IMPACT OF IOT AND REVENUE-SHARING ON SINGLE AND TWO-STAGE PRICING STRATEGIES FOR FOOD SUPPLY CHAINS

by

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Declaration of Authorship

I declare that this thesis is my own work and, to the best of my knowledge and belief, it does not contain any material published or written by a third party, except where permission has been obtained and/or appropriately cited through full and accurate referencing.

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Dedication

To my biggest pillar of support, my sister…

Abstract

With approximately one-third of the global production of food going to waste, immense research efforts are being directed towards identifying the underlying causes and potential solutions of this issue. Since a substantial amount of food waste can be attributed to the quality deterioration of perishable products within the food supply chains (FSC), therefore, one of the primary causes of this issue can be concluded to be inefficient FSCs. To combat this issue, this research examines the potential benefits of using Internet of Things (IoT) technology in the food supply chain within the framework of a two-echelon food supply chain comprising of a supplier and a retailer, and develops mathematical models to study the impact of real-time quality monitoring through IoT on single and two-stage pricing strategies. To this end, a literature review that lays the groundwork for the single and two-stage pricing models, developed in this research, is conducted. The model for each pricing strategy is developed within the decentralized, centralized, and revenue-sharing supply chain structure. The optimal points, used to analyze the individual and collective decisions of the supplier and the retailer, are derived for each model. The results of the numerical analysis indicate that the decision to employ IoT technology depends on the investment cost incurred and its correlation with the critical thresholds for the retailer, supplier, and the overall supply chain. These thresholds are determined through a combination of parameters that include the unit product cost, potential market size, quality deterioration rate, price and quality sensitivity factors, and the initial, organoleptic and critical quality of the perishable food products. Finally, the lower and upper bounds for the retailer's revenue-sharing factor are ascertained, through a combination of the aforementioned parameters and the wholesale price, for an effective coordination that benefits both the supplier and the retailer.

Keywords: ***Perishable food; quality deterioration; IoT; single pricing; two-stage pricing; revenue-sharing.***

Table of Contents

List of Figures

List of Tables

List of Abbreviations

FSC	Food Supply Chain
GSI	Global Stability Index
IoT	Internet of Things
IP	Intelligent Packaging
PQR	Product Quality Risk
QF	Quantity Flexibility
QM	Quality Management
RFID	Radio Frequency Identification
SC	Supply Chain
SCM	Supply Chain Management
SCQM	Supply Chain Quality Management
WSN	Wireless Sensor Network

Chapter 1. Introduction

This chapter provides a short background on the global concerns on food wastage within supply chains followed by the objectives and contributions of this research. In addition, the significance of this research and the organization of the thesis have also been mentioned.

1.1. Food Losses and Waste in the Global Food Supply Chain

Approximately one-third of the food produced globally for human consumption does not reach the end consumer because it is either lost or wasted along the various points in the food supply chain (FSC) [1], [2]. The magnitude of the problem is astounding as 1.6 billion tons of food, equivalent to an estimated worth of $1.2 trillion, is lost or wasted worldwide on an annual basis. Moreover, with the issue mounting incessantly, the yearly food loss and waste is estimated to grow to 2.1 billion tons of food – worth about $1.5 trillion by the year 2030. Additionally, about 8% of the global emissions of greenhouse gases can be attributed to food loss and waste [3]. Therefore, this issue is of paramount importance and there is a dire need to address it to enhance food quality and safety, combat hunger, and reduce the economic and ecological impact [1].

It is imperative to develop an understanding of the difference between food loss, food waste, and food wastage, and the circumstances in which they occur in order to identify the underlying causes and tackle this issue efficiently. Food loss mainly refers to a decrease in quality or mass of edible food originally meant for human consumption. This is usually caused by inefficiencies in the FSCs such as limited technology, poor infrastructure, and lack of coordination among the different actors in the supply chain, and it typically occurs during the stages of post-harvest, production, and processing [1], [4]. On the other hand, food waste refers to the removal of food appropriate for human consumption either through choice, or due to spoilage or expiry. This generally occurs at the end of the supply chain, the retailer and consumer, and is often a consequence of oversupply due to inaccurate market predictions or individual consumer habits [1], [2], [4]. However, food wastage encompasses both food loss and waste as it relates to any amount of food lost by deterioration or waste [4].

1.2. Thesis Objectives

Since food wastage and economic losses due to inefficient food chains is one of the key global concerns nowadays, extensive efforts are underway in an attempt to minimize these issues. The objective of this research is to investigate the effect of IoT and coordination mechanisms on the efficiency of a two-echelon FSC, using single and two-stage pricing strategies. This can be achieved through the following:

- Development and analysis of a mathematical model incorporating real-time information about food quality obtained through IoT will be done within the aforementioned setting.
- Development and analysis of mathematical models under revenue-sharing contracts will be done within the aforementioned setting to investigate the change in optimal pricing. The use of real-time information from IoT to enhance the supply chain contracts will also be studied.

1.3. Research Significance

Food losses or waste occur throughout all the stages of the supply chain – namely production, handling, storage, processing, packaging, distribution, retail and consumption. However, it is most pronounced at the beginning and ending stages of the supply chain, production and consumption. Some of the foremost drivers of the issue have been identified as inappropriate supply chain infrastructure, supply chain inefficiency, and lack of collaboration between the different members of the FSC. The right supply chain infrastructure incorporating advanced solutions could substantially preserve and lengthen the shelf life of food, resulting in a potential annual reduction of food wastage worth \$150 billion annually. Furthermore, adopting digital tools and processes within the supply chain would permit improved demand visibility, food traceability, and dynamic product pricing. This can lead to an improved supply chain efficiency and result in annual food savings worth \$120 billion. Moreover, better coordination mechanisms between the different players involved in the FSC can relieve the world of \$60 billion worth of food waste annually [3].

This thesis contributes to literature by adding an IoT perspective to existing mathematical models for single and two-stage pricing strategies, and also by investigating the impact of coordination through revenue-sharing contracts on the aforesaid models.

1.4. Thesis Organization

The rest of this thesis has been organized as follows: Chapter 2 presents a detailed review of the areas that are closely related to the considered topic of research – supply chain quality management, supply chain contracts, real-time quality monitoring using IoT, and pricing strategies for the FSC. Chapter 3 highlights the development and analysis of the single price FSC model under decentralized, centralized, and coordinated system with the effect of incorporating IoT for quality monitoring purposes. Chapter 4 presents the development and analysis of the two-stage FSC price model within the same settings as aforementioned for the single price model. Finally, Chapter 5 concludes the thesis report and provides recommendations for future research work.

Chapter 2. Literature Review

This chapter encompasses an extensive review on the available literature pertinent to supply chain quality management, supply contracts, pricing strategies for perishable food items, and the use of technology within the food supply chain. Key representative studies and efforts in the aforementioned areas have also been highlighted. The primary objective of this literature review was to study and acquire a comprehension of the underlying concepts and state-of-the-art knowledge to construct the foundation for this research.

2.1. Supply Chain Quality Management (SCQM)

2.1.1. Integration of supply chain management and quality management. As the intensity of global business competition escalates from enterprise level to supply chain level, a higher degree of synchronization between different partners involved in the network has become indispensable to acquire a competitive advantage over competing supply chains [5]. Consequently, the recent emergence of supply chain quality management (SCQM) as an area of research has garnered mounting interest in studies relating to its theoretical framework and implementation. However, a clear comprehension of SCQM necessitates deconstruction of the aforesaid term into the fragments of supply chain management (SCM) and quality management (QM).

SCM encompasses the coordination and synergy of all partners involved in the supply chain network including suppliers, manufacturers, distributors, retailers, customers, and any other intermediaries [6]. Furthermore, collaboration between the various channel partners leads to a superior operational efficiency by coordinating supply with the demand requirement of the customer. As a result, the joint objectives of minimizing the channel-wide costs and maximizing customer satisfaction can be accomplished, bestowing the network with a leveraged strategic standing as opposed to rival supply chains [5], [7].

Alternatively, QM is a management philosophy which is directed towards unremitting process improvements to achieve customer satisfaction. The implementation of internal quality practices gives rise to an enriched quality culture in an organization, which inevitably leads to enhanced organizational efficiency, competitiveness, and sustainability [6]. Moreover, it is a means of acquiring excellence in the products and/or services offered by enhancing organizational performance, improving relationship with suppliers, attaining employee satisfaction, and exceeding customer expectations [5], [6].

The interface between the two domains, SCM and QM (illustrated in Figure 1), demonstrates the parallels and contrasts between the two concepts to highlight the conflation that gives rise to the concept of SCQM. One of the generic dissimilarities between SCM and QM is that both originated from multiple disciplines. SCM transpired from transportation and logistics networks, material distribution, services, and supply base integration amongst others. On the other hand, QM emerged from total quality management to encompass both soft and hard practices, promote a culture of continuous learning and excellence oriented towards the customers, and eliminate any impediments to performance and teamwork. Moreover, another essential difference between the two conceptions is that SCM is predominantly viewed as an external process mostly directed towards upstream actions, whereas QM is regarded as mostly internal operations focused towards the provision of quality products and services, although some external activities may be involved [8].

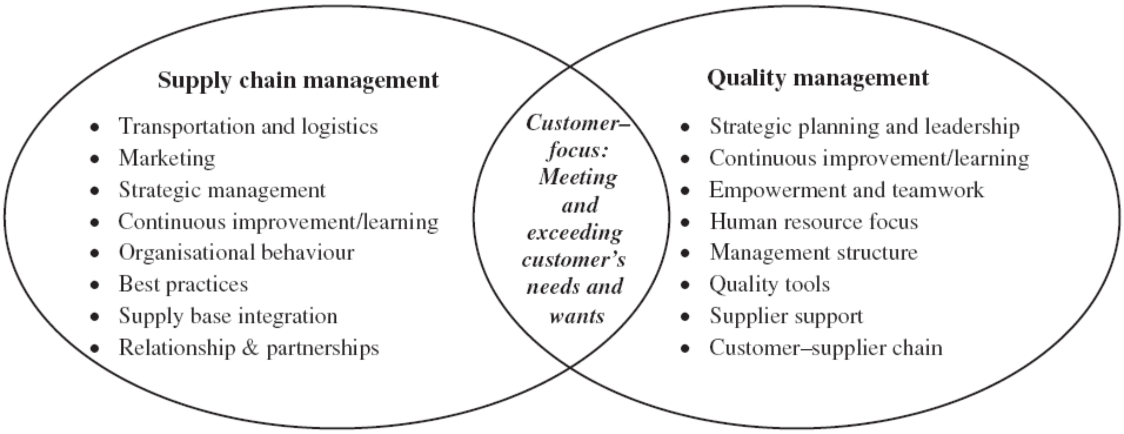

Figure 1: SCM and QM interface [8]

On the contrary, the existence of some evident similarities between SCM and QM point towards the prospects of an amalgam. At the outset, both of the aforementioned concepts emerged within the sphere of operations management and comprise of several interrelated operations that complement each other. The significance of a systems-based outlook of operations is accentuated in both, and both are aimed towards gaining a competitive edge over rivals [5], [8]. Additionally, both involve immense communication and coordination amongst the multiple levels of organization and operations in order to be effectual. Most significantly, customer satisfaction is the focal point of both SCM and QM [8]. Therefore, these similarities provide an interface between the two concepts of SCM and QM, resulting in the advent of the novel concept of SCQM.

