomes compared to the refund policy, (b) the commission is negatively related to the manufacturer's decisions and profit; even a higher commission is not favorable for the EP, (c) besides providing win-win outcomes to both the channel individuals, the proposed contract is capable of enhancing overall performance. This study contributes in finding the best return policy and improving channel performance through the execution of an appropriate contract.

## 1. Introduction

In the last few decades, with the improvement of the global economy, people's lifestyles have been changed drastically. People are creating a lot of greenhouse gas (GHG) to keep themselves comfortable, which is causing various social and natural disasters like earthquakes, heavy rains, floods, desert storms, etc. Today they realize that they need to think of something new to ensure their survival, which drives them in putting more accentuation on utilizing environmentally-friendly products. Governments in both developed and developing countries are also introducing some rules and regulations for reducing GHG emissions (Xu et al., 2017). Increasing natural contamination, government enactments, and changes in buyers' buying practices are convincing an ever-increasing number of manufacturers to green their products (Mondal & Giri, 2021). The introduction of green innovation in production planning assists the companies in obtaining competitive business advantages as well as improving their corporate images (Du et al., 2017; Ghazali et al., 2017). Thus, the study of green supply chain management (GSCM) is attracting more attention from a growing number of scholars. GSCM incorporates the accompanying common topics however not restricted to establishing a low carbon framework, developing a closed-loop supply chain, developing a reverse supply chain, coordinating the channel individuals through proper contracts, executing natural guidelines, etc. (Chai et al., 2018; Gao et al., 2020; Heydari et al., 2021; Jaber et al., 2013; Kumar et al., 2019; Li, Huang et al., 2021; Madani & Rasti-Barzoki, 2017; Zhu & He, 2017).

Green innovation has been perceived as one of the significant factors for financial development and natural assistance (Ranjan & Jha, 2019). It refers to enhancing product compatibility without compromising product performance and quality (Azevedo et al., 2011). Weng et al. (2015) examined a number of literary works and introduced green innovation as software or hardware technology development, new or altered interaction, and authoritative advancement that could help the environment with sustainable development. The manufacturer can incorporate advanced technology during production and recycling, periodically review the product, and enhance the warranty and return policies. So, it needs much research & development (R&D) funds, modern technologies, etc. In this circumstance, the customers' willingness to pay for green products plays a vital role. An overall study by Accenture displays that more than 80% of customers incline towards the products' greening level (GL) while purchasing and they prefer to pay more for these products (Li, Zhang et al., 2019). In reality, there are various scenarios of how companies continue to strive for green innovation. For instance, Shanghai General Motors' "Green Future" strategy has reduced fuel consumption by 13.5%, water consumption

* Corresponding author.
*E-mail addresses:* chirantan.mondal94@gmail.com (C. Mondal), bcgiri.jumath@gmail.com (B.C. Giri).

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# Tax-subsidy or reward-penalty? Determining optimal strategy in sustainable closed-loop supply chain under quality-dependent return

Chirantan Mondal and Bibhas C. Giri

Department of Mathematics, Jadavpur University, Kolkata, India

**ABSTRACT**

In today's competitive business world, focusing solely on financial considerations can limit market demand in any industry. Keeping this in mind, this study deals with a sustainable closed-loop supply chain (CLSC) comprising an environmentally conscious manufacturer, a retailer, and a third-party collector (TPC) under the influence of government intervention. The manufacturer offers a return policy for the defective product up to a certain time, and the TPC offers an acquisition price to consumers for returning their used products. The government can offer no intervention or a tax-subsidy policy in the forward logistics, or a reward-penalty mechanism (RPM) in the reverse logistics, or both. Relying on different government policies, four models are developed first. After that, two collaborative models, viz. manufacturer-retailer collaboration and manufacturer-TPC collaboration, are developed for improving channel performance under the manufacturer-led Stackelberg gaming approach. Numerical results disclose that the government subsidy to consumers provides better functionality to channel individuals, consumers, and the environment. If the government considers imposing a tax, the RPM can help to improve channel execution marginally. A collaborative strategy between the manufacturer and the retailer under government taxation and RPM becomes the most efficient strategy for enhancing the triple bottom line of sustainability.

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Closed-loop supply chain; sustainability; product quality; collection rate of used products; tax-subsidy; reward-penalty mechanism (RPM)

## 1. Introduction

At present, climate change and the depletion of natural resources have made human existence miserable. Scientists and researchers have found that, in most cases, people's daily activities are largely responsible for this. Many agencies, organisations, firms, and factories around the world play a significant role in exploiting the natural resources needed for daily life and their actions have an influence on the population's future existence. The time has come to think about how to deal with these catastrophes and present a cleaner world to future generations. Consumers are also beginning to show their inescapable focus on environmental and social obligations. In achieving these goals, stakeholders have explored a good policy and discovered the concept of sustainability as one of the decent redresses. Sustainability is something that forces a company to think about the triple bottom line. This means that, as a business organisation, a company should look into improving its financial objectives as well as the environmental and social responsibilities for the global interest (Awan et al., 2018; Z. Chen & Andresen, 2014; Sinayi & Rasti-Barzoki, 2018). Environmental responsibilities incorporate improving environmental quality and monitoring the viability of used products. An organisation can improve environmental quality by utilising newer and emerging technologies, less harmful raw materials which can prevent several diseases and pollution, i.e. by establishing an environment that augments peoples' solace and pleasure in living. On the other hand, a firm can monitor the viability of used products through recycling or remanufacturing them. It benefits organisations in a variety of ways, including preserving resources for future use, reducing environmental risks, determining the gap between real and expected effectiveness, and establishing active interactions with customers. For this reason, major manufacturing companies such as HP, Dell, Apple, Samsung, Xerox, Unilever, IBM, and Adidas have started to include remanufacturing in their typical production planning (C.-K. Chen & Akmalul'Ulya, 2019; Wei et al., 2019). Product quality control is crucial when it comes to remanufacturing of used products. So, some big manufacturing companies

**CONTACT** Chirantan Mondal chirantan.mondal94@gmail.com, chirantan.jumath@gmail.com Department of Mathematics, Jadavpur University, Kolkata 700 032, India