2.1.2. Definition of supply chain quality management. With the shift in business competition from a single organization to supply chain, the aforementioned systems-based view of QM becomes applicable to the entire supply chain, which leads to the emergence of SCQM, an integration of SCM and QM principles with their mutual goals of achieving customer satisfaction [5]. Therefore, SCQM can be defined as the formal collaboration and consolidation of each supply chain partner organization's business processes for the continuous measurement, analysis, and improvement of supply chain performance [9]. It seeks to leverage the opportunities created through the coalescence of suppliers, manufacturers, distributors, retailers, and all other intermediaries for the appropriate production and distribution of products and services at minimal cost [10]. Consequently, the established connections between the upstream and downstream flows results in the creation of value, improvement of processes, products, and services, and attainment of satisfaction of the intermediate and end customers [5], [9].

2.1.3. SCQM tools and practices. Several recent studies draw attention towards the practices that lay the groundwork for SCQM and elucidate the nature of this newly formed area of research. While several dissimilar constructs have been identified as vital enablers for SCQM in various studies, these set of shared theories can be abridged into a few core practices: quality leadership, customer focus, supplier focus, information technology, and integration [11].

2.1.3.1. Quality leadership. This practice denotes the managerial activities and decisions pertinent to the formation of a working milieu which facilitates continuous improvement both within and amongst the various firms involved in a supply chain network [11], [12].

2.1.3.2. Customer focus. This construct of SCQM entails considering customers both internal and external to the firm as the ultimate determiners of quality, drivers of business value in the long run, and the primary originators of commercial success. Furthermore, it also refers to the requirement of a proactive and prompt approach of reaching out to the customers to address their requirements and concerns [11].

2.1.3.3. Supplier focus. This fragment necessitates that firms perceive suppliers as indispensable partners of the value chain creation, and that they build a work ecosystem that promotes a synergetic view of quality and growth. This, however, is heavily reliant upon the degree of trust that exists between the different partners involved in all levels of the supply chain [11].

2.1.3.4. Information technology. This idea of SCQM specifies the importance of information sharing and communication using Information Technology (IT) towards the achievement of an optimized quality execution within multi-echelon supply chains. With the ongoing advancement in IT and the advent of Internet of Things (IoT), there are numerous opportunities to automate and ease the integration, analysis, and exchange of massive amounts of data, thus improving the management of supply chain and quality. This entails the creation of an information architecture which, if managed proficiently, provides a competitive advantage to each member of the network through excellence in operational efficacy [11], [13].

2.1.3.5. Integration. Integration insinuates the immense significance of a strong coalition and synchronization between all members of the supply chain for the deployment of an articulate SCM structure contributing towards an improved channel performance [11].

2.2. Supply Chain Contracts

2.2.1. Introduction to supply chain contracts. As aforementioned, SCM entails the management of flow of information, material, and money within an extensive network comprising of suppliers, manufacturers, distributers, retailers, customers, and any other intermediaries involved [14]. These flow exchanges between a pair of network partners are deemed as essential routine affairs since they substantially impact critical supply chain decisions pertinent to the quantity and pricing. The decision maker can either be a single network partner, representing an integrated or centralized supply chain, or there can be multiple decision makers with varying incentives and accessible information, denoting a decentralized supply chain [15], [16].

An ideal situation is considered to be one in which the supply chain comprises of a unique decision maker who optimizes the performance of the entire network by utilizing the information from all the supply chain members. However, decentralized systems are more predominant due to constant upsurge in globalization and outsourced activities, which result in dispersion of the decision-making rights amongst the multiple parties in the network. Consequently, an element of risk is induced to the supply chain performance since information symmetry and coordination amongst the various decision makers become more challenging. Each decision maker may have access to differing private information and incentivize the optimization of a different personal objective function, which may not necessarily be optimal for the entire supply chain. Therefore, the aggregate projected profit from a decentralized supply chain is less than that of a centralized one, since the locally optimal decisions may not be globally optimum for the entire supply chain, resulting in a suboptimal overall performance [15].

As an attempt to facilitate coordination across the network for the provision of adequate private information and incentives, supply chains recourse to formal contracts that propel disclosure of the aforesaid to lead to an improved system-wide performance and facilitate enduring partner relationships [15]. Consequently, a supply chain contract can be described as a coordination mechanism that offers incentives to all the members involved so that the behavior of the decentralized system closely or precisely resembles that of the centralized one [17]. Therefore, supply chain contracts have a threefold objective: optimization of the overall profit of the supply chain; minimization of inventory costs due to overstocks and loss of goodwill due to understocks; and a fair distribution of the risk stemming from uncertainty between the supply chain partners [18], [19]. In this research, contracts enabling the channel coordination of a two-echelon supply chain have been considered within the context of a newsvendor model.

2.2.2. Structure of a single-period supply chain. The supply chain contracts reviewed in this section are based on a single-period supply chain model comprising of two firms – a single upstream supplier with a single downstream retailer – which form the basis for more complex supply chain networks. There is a single selling period with a stochastic market demand, which provides the retailer with a single opportunity to order stock from the supplier prior to the commencement of the selling season [20]. The contractual terms are negotiated and agreed upon by the two firms, after which the retailer places an order to the supplier for a specific product quantity, and the supplier produces the products and sells them to the retailer. The single-period, two-firm supply chain model with the direction of financial, material, and information flow is depicted in Figure 2 below. As illustrated, the information about the product demand flows from the market to the retailer, which is then passed on to the supplier. On the contrary, the material flows from the supplier to the retailer as the former delivers the produced goods to the latter. Finally, the flow of money initiates from the market and goes on to the retailer and the supplier.

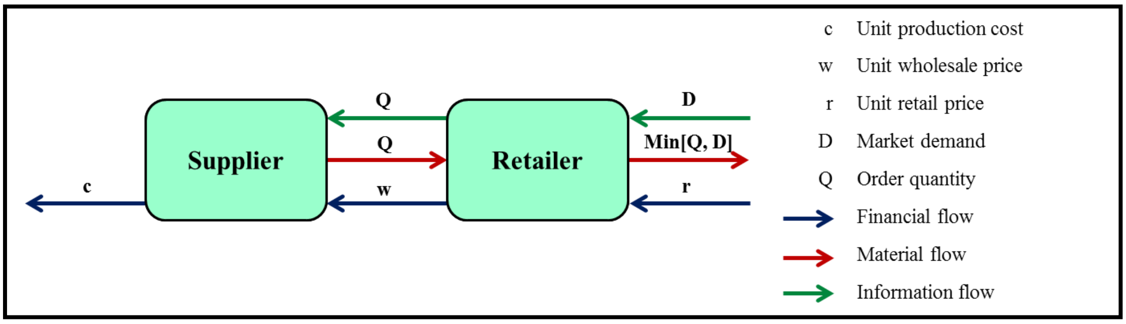

Figure 2: Generic model of single-period supply chain (adapted from [21])

Within the aforesaid single-period framework, the retailer orders a quantity of Q products from the supplier based on the forecasted market demand of the product, D, which is uncertain and subject to price- and quality-sensitivity in actuality. Furthermore, the supplier incurs a constant production cost of c per unit produced, and sells the products to the retailer at a wholesale price of w per unit. Alternatively, the retailer sells the products to its customers at a retail price of r per unit sold and can salvage each unsold product for s per unit[15]. While some models may hold the order quantity, Q, as the paramount decision variable, other models may assume the retail price as the primary decision variable, in which case the demand is commonly presumed to be a deterministic, downward-sloping function [15].

2.2.3. The newsvendor model. As aforementioned, the supply chain contracts discussed within this study have been considered within the framework of a newsvendor model. The classic newsvendor model, also known as the newsboy model, comprises of two entities, one supplier and one retailer subject to a stochastic market demand of a product bearing a brief lifecycle [20], [22]. Moreover, the retailer is presented with a single opportunity to order a product before the beginning of a selling season, after which only that specific ordered quantity can be utilized to fulfil the season’s demand [23]. Therefore, the retailer encounters a newsvendor problem wherein the retailer is required to order a quantity such that it offsets the stochastic customer demand and leads to optimized profits [20].

The events within the newsvendor problem transpire in the below-mentioned chronological order:

- A contract is proffered by the upstream supplier to the downstream retailer.
- The offered contract is either acceded to or declined by the retailer.
- A product order quantity of Q is placed by the retailer to the supplier, based on the supposition that the contract is accepted by the retailer.
- The ordered quantity of products is manufactured by the supplier and shipped to retailer before the selling season begins.
- Commencement of the selling season and materialization of the season market demand take place.
- The transfer payments are settled between the two entities in accordance with the agreed contractual terms. However, in the event that the contract is declined by the retailer, each party receives a default payout and the process does not proceed further [20].

2.2.3.1. The cost function. The foremost step in the newsvendor model is the development of a function to determine all the relevant costs based on the amount of leftover inventory, where the demand is assumed to be a continuous nonnegative random variable D with a cumulative distribution function $F(x)$ and a density function $f(x)$. Furthermore, the decision variable in this model is the number of units Q to be ordered at the beginning of the selling period. The total expected cost comprises of the overage cost c_o, the unit cost of holding the unsold inventory at the end of the selling season, and the underage cost c_u, the unit cost of unsatisfied demand in terms of goodwill loss [23]. The latter incorporates the goodwill penalty cost for each unit of demand left unsatisfied by the supplier g_s and the retailer g_r as depicted below [20]:

$$c_u = g_s + g_r \tag{1}$$

Subsequently, the total expected cost *G(Q)* incurred at the end of the selling season can be expressed as a function of the stochastic demand *D* and order quantity *Q* when *x* units are sold [23]:

$$G(Q) = c_o \int_0^Q (Q - x) f(x) dx + c_u \int_Q^\infty (x - Q) f(x) dx \tag{2}$$

2.2.3.2. The optimal policy. Since the order quantity *Q* is the decision variable, the newsvendor model determines an optimal value of *Q* that minimizes the total expected costs *G(Q)* incurred at the end of the selling season, and thus, maximizes the supply chain profit [23]. This is obtained through the first and second derivatives of the cost function:

$$\frac{dG(Q)}{dQ} = c_o F(Q) + c_u (1 - F(Q)) \tag{3}$$

$$\frac{d^2 G(Q)}{dQ^2} = (c_o + c_u) F(Q) \geq 0 \tag{4}$$

Since the second derivative of the total expected cost is established as nonnegative, the cost function *G(Q)* is determined to be a convex function of *Q* as shown in Figure 3. Therefore, the optimal order quantity *Q** that minimizes the total cost, obtained by equating the first derivative of *G(Q)* to zero, can be expressed in terms of the critical ratio or the critical fractile [23], [24]:

$$F(Q^*) = \frac{c_u}{(c_o + c_u)} \tag{5}$$

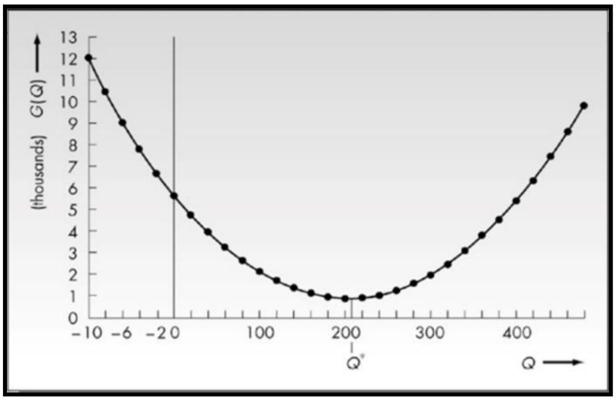

Figure 3: Expected cost function for the basic newsvendor model [23]

2.2.4. Contract types. This subsection provides an overview of the various types of supply chain contracts that have been addressed extensively in contracting literature in view of the aforementioned newsvendor model. Although all contracts are devised to improve the supplier-retailer relationship by fulfilling the joint objectives, they differ based on the incentives offered to prompt the partners towards effective coordination. The evaluation criteria that can be used to assess the potencies and defects of a contract includes the following:

- The level of supply chain coordination, which dictates that none of the partners should have an autonomous incentive to deviate from the supply chain's optimal decisions
- The administrative costs associated with a contract, generally due to information and material flow exchange, which has a direct impact on the efficiency of the specific contract
- The arbitrary sharing of total risk and total supply chain profits to facilitate an impartial allocation of the risk and benefits across the network [15], [20], [25]

2.2.4.1. Wholesale price contract. With a wholesale contract, a supplier sells a singular product to a retailer at wholesale price, w per unit, set by the supplier. The retailer determines the order quantity Q for an optimal stock level, and the arbitrary demand of the product is realized during the selling season. With this contract, the retailer retains the entire revenue generated through the product sales at p per unit but does not have the opportunity to return the unsold products to the supplier. However, the unsold items can be salvaged by the retailer at s per unit [25], [26]. The transfer payment that takes place within this contract is as follows [20]:

$$T_w(Q, w) = wQ \tag{6}$$

Govindan *et al* [27] expressed the profit functions of the retailer and the supplier within a wholesale price contract in terms of the unit production cost to the supplier c_s, marginal cost to the retailer c_r, goodwill costs to the supplier g_s and retailer g_r, salvage costs to the suppler s_s and retailer s_r, and expected sales $S(Q)$ as:

$$\pi_r(Q) = pS(Q) + s_r\big(Q - S(Q)\big) - g_r\big(D - S(Q)\big) - c_rQ - wQ \tag{7}$$

$$\pi_s(Q) = s_s\big(Q - S(Q)\big) - g_s\big(D - S(Q)\big) - c_s Q + wQ \tag{8}$$

Moreover, the total supply chain profit is merely the sum of the retailer and supplier profits, while the optimal order quantity is found by differentiating the profit function of the supply chain as [27]:

$$F(Q^*) = 1 - \frac{c_r + c_s - s_r}{p - s_r + g_r + g_s} \tag{9}$$

2.2.4.2. Buyback contract. Within a buyback contract, the retailer places an order of Q units to the supplier at the beginning of the selling season, the supplier charges the retailer a wholesale price *w* per unit and the retailer sells them in the market at *p* per unit. However, any unsold quantity at the end of the selling season, up to Q units, is bought back by the supplier at a buyback price *b*, which is a fraction of the wholesale price. In this manner, the supplier shares the responsibility and risk of unsold inventory with the retailer [25], [27], [28]. The following transfer payment from the retailer takes place [25]:

$$T_b(Q, w, b) = bS(Q) + (w - b)Q \tag{10}$$

While the optimal order quantity for the supply chain takes the same form as before, the profit functions for the two firms are expressed by Govindan *et al* [27], using the same notations as in the wholesale agreement, as shown below:

$$\pi_r(Q) = pS(Q) + b\big(Q - S(Q)\big) - g_r\big(D - S(Q)\big) - c_r Q - wQ \tag{11}$$

$$\pi_s(Q) = (s_s - b)\big(Q - S(Q)\big) - g_s\big(D - S(Q)\big) - c_s Q + wQ \tag{12}$$

2.2.4.3. Revenue-sharing contract. Under a revenue-sharing contract, the supplier sells the products to the retailer at a discounted wholesale price w_r per unit before the market demand is realized. However, the retailer keeps only a fraction ϕ of the revenue earned at the end of the selling period, while the remaining fraction $(1\text{-}\phi)$ is given to the supplier in return for the lower wholesale price [18], [28]. The following transfer payment takes place:

$$T_r(Q, w_r, \varphi) = (w_r + (1 - \varphi)s_r)Q + (1 - \varphi)(p - s_r)S(Q) \tag{13}$$

Govindan *et al* [27] described the profit functions of the retailer and the supplier, with the same expression for optimal order quantity, as follows:

$$\pi_r(Q) = \varphi\{pS(Q) + s_r(Q - S(Q)) - g_r(D - S(Q))\} - c_rQ - wQ \tag{14}$$

$$\begin{gathered}\pi_s(Q) = (1 - \varphi)\{pS(Q) + s_r(Q - S(Q)) - g_r(D - S(Q))\} \\ -g_s(D - S(Q)) - c_sQ + wQ\end{gathered} \tag{15}$$

2.2.4.4. Quantity flexibility contract. Under the quantity flexibility (QF) contract, the supplier sells the product to the retailer at w_q per unit, but provides compensation to the retailer for losses incurred on unsold units and thus, safeguards the retailer on a portion of the order. Consequently, the supplier sends a credit note of $(w_q + c_r - s_r)min\ (I, \delta Q)$ to the retailer at the end of the sales period where *I* and *Q* are the unsold product and optimal order quantities, respectively, and $\delta \in [0, 1)$ is a contract parameter [20]. Moreover, within this agreement, the retailer is permitted to alter the order quantity as the point of sale approaches and the market demand becomes more visible over time. However, this can only be done within the quantity limits settled upon with the supplier in the contract [28]. The following transfer payment takes place within this agreement [20]:

$$T_q(Q, w_q, \delta) = w_qQ - (w_q + c_r - s_r)\int_{(1-\delta)Q}^{Q} F(y)dy \tag{16}$$

Govindan *et al* [27] defines the retailer and supplier profit functions based on three scenarios differing by demand levels. The first instance considers a demand *D* that is higher than the commitment quantity $(1 - \delta)Q$:

$$\pi_r(Q) = pS(Q) + s_r((1 - \delta)Q - D) - c_r((1 - \delta)Q) - w_q((1 - \delta)Q) \tag{17}$$

$$\pi_s(Q) = -c_s((1 - \delta)Q) + w_q((1 - \delta)Q) \tag{18}$$

The second scenario entails a market demand *D* that exceeds the commitment quantity $((1 - \delta)Q)$ but is less than the optimal order quantity *Q*:

$$\pi_r(Q) = pS(Q) + w_q(Q - D) - c_rQ - w_qQ \tag{19}$$

$$\pi_s(Q) = (s_s - w_q)(Q - D) - c_sQ + w_qQ \tag{20}$$

Finally, the third scenario comprises of a demand *D* that is greater than the optimal order quantity *Q*, and consequently greater than the commitment quantity $((1 - \delta)Q)$:

$$\pi_r(Q) = pS(Q) - g_r\big(D - S(Q)\big) - c_r Q - w_q Q \tag{21}$$

$$\pi_s(Q) = -g_s\big(Q - S(Q)\big)c_s Q + w_q Q \tag{22}$$

2.2.4.5. Sales rebate contract. Within the sales rebate agreement, the supplier sells a product to the retailer at a wholesale price of w_s per unit. During the sales period, when the market demand is realized, the supplier offers the retailer a rebate r for each additional unit sold above a threshold quantity of n units [18]. The transfer payment in this case takes place as follows:

$$T_s(Q, w_s, r, n) = \begin{cases} w_s Q, & Q < n \\ (w_s - r)Q + r(n + \int_n^Q F(y)dy), & Q > n \end{cases} \tag{23}$$

2.2.4.6. Quantity discount contract. Although there are several types of quantity discount contracts, the one highlighted in this section entails an all-unit quantity discount. Under this contract, the supplier sells the product to the retailer at a per unit wholesale price $w_d(Q)$, which is a decreasing function of the order quantity Q [18]. As a result, the wholesale price per unit decreases with increase in the order quantity. The transfer payment associated with this type of contract is:

$$T_q(Q, w_d(Q)) = w_d(Q)Q \tag{24}$$

2.2.4.7. Two-part tariff contract. The two-part tariff contract is a specific instance of the wholesale price contract where the supplier's unit wholesale price w is equivalent to the supplier's unit production cost c_s. Prior to the selling period, the supplier and retailer negotiate and settle on a fixed franchise fee F which is to be paid by the retailer at the end of the period. In this case, the entire risk related to market demand is assigned to the retailer [18]. The transfer payment takes place as follows:

$$T_{w2p}(Q, w) = wQ + F \tag{25}$$

2.3. Quality in the Perishable Food Supply Chain

With excessive amounts of food waste being generated worldwide due to the continuous deteriorating quality characteristic of perishable items, it is essential to explore methods to reduce the amount of food being wasted due to spoilage. One critical aspect to be considered is the inappropriate pricing strategies in the perishable food supply chain which contribute towards more food waste and loss in revenue.

2.3.1. Pricing models. While the contracts and models in the preceding section discussed general product optimal order strategies based on a stochastic customer demand, this subsection will highlight two generally adopted pricing strategies for the perishable food supply with reference to the continuous deterioration of food quality. The same two-echelon model comprising of a single supplier and a single retailer is considered, however, the supplier now sells a perishable food product to the retailer who, in turn, sells them to the end customers.

2.3.1.1. Demand function. A study conducted by Tsiros *et al* [29] on the perception and behavior of consumers towards perishable grocery items revealed that consumer willingness to pay for a product declines as the quality of the product decreases throughout its shelf life. It is expected to decrease linearly for products that have a relatively low associated product quality risk (PQR) such as carrots, lettuce and milk, and it decreases exponentially for those with a comparatively higher PQR attached such as chicken and meat. Therefore, the demand function can be formed to incorporate product price and quality sensitivity using D_o as a non-negative demand parameter that depends on the potential market, α as the price sensitivity factor, β as the quality sensitivity factor, and $p(t)$ and $q(t)$ as price and quality levels, respectively [30], [31]:

$$f(t) = D_o - \alpha p(t) + \beta q(t) \tag{26}$$

The quality level $q(t)$ can be expressed linearly or exponentially in terms of the initial quality q_o and deterioration rate λ as follows [30], [31]:

$$q(t) = q_o - \lambda t \tag{27}$$

$$q(t) = q_o e^{-\lambda t} \tag{28}$$

2.3.1.2. Single pricing model. Considering a simplified case based on representative literature, where the product quality level is determined as a linear function of time, the wholesale price set by the supplier and the retail price set by retailer are studied as the decision variables. Within the single pricing strategy, the retail price per unit $p(t)$ is assumed to be constant at p_1 during the selling period T. The market demand D_1 encountered by the retailer within this model can be expressed as [31]:

$$D_1 = \int_0^T [D_o - \alpha p_1 + \beta(q_o - \lambda t)]dt \tag{29}$$

The retailer is faced by the decision problem to settle on an optimal retail price p_1 such that the retailer profit is maximized, whereas the supplier is required to decide on an optimal wholesale price w_1 that maximizes the supplier profit and offsets the unit production cost c. Therefore, the profit functions for the retailer, supplier, and the entire supply chain within the single pricing model are expressed as follows [31]:

$$\pi_{r1}(p_1) = (p_1 - w_1)\left[(D_o - \alpha p_1 + \beta q_o)T - \frac{1}{2}\beta\lambda T^2\right] \tag{30}$$

$$\pi_{s1}(w_1) = (w_1 - c)\left[(D_o - \alpha p_1 + \beta q_o)T - \frac{1}{2}\beta\lambda T^2\right] \tag{31}$$

$$\Pi_1 = \pi_{r1}(p_1) + \pi_{s1}(w_1) \tag{32}$$

Furthermore, the optimal values for the decision variables, the supplier's wholesale price w_1 and the retailer's market price p_1, can be found from the following expressions [31]:

$$p_1^* = \frac{c\alpha + D_o + \beta q_o}{2\alpha} \tag{33}$$

$$w_1^* = \frac{3c\alpha + D_o + \beta q_o}{4\alpha} \tag{34}$$

2.3.1.3. Two-stage pricing model. Considering the same simplified case of linearly decreasing quality level as the preceding model, the wholesale price, retail price, and price discount time are studied as the decision variables. Within the two-stage pricing strategy, there is a markdown in price after a specific period, therefore, the unit retail price *p(t)* is assumed to be a piecewise function of time p_2, expressed as shown below [31]:

$$p_2(t) = \begin{cases} p_{21}, & 0 < t < T_1 \\ p_{22}, & T_1 < t < T \end{cases} \tag{35}$$

The market demand D_2 encountered by the retailer within this model can be expressed as follows [31]:

$$D_2 = \int_0^{T_1} [D_o - \alpha p_{21} + \beta(q_o - \lambda t)]dt + \int_{T_1}^{T} [D_o - \alpha p_{22} + \beta(q_o - \lambda t)]dt \tag{36}$$

The supplier is faced with the same decision problem as before, which is to decide on an optimal wholesale price w_2 such that it maximizes the supplier profit over the production cost c per unit. However, the retailer is now required to decide on an optimal initial retail price p_{21}, an optimal markdown price p_{22}, and an optimal markdown time T_1 so that the retailer profit is maximized. As a result, the retailer, supplier, and supply chain profit functions are expressed in terms of the markdown cost M as [31]:

$$\begin{aligned}\pi_{r2}(p_{21}, p_{22}, T_1) &= p_{21}\int_0^{T_1}[D_o - \alpha p_{21} + \beta(q_o - \lambda t)]dt \\ &+ p_{22}\int_{T_1}^{T}[D_o - \alpha p_{22} + \beta(q_o - \lambda t)]dt - w_2 D_2 - M\end{aligned} \tag{37}$$

$$\pi_{s2}(w_2) = (w_2 - c)\begin{bmatrix}\displaystyle\int_0^{T_1}[D_o - \alpha p_{21} + \beta(q_o - \lambda t)]dt \\ \displaystyle+\int_{T_1}^{T}[D_o - \alpha p_{22} + \beta(q_o - \lambda t)]dt\end{bmatrix} \tag{38}$$

$$\Pi_2 = \pi_{r2}(p_{21}, p_{22}, T_1) + \pi_{s2}(w_2) \tag{39}$$

Furthermore, the optimal values for the decision variables, the wholesale price w_2, the retail prices p_{21} and p_{22}, and the markdown time T_1 can be determined using the following expressions [31]:

$$p_{21}^* = \frac{6c\alpha + 7D_o + 7\beta q_o}{13\alpha} \tag{40}$$

$$p_{22}^* = \frac{8c\alpha + 5D_o + 5\beta q_o}{13\alpha} \tag{41}$$

$$T_1^* = \frac{4(D_o + \beta q_o - c\alpha)}{13\beta\lambda} \tag{42}$$

$$w_2^* = \frac{10c\alpha + 3D_o + 3\beta q_o}{13\alpha} \tag{43}$$

2.3.2. Food quality deterioration kinetics. Food quality can be described as an aggregation of unique properties that distinguishes one unit from another and directly impacts the consumer's level of acceptability of the particular food product. Food items are faced with continuous quality degradation due to their biologically and physiochemically active nature, and thus, can preserve their required degree of organoleptic qualities for a finite period of time, generally known as the shelf-life of the product. Organoleptic qualities can be defined as food qualities that can be identified by the sense organs, such as color, flavor, odor, and texture. It is essential to determine the levels at which a consumer can detect change in certain quality characteristics or occurrence of undesirable attributes in the food product to identify a cut-off acceptability level that corresponds to the lowest acceptable level of organoleptic quality [32].

2.3.2.1. Principles of reaction modeling. Based on underlying principles of chemical kinetics, a general expression for the rate of food deterioration can be formed based on composition paraments C_i and environmental factors E_j [32]:

$$\frac{dQ}{dt} = F(C_i, E_j) \tag{44}$$

The composition constitutes of factors such as concentration of reactive components, enzymes, inorganic catalysts, water activity, pH, and microbial counts. On the contrary, environmental factors include external aspects such as temperature, humidity, light exposure, pressure of gases, and mechanical stress. However, the impact of these environmental factors is often excluded in the formation of models for simplification. As a result, the rate of deterioration and thus, the change in quality levels can be determined by considering the degradation of crucial constituents, often referred to as characteristic, limiting, or most rapidly changing attributes, to undesirable components. Therefore, the loss rate of a desirable attribute *A* and the formation rate of an undesirable factor *B* can be expressed in terms of the pseudo rate constants *k* and *k'*, and the reaction order *m* and *m'* as follows [32]–[34]:

$$r_A = -\frac{d[A]}{dt} = k[A]^m \tag{45}$$

$$r_B = +\frac{d[B]}{dt} = k'[B]^{m'} \tag{46}$$

Therefore, the quality function of food with respect to the limiting desirable factor *A*, *Q(A)=kt*, can be determined through the integration of the reaction rate for *A*. However, the expression obtained for *Q(A)* varies depending on the order of the reaction with respect to *A*, as shown in Table 1.

Table 1: Quality functions for different pseudo reaction orders (adapted from [32])

Pseudo reaction order *m*	**Quality function *Q(A)***
0	$A_o - A_t$
1	$\ln(A_o/A_t)$
2	$1/A_t - 1/A_o$
m(m≠1)	$\frac{1}{m-1}(A_t^{1-m} - A_o^{1-m})$

Additionally, some of the most important food deterioration processes that involve zero or first order reaction kinetics are listed in Table 2, while the quality loss function for both reaction orders is demonstrated in Figure 4.

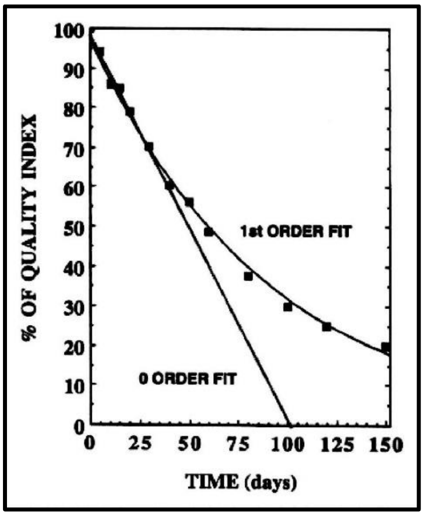

Figure 4: Zero and first order food quality loss as a function of time [32]

Table 2: Typical food degradation processes with zero or first order reactions (adapted from [32])

Pseudo reaction order	**Quality degradation reaction**
Zero	Overall quality of frozen foods
	Nonenzymatic browning
First	Vitamin loss
	Microbial growth/death
	Oxidative color loss
	Texture loss in heat processing

2.3.2.2. Effect of temperature. Although the hitherto highlighted models wherein the effect of environmental factors was negated, these factors significantly affect the deterioration rates and thus, the kinetic models for loss in shelf-life. Consequently, the temperature factor is frequently studied and incorporated into the pseudo reaction rate constant since it strongly influences the rate of degradation. One of the most predominant and universally accepted models used to explore the dependence of quality on temperature is the Arrhenius model [32], [33], [35]:

$$k = A\,exp\left(\frac{-E_a}{RT}\right) \tag{47}$$

The parameter k refers to the pseudo reaction rate constant, A is the pre-exponential factor or Arrhenius constant, E_a is the reaction activation energy, R is the universal gas constant, and T is the absolute temperature. The equation can be linearized as follows [32], [33], [35]:

$$ln\,k = ln\,A - \frac{E_a}{RT} \tag{48}$$

2.3.2.3. Modeling microbial growth. The development of undesirable microbes can cause microbiological changes within a food product which have a direct impact on quality, specifically when it results in the formation of pathogens, which are microorganisms that cause infections and diseases. As a result, the prediction of microbial growth in food is crucial towards the prediction of product shelf-life. One of the most frequently used models for the growth of microorganisms is the modified Gompertz model. This model is expressed in terms of the microorganism count N, the initial count of microorganisms N_o, the asymptotic maximum count of microorganisms A_s, the maximum growth rate μ_{max}, and the lag phase λ [35]:

$$ln\frac{N}{N_o} = A_s \exp\left\{-\exp\left[\frac{\mu_{max}e}{A_s}(\lambda - t) + 1\right]\right\} \tag{49}$$

The exponential growth model can also be used for microbial growth predictions using the absolute temperature T, growth rate μ_{ref} at a reference temperature T_{ref}, activation energy E_a, universal gas constant R, maximum growth rate μ_{max}, and microorganism count N [36], [37]:

$$\frac{dN}{dt} = \mu_{max} N \tag{50}$$

$$\mu_{max} = \mu_{ref}\, exp\left[-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \tag{51}$$

In addition, Baranyi and Roberts [38] formed a dynamic model for the prediction of bacterial growth in food in terms of similar parameters including time *t*, microbial population concentration *x*, maximum bacterial population concentration x_{max}, and concentration *q* of a component critical to bacterial growth [37], [39]:

$$\frac{d}{dt}x = \mu_{max}\left(\frac{q}{q+1}\right)\left(1 - \frac{x}{x_{max}}\right)x \tag{52}$$

$$\frac{d}{dt}q = \mu_{max} q \tag{53}$$

The maximum bacterial growth rate is determined by the square root model using a constant *b*, temperature *T* and a hypothetical minimum temperature T_{min} for growth [37], [39]:

$$\sqrt{\mu_{max}} = b(T - T_{min}) \tag{54}$$

2.3.2.4. Global stability index. Since numerous indices exist for food quality, Achour [34] proposed a method to universally quantify the degradation of physiochemical, microbiological, and organoleptic quality of food using a multi-quality index known as the Global Stability Index (GSI). This index incorporates the variations in all relevant quality criterions in a specific food product with respect to time, and consolidates them into a single parameter. Therefore, the GSI can be useful in the comparison of the deterioration rates and relative stability of dissimilar products stored under similar conditions [34], [40], [41].

The Global Stability Index, GSI_j, varies between zero and one, where a value close to unity indicates that the initial quality is well-maintained and the product is more stable. On the contrary, the stability decreases as the value approaches zero and reflects a decreasing shelf-life of the product. This index can be estimated for *n* criteria by forming an expression based on the variation terms V_{ij} for criterion *i* at *j* time units and the weighing factor α_i which reflects the relative significance of criterion *i* in measuring the quality of the specific food product [34], [40], [41]:

$$GSI_j = 1 - \sum_{i=1}^{n} \alpha_i V_{ij} \tag{55}$$

The variation term V_{ij} for each quality criterion varies between zero and one, and it can be expressed in terms of the observed value C_{ij} of criterion i at j units of time, the initial criterion value C_{io}, and the threshold value L_i of the specific criterion [34], [40], [41]:

$$V_{ij} = \frac{(C_{ij} - C_{io})}{(L_i - C_{io})} \tag{56}$$

2.4. IoT in the Food Supply Chain

The Internet of Things (IoT) paradigm is a network infrastructure that enables internet-based communication and interaction of everyday objects and physical devices embedded with electronics. It facilitates the exchange of information between objects for cooperation and permits remote monitoring and control of the devices [42], [43]. Therefore, IoT can be implemented within the food supply chains in order to reduce the management challenges faced due to the short shelf-lives of perishable food products.

Figure 5 demonstrates the quality changes that occur within the limited lifetime of a perishable product which can be divided into two phases, apparent stability and visible changes.

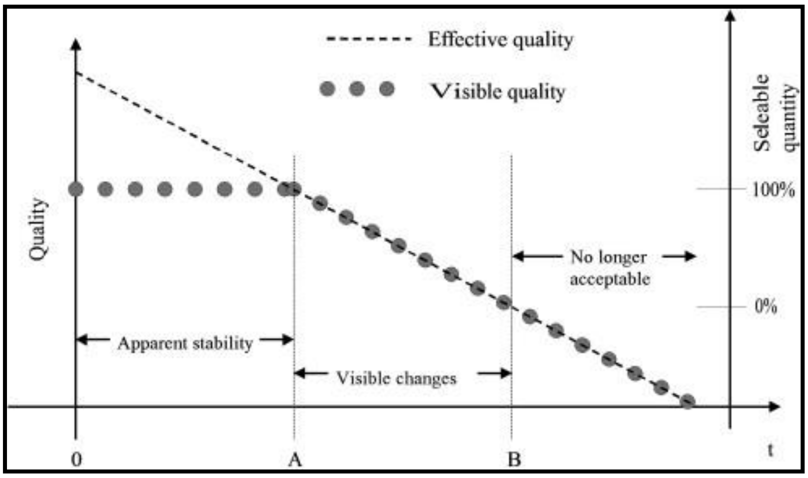

Figure 5: Effective and visible changes in food quality with time [44]

As shown in Figure 5, the optimal food quality is observed at time zero after which it diminishes from time zero to time A but without any noticeable changes.

During this period, there is a decrease in the real quality but the visible or organoleptic quality of the product remains the same. However, observable changes in quality begin to occur from time A until time B, after which the product is rendered unacceptable and the consumers are reluctant to purchase it [44], [45]. Therefore, IoT can be employed in the food supply chain to monitor and detect early signs of indiscernible losses in quality and reduce the amount of food wasted due to deterioration.

2.4.1. Radio frequency identification systems. Radio frequency identification (RFID) is a renowned technology that is widely used for automatic identification of objects and traceability of products within supply chains. It can also be employed for real-time monitoring, identification, shelf life prediction and decision making of perishable food items. As a result, an RFID system is an emerging technological system that is used to transmit an entity's identity wirelessly through radio waves in the form of a unique identification number. It enables readers to automatically capture data on RFID tags which is then converted into a digital form to be embedded into an information system on a computer [46]–[48].

An RFID system constitutes of three major components: a tag, a reader, and a middleware. The tag is a transponder that contains the unique identification number, a miniature antenna connected to a microchip, and a memory chip to store data. It interacts with the reader that is linked to a computer system and emits radio signals to receive a response from the tag. The middleware, on the other hand, connects the RFID system hardware to the applications of the enterprise [47], [48]

2.4.2. Intelligent packaging systems. Intelligent packaging (IP), or smart packaging, is a packaging technology that has the ability to monitor the interactions between the food item, the surrounding environment, and the packaging itself through the use of internal and external indicators, and communicate the information to the user. It is capable of performing multiple intelligent functions such as sensing, detecting, recording, tracking, communicating and using scientific judgment, without exerting an impact on the food. Consequently, these intelligent functions facilitate appropriate decision making for shelf life extension, safety enhancement, quality improvement, provision of information, and early warnings about potential problems [47]–[52].

Although an IP system constitutes of several miniature smart devices to acquire, store, and transfer information, a conventional system comprises of three core technologies: indicators, data carriers, and sensors. Indicators provide information about environmental conditions or the absence or presence of a particular component attributing to food quality. Data carriers such as RFID tags enable the efficient flow of information within the food supply chain, and sensors provide a rapid detection, tracing, and quantification of specific properties and analytes within the food items [47], [51].

2.4.3. Wireless sensor networks. A wireless sensor network (WSN) constitutes of a network of spatially dispersed sensors with the ability to sense, process, and communicate real-time information to a base station effectively and at a reasonable cost. Different types of sensors, such as temperature, vibration, and humidity sensors, can be used in a WSN to sense and monitor the quality of perishable food items within a supply chain. These sensors record information pertinent to the environmental and physical conditions of perishable items, convert it into a digital form, and then communicate it through a gateway to the base station for storage purposes. In turn, the base station uses a mobile network to send the sensor data to a central station. Alternatively, a smartphone can also be utilized as a gateway to collect the sensor data through Bluetooth and transmit it to the base station using wireless communication [46], [48].

2.4.4. Real-life example. In an effort to reduce the amount of post-harvest food wasted in the supply chain, Zest Fresh is a real-life solution developed by Zest Labs, a shelf life and freshness management company. This solution permits proactive monitoring and management of food freshness throughout the supply chain, thus, reducing food waste by 50% and enhancing profit margins by at least 6% [53].

A pioneering freshness management solution in the food industry, Zest Fresh is developed on the basis that most of the issues resulting in fresh food being wasted transpire within the initial 24 to 48 hours post-harvest. The food freshness capacity, also known as the maximum food shelf life, can vary by five or more days depending on the conditions, quality, and time of the food produce from farm to store. As a result, Zest Fresh enables end-to-end visibility of the cold supply chain, at an individual pallet level, for proactive management from the moment the fresh produce is picked to the time it is delivered to the store [53].

Furthermore, Zest Fresh employs the use of wireless IoT temperature sensors, which are embedded inside each pallet at the time of harvest for autonomous data collection and monitoring pertinent to processing and conditions of the produce. The gathered information is merged with machine learning and cloud-based predictive analytics to enhance freshness management at each level of the food supply chain. This solution also incorporates the dynamic Zest Intelligent Pallet Routing (ZIPR) Code, which is a freshness metric used to optimize the management and shipping of produce for improved product freshness, product margins, and consumer satisfaction. This allows pallets with reduced shelf lives to be delivered to stores that are geographically closer to be consumed at an optimal quality before spoilage. Likewise, it also enables prioritization of pallets at the retail end for better delivered freshness, and consequently, reduces the amount of food wasted and improves customer satisfaction [53].

Chapter 3. Single Price Model

This chapter presents the steps involved in the development of the single price model for decentralized, centralized, and coordinated two-echelon supply chains. Each system is developed with and without the use of IoT for continuous food quality monitoring. Numerical analysis to explore the effect of specific parameters on the supply chain profits and decisions has also been presented for each system.

3.1. Assumptions and Notations

The mathematical model for the single pricing strategy is developed grounded on the following assumptions:

1. The two-level perishable food supply chain is comprised of an upstream supplier and a downstream retailer.
2. The retail price and food quality exert an influence on the consumer demand, wherein the demand falls with price and rises with quality.
3. The selling period begins at time t_3 when the retailer receives the food stock from the supplier at quality q_3, and it ends at t_c when the stock reaches the critical quality q_c.
4. The time t_h at which the sensory quality changes begin to occur is also considered as the price markdown time and it is fixed.

The notations used throughout the development of the single price model are exhibited in Table 3, whereas the quality deterioration process followed for the development of the model is shown in Figure 6.

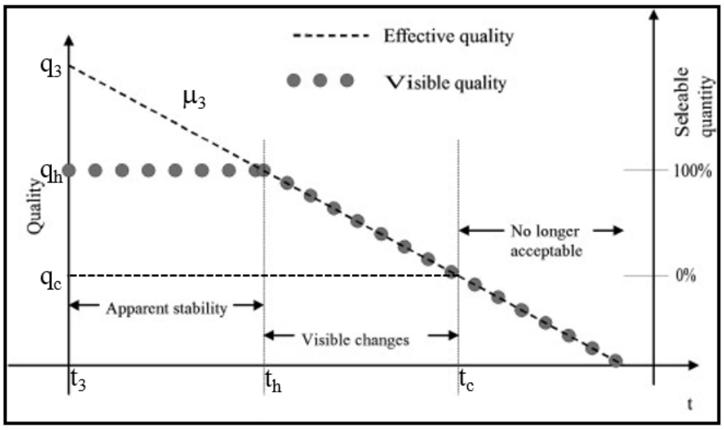

Figure 6: Product quality deterioration process (adapted from [44])

Table 3: Notations for single price model

Notation	Description
D_0	Potential market size
α	Price sensitivity factor
β	Quality sensitivity factor
$p(t)$	Product price at time t
$q(t)$	Product quality at time t
$D(t)$	Demand function at time t
q_3	Initial quality level at retailer
q_h	Highest quality level beyond which organoleptic quality changes occur
q_c	Critical quality level below which the product is considered a waste
μ_3	Instantaneous deterioration rate of food quality at retailer
μ_{31}	Instantaneous deterioration rate at retailer without IoT
μ_{32}	Instantaneous deterioration rate at retailer with IoT
t_3	Time at which the product arrives at retailer
t_h	Time at which organoleptic quality changes begin to occur
t_c	Time beyond which the product is unsaleable due to poor quality
D_1	Demand rate at retailer for single price strategy
c	Unit product cost to supplier
w_1	Unit wholesale price for single price strategy
p_1	Unit retail price for single price strategy
I	Cost to invest in IoT to monitor product quality
I_r	Fixed cost to retailer for investment in IoT
I_s	Fixed cost to supplier for investment in IoT
π_r	Retailer’s profit
π_s	Supplier’s profit
Π	Total supply chain profit
Π_c	Centralized supply chain profit

3.2. Demand Function

As aforementioned, the demand rate is negatively influenced by higher retail prices and positively influenced by improved product quality, therefore, the following demand function is used to derive the single price model:

$$D(t) = D_0 - \alpha p(t) + \beta q(t) \tag{57}$$

3.2.1. No investment in IoT. When the supply chain players do not invest in an IoT infrastructure to monitor and augment product quality, the quality can only be measured when observable changes begin to occur, while any quality changes prior to that are undetectable. Consequently, the quality is assumed to be q_h during the period it appears to be stable, decreasing linearly with time afterwards. Furthermore, the unit retail price remains constant at p_1 throughout the selling period which commences at time t_3 when the product arrives at the retailer. Therefore, the deterministic customer demand for the single price strategy without investment in IoT is mathematically expressed as the following:

$$D_1 = \int_0^{t_h - t_3} \left(D_0 - \alpha p_1 + \beta q_h\right) dt + \int_{t_h - t_3}^{t_c - t_3} \left(D_0 - \alpha p_1 + \beta\left(q_3 - \mu_3 t\right)\right) dt \tag{58}$$

$$D_1 = \frac{1}{\mu_3}\left\{-\frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_1 + \beta q_3\right)\left(q_3 - q_c\right)\right\} \tag{59}$$

3.2.2. Investment in IoT. When the supply chain players invest in IoT to improve discernibility of product quality, the quality can be detected at all times even when visible changes do not occur. As a result, the quality is assumed to be a linearly decreasing function of time throughout the demand period at a constant unit retail price p_1 as mentioned precedingly. Hence, the deterministic customer demand for the single price strategy with deployment of an IoT infrastructure is expressed as follows:

$$D_1 = \int_0^{t_c - t_3} \left(D_0 - \alpha p_1 + \beta\left(q_3 - \mu_3 t\right)\right) dt \tag{60}$$

$$D_1 = \frac{1}{\mu_3}\left\{-\frac{1}{2}\beta\left(q_3 - q_c\right)^2 + \left(D_0 - \alpha p_1 + \beta q_3\right)\left(q_3 - q_c\right)\right\} \tag{61}$$

3.3. Single Price Model for a Decentralized System

The model is initially considered for a decentralized system wherein the supplier and the retailer are both decision makers incentivizing their own personal objectives. The retailer optimizes the retail price p_1 to maximize his profit, which is subsequently used by the supplier to optimize the wholesale price w_1 to maximize his own profit, whereas the supply chain profit is merely a summation of the retailer and supplier profits.

3.3.1. No investment in IoT. For a decentralized system under the single pricing scheme that does not invest in an IoT infrastructure for quality monitoring, the retailer's profit function π_r is a multiplication of his marginal profit with the customer demand as depicted below:

$$\pi_r = \left(p_1 - w_1\right) D_1 \tag{62}$$

$$\pi_r = \frac{\left(p_1 - w_1\right)}{\mu_3}\left\{-\frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_1 + \beta q_3\right)\left(q_3 - q_c\right)\right\} \tag{63}$$

Likewise, the supplier's profit function π_s under the same setting is a product of his marginal profit and the customer demand faced as shown below:

$$\pi_s = \left(w_1 - c\right) D_1 \tag{64}$$

$$\pi_s = \frac{\left(w_1 - c\right)}{\mu_3}\left\{-\frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_1 + \beta q_3\right)\left(q_3 - q_c\right)\right\} \tag{65}$$

Finally, the overall decentralized supply chain profit Π is found by combining the individual profits of the retailer and the supplier as follows:

$$\Pi = \pi_r + \pi_s \tag{66}$$

Through maximization of the retailer and supplier's individual profits, the optimal retail price p_1^* and the optimal wholesale price w_1^* for a decentralized system under the single pricing strategy that does not invest in IoT deployment are determined as the following:

$$p_1^* = \frac{-3\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + 6\left(D_0 + \beta q_3\right)\left(q_3 - q_c\right)}{8\alpha\left(q_3 - q_c\right)} + \frac{c}{4} \tag{67}$$

$$w_1^* = \frac{-\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + 2\left(D_0 + \beta q_3\right)\left(q_3 - q_c\right)}{4\alpha\left(q_3 - q_c\right)} + \frac{c}{2} \tag{68}$$

This reveals that the retailer's optimal price p_1^* and the supplier's optimal wholesale price w_1^* exist within this setting and are unique. Additionally, it is observed that these optimal prices are not affected by the deterioration rate.

3.3.2. Investment in IoT. Within a decentralized system that invests in IoT for enhanced visibility and control of product quality, the retailer's profit π_r is a product of his marginal profit and the consumer demand with a deduction of the fixed cost I_r that the retailer expends on IoT as demonstrated below:

$$\pi_r = (p_1 - w_1) D_1 - I_r \tag{69}$$

$$\pi_r = \frac{(p_1 - w_1)}{\mu_3} \left\{ -\frac{1}{2}\beta (q_3 - q_c)^2 + (D_0 - \alpha p_1 + \beta q_3)(q_3 - q_c) \right\} - I_r \tag{70}$$

Similarly, the supplier's profit function π_s under the same aforementioned situation is a multiplication of his marginal profit with consumer demand and a fixed cost I_s for investing in IoT as presented below:

$$\pi_s = (w_1 - c) D_1 - I_s \tag{71}$$

$$\pi_s = \frac{(w_1 - c)}{\mu_3} \left\{ -\frac{1}{2}\beta (q_3 - q_c)^2 + (D_0 - \alpha p_1 + \beta q_3)(q_3 - q_c) \right\} - I_s \tag{72}$$

Finally, the overall profit for this decentralized supply chain Π is computed as an addition of retailer and supplier profits as shown below:

$$\Pi = \pi_r + \pi_s \tag{73}$$

As in the preceding system without IoT investment, the optimal retail price p_1^* and optimal wholesale price w_1^* for a decentralized system under the single price policy with IoT deployment are obtained through individual profit maximization as follows:

$$p_1^* = \frac{6D_0 + 3\beta(q_3 + q_c)}{8\alpha} + \frac{c}{4} \tag{74}$$

$$w_1^* = \frac{2D_0 + \beta(q_3 + q_c)}{4\alpha} + \frac{c}{2} \tag{75}$$

As in the previous setting, the optimal retail price p_1^* and the optimal wholesale price w_1^* exist, are unique, and are not affected by the quality deterioration rate.

3.3.3. Critical thresholds for IoT investment. Since investing in an IoT infrastructure enables better visibility into product quality, it also aids in improving the quality itself by providing more control over the rate at which the food products degenerate. Consequently, investing in IoT would lead to a reduced deterioration rate, which, in turn, would hypothetically result in a better financial performance for the supply chain. However, whether utilizing IoT delivers profits superior to those that are earned when IoT is not employed is determined by the investment cost I and its relation with certain investment critical thresholds.

Foremost, in order for IoT to prove beneficial for the retailer, his investment I_r must be lower than his critical investment threshold I_R. This threshold is determined by computing the difference between the retailer's profits when the initial deterioration rate μ_{31} is reduced to μ_{32} using IoT and equating it to zero, as expressed below:

$$I_R = \frac{\left\{ \begin{array}{l} \left(\dfrac{1}{\mu_{32}} - \dfrac{1}{\mu_{31}} \right) \left[\beta^2 (q_3 - q_c)^4 - 4\beta (D_0 + \beta q_3 - \alpha c)(q_3 - q_c)^3 + 4(D_0 + \beta q_3 - \alpha c)^2 (q_3 - q_c)^2 \right] \\ - \left(\dfrac{\beta (q_3 - q_h)^2}{\mu_{31}} \right) \left[\beta (q_3 - q_h)^2 + 2\beta (q_3 - q_c)^2 - 4(D_0 + \beta q_3 - \alpha c)(q_3 - q_c) \right] \end{array} \right\}}{64\alpha (q_3 - q_c)} \tag{76}$$

If the retailer's investment is less than his critical threshold ($0 < I_r < I_R$), then the retailer reaps more profits with investment in IoT. On the contrary, if his investment exceeds the critical threshold ($I_r > I_R$), then investing in IoT is not justified for the retailer since it does not deliver additional profit.

Likewise, IoT would only be advantageous to the supplier if the supplier's investment I_s is lower than the supplier's critical threshold I_S. This threshold, obtained in a similar manner to the retailer by finding the difference between the supplier's profits without IoT at a deterioration rate μ_{31} and with IoT at a reduced deterioration rate μ_{32}, is determined as the following:

$$I_S = \frac{\left\{ \begin{array}{l} \left(\dfrac{1}{\mu_{32}} - \dfrac{1}{\mu_{31}} \right) \left[\beta^2 (q_3 - q_c)^4 - 4\beta (D_0 + \beta q_3 - \alpha c)(q_3 - q_c)^3 + 4(D_0 + \beta q_3 - \alpha c)^2 (q_3 - q_c)^2 \right] \\ - \left(\dfrac{\beta (q_3 - q_h)^2}{\mu_{31}} \right) \left[\beta (q_3 - q_h)^2 + 2\beta (q_3 - q_c)^2 - 4(D_0 + \beta q_3 - \alpha c)(q_3 - q_c) \right] \end{array} \right\}}{32\alpha (q_3 - q_c)} \tag{77}$$

If the supplier's contribution to the IoT investment is less than his critical threshold ($0 < I_s < I_S$), then the he earns increased profits with IoT. On the other hand, if the investment surpasses the critical threshold ($I_s > I_S$), then investing in IoT is not validated for the supplier since he gains more profits without it.

Finally, the retailer and supplier's aggregated investment I would only be justified if it falls within the supply chain's critical investment threshold I_T. This threshold is found by obtaining the difference between the total supply chain profits with and without IoT, or by simply adding up the supplier and retailer's critical thresholds, as follows:

$$I_T = \frac{3\left\{ \begin{array}{l} \left(\dfrac{1}{\mu_{32}} - \dfrac{1}{\mu_{31}} \right) \left[\beta^2 (q_3 - q_c)^4 - 4\beta (D_0 + \beta q_3 - \alpha c)(q_3 - q_c)^3 + 4(D_0 + \beta q_3 - \alpha c)^2 (q_3 - q_c)^2 \right] \\ - \left(\dfrac{\beta (q_3 - q_h)^2}{\mu_{31}} \right) \left[\beta (q_3 - q_h)^2 + 2\beta (q_3 - q_c)^2 - 4(D_0 + \beta q_3 - \alpha c)(q_3 - q_c) \right] \end{array} \right\}}{64\alpha (q_3 - q_c)} \tag{78}$$

If the decentralized system's total IoT investment is lower than its critical threshold ($0 < I < I_T$), then the supply chain benefits from IoT with increased profits. However, if the investment goes above the critical threshold ($I > I_T$), then investing in IoT is not rationalized for the supply chain.

3.3.4. Numerical analysis. A numerical example is presented in order to evaluate the impact of various parameters on the decentralized system investments within the single pricing strategy. For consistency, parameter values are assigned as exhibited in Table 4, wherein the values for the initial quality deterioration rate without IoT μ_3, the initial quality at the retailer q_3, the potential market size D_0, the price sensitivity factor α, the quality sensitivity factor β, and the unit product cost c are taken from prior work in literature [31].

Table 4: Initial parameter assignment

μ_3 (/hr)	q_3	q_h	q_c	D_0 (units/hr)	α	β	c ($/unit)
0.0067	0.95	0.60	0.30	9.79	1.83	1.83	3.99

3.3.4.1. Effect of quality deterioration rate on profits. In order to analyze the effect of reducing the deterioration rate using IoT on the decentralized system's profits, the individual and overall system profits are initially computed for various deterioration rates without including the cost of investment. As shown in Table 5, the initial deterioration rate of 0.0067/hr is reduced to rates varying from 0.006/hr to 0.003/hr, followed by calculating the supplier, retailer, and total supply chain profits at each deterioration rate. Subsequently, the percentage difference in each of the profits is calculated as compared to the original rate of 0.0067/hr, also shown in Table 5.

Table 5: Effect of reducing deterioration rate on decentralized profits

μ_3 (/hr)	π_s ($)	$\Delta\pi_s$ (%)	π_r ($)	$\Delta\pi_r$ (%)	π ($)	$\Delta\pi$ (%)
0.0067	79.314	0.00%	39.657	0.00%	118.971	0.00%
0.006	97.617	23.08%	48.808	23.08%	146.425	23.08%
0.0055	106.491	34.26%	53.246	34.26%	159.737	34.26%
0.005	117.140	47.69%	58.570	47.69%	175.710	47.69%
0.0045	130.156	64.10%	65.078	64.10%	195.234	64.10%
0.004	146.425	84.61%	73.213	84.61%	219.638	84.61%
0.0035	167.343	110.99%	83.672	110.99%	251.015	110.99%
0.003	195.234	146.15%	97.617	146.15%	292.850	146.15%

As represented in Table 5 and Figure 7, when the deterioration rate of food products is reduced, the retailer and supplier gain higher profits, and thus, so does the overall supply chain. It is also observed that the retailer and supplier have the same percentage increase in profits from the decreased decay rates. Therefore, the cost to invest must be distributed equally between the two entities as demonstrated below:

$$I_r = I_s = 0.5I \tag{79}$$

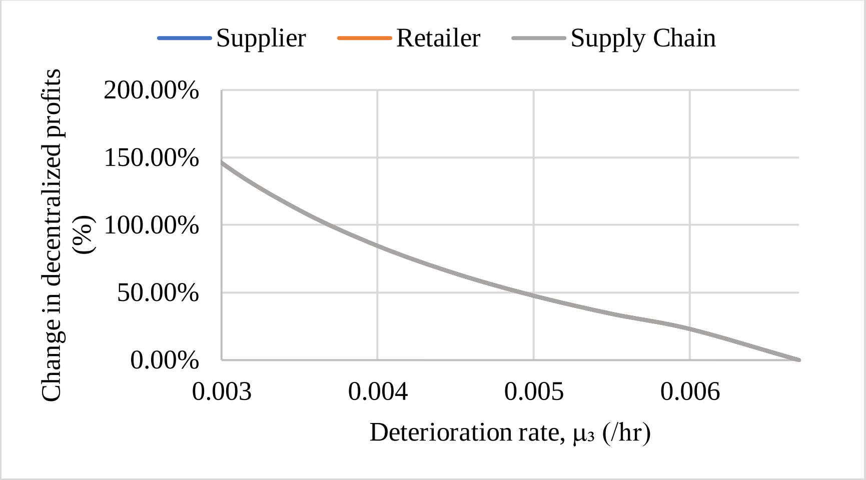

Figure 7: Effect of reducing deterioration rate on decentralized profits

3.3.4.2. Effect of initial quality. Considering an initial deterioration rate μ_{31} of 0.0067/hr as used before and a specific reduced deterioration rate μ_{32} of 0.004/hr, the effect of the initial quality level at the retailer q_3 is studied on the critical investment thresholds established earlier for the retailer I_R, supplier I_S, and the overall decentralized supply chain I_T.

As illustrated in Figure 8, the initial quality level is varied from 0.60 to 1.00, with the three critical thresholds calculated at each level. It is discerned that an increase in initial quality, which reflects the value of the perishable food products, will increase the three critical thresholds I_R, I_S, and I_T. Furthermore, it is recognized that the retailer has a lower threshold than the supplier at each value, while the supply chain threshold is higher than both since it is an accumulation of the two.

Therefore, as shown in Figure 8, if the retailer and supplier's individual investment costs, earlier determined to be equal, are less than I_R, both the retailer and the supplier will gain more profits by investing in IoT. Moreover, if the investment contributions are greater than I_R but less than I_S, only the supplier will benefit from investing in IoT as the retailer will have lower profits with IoT. However, if the individual investment exceeds I_S, then neither the supplier nor the retailer will benefit from investing in IoT.

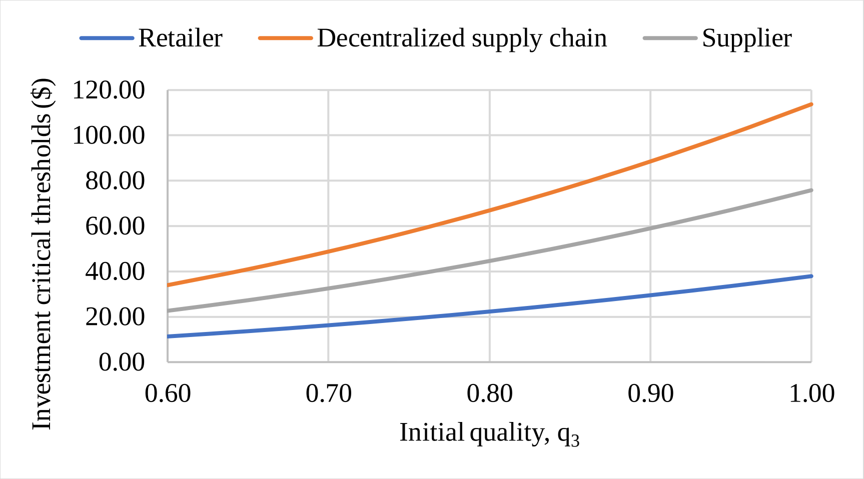

Figure 8: Effect of initial quality on investment thresholds for decentralized system

3.3.4.3. Effect of relative elasticity. The relative elasticity α/β, a ratio of the price sensitivity factor over the quality sensitivity factor, measures the relative influence of price and quality on consumer demand for perishable products. A ratio greater than 1, i.e. $\alpha/\beta > 1$, indicates that the price has a stronger impact on demand as compared to quality, whereas the opposite is true for a ratio less than 1, i.e. $\alpha/\beta < 1$.

Initially, the effect of relative elasticity on the decentralized system profits at the reduced deterioration rate of 0.004/hr, not inclusive of the fixed IoT cost, is studied by varying the ratio between 0.001 and 0.01. As illustrated in Figure 9, when the ratio is substantially low, the profits are relatively higher as opposed to when the ratio is higher. This signifies that both the retailer and the supplier gain more profits when the demand is more sensitive to quality as compared to price. On the contrary, the profits decrease significantly as the demand's sensitivity to price increases.

Moreover, the effect of relative elasticity is also examined on investment critical thresholds of the decentralized system at the improved deterioration rate of 0.004/hr, with the ratio varied from 0.001 to 0.01 as before. Figure 10 demonstrates that when the elasticity ratio is lower than 0.002, the critical thresholds for both the retailer and the supplier are high. Therefore, it does not necessarily require very low costs of investment for the system to benefit from IoT when the demand is much more sensitive to quality as compared to price. Conversely, both the thresholds decline significantly when the ratio increases above 0.002 and the influence of price begins to strengthen.

Therefore, it is more likely for the entire supply chain to benefit from not investing in IoT when the customer demand is more sensitive to price relative to quality.

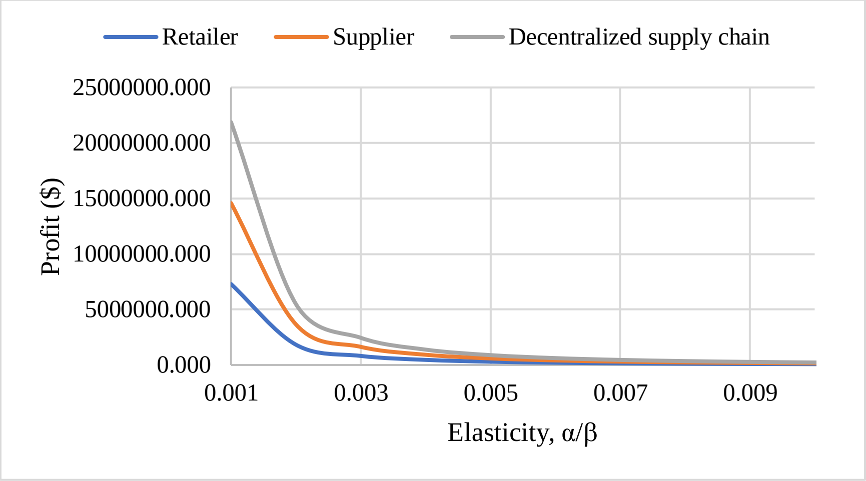

Figure 9: Effect of relative elasticity on decentralized profits

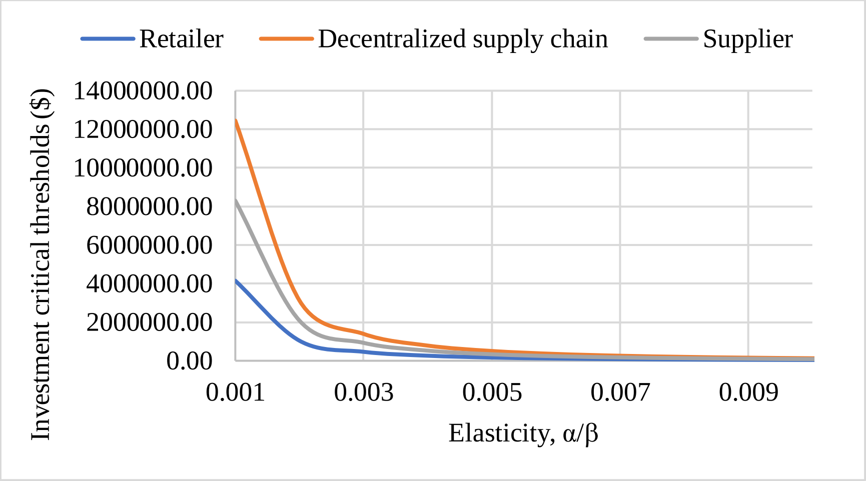

Figure 10: Effect of relative elasticity on investment thresholds for decentralized system

3.4. Single Price Model for a Centralized System

In order to optimize the performance of the supply chain, the model is also examined for a centralized system in which there is a unique decision maker incentivizing the objectives of the integrated supply chain. The unified network optimizes the unit retail price p_1 in order to maximize the aggregated profit of the supply chain.

3.4.1. No investment in IoT. For a centralized system following the single price strategy without employing IoT to track quality, the function for the collective supply chain profit Π_c is a product of its marginal profit, i.e. the difference between the unit retail price and product cost per unit, and the customer demand as shown subsequently:

$$\Pi_c = (p_1 - c)D_1 \tag{80}$$

$$\Pi_c = \frac{(p_1 - c)}{\mu_3}\left\{-\frac{1}{2}\beta\left[(q_3 - q_h)^2 + (q_3 - q_c)^2\right] + (D_0 - \alpha p_{c1} + \beta q_3)(q_3 - q_c)\right\} \tag{81}$$

Unlike the decentralized system, the optimal retail price p_1^* for a centralized system under the single price approach that does not benefit from IoT is determined via maximization of the total network profit, as expressed below:

$$p_1^* = \frac{-\beta\left[(q_3 - q_h)^2 + (q_3 - q_c)^2\right] + 2(D_0 + \beta q_3)(q_3 - q_c)}{4\alpha(q_3 - q_c)} + \frac{c}{2} \tag{82}$$

This illustrates that the retailer's optimal price p_1^* within this centralized setting exists and is unique. Moreover, it is also observed it is not affected by the deterioration rate.

3.4.2. Investment in IoT. A centralized system that capitalizes in IoT for better food quality has an overall profit Π_c that is found by multiplying its marginal profit with the respective customer demand, and then deducting the fixed amount I_c invested in the IoT infrastructure as illustrated below:

$$\Pi_c = (p_1 - c)D_1 - I_c \tag{83}$$

$$\Pi_c = \frac{(p_1 - c)}{\mu_3}\left\{-\frac{1}{2}\beta(q_3 - q_c)^2 + (D_0 - \alpha p_{c1} + \beta q_3)(q_3 - q_c)\right\} - I_c \tag{84}$$

Similar to the previous system without IoT, the optimal retail price p_1^* for a centralized system employing the single price rule and deploying IoT is attained through maximization of the collective supply chain profit as the following:

$$p_1^* = \frac{-\beta(q_3 - q_c) + 2(D_0 + \beta q_3)}{4\alpha} + \frac{c}{2} \tag{85}$$

As before, the retailer’s optimal retail price p_1^* exists within this setting, is unique, and is independent of the quality deterioration rate.

3.4.3. Critical thresholds for IoT investment. Just as in the decentralized system, a centralized system can theoretically improve its financial performance by capitalizing on IoT resources to reduce the rate at which the products deteriorate. However, the cost of investment I must be within a specific investment critical threshold I_C, which is obtained through the difference between the centralized supply chain profits when IoT is not used with a higher decay rate of μ_{31} versus when IoT is employed to bring the rate down to μ_{32} as demonstrated below:

$$I_C = \frac{\left\{ \begin{array}{l} \left(\frac{1}{\mu_{32}} - \frac{1}{\mu_{31}}\right)\left[\beta^2 (q_3 - q_c)^4 - 4\beta(D_0 + \beta q_3 - \alpha c)(q_3 - q_c)^3 + 4(D_0 + \beta q_3 - \alpha c)^2 (q_3 - q_c)^2\right] \\ -\left(\frac{\beta(q_3 - q_h)^2}{\mu_{31}}\right)\left[\beta(q_3 - q_h)^2 + 2\beta(q_3 - q_c)^2 - 4(D_0 + \beta q_3 - \alpha c)(q_3 - q_c)\right] \end{array} \right\}}{16\alpha(q_3 - q_c)} \tag{86}$$

If the centralized system’s investment cost is below its critical investment threshold ($0 < I < I_C$), it gains higher profits with the deployment of IoT. Contrarily, investing in IoT is not beneficial for the system if goes over the threshold ($I > I_C$).

3.4.4. Numerical analysis. As earlier, a numerical example is presented to analyze the effect certain parameters have on the investment decisions of the centralized system using the single price strategy. The parameter assignments are the same as those within the decentralized system (refer to Table 4).

3.4.4.1. Effect of centralization. In order to analyze the effect of centralization on the supply chain, the overall supply chain profits for the decentralized system are compared to those of the centralized system at different deterioration rates, without including the fixed IoT investment cost. As presented in Table 6, the quality deterioration rate is reduced from 0.0067/hr to several values down to 0.003/hr, followed by computing the decentralized profit $\prod$ and centralized profit $\prod_c$ at each rate. The percentage difference between the two profits $\Delta\prod$ is then determined for each deterioration rate.

Table 6: Difference between decentralized and centralized supply chain profits at varying deterioration rates

μ_3 (/hr)	**π ($)**	**π_c ($)**	**$\Delta\pi$ (%)**
0.0067	118.971	158.628	33.33%
0.006	146.425	195.234	33.33%
0.0055	159.737	212.982	33.33%
0.005	175.710	234.280	33.33%
0.0045	195.234	260.312	33.33%
0.004	219.638	292.850	33.33%
0.0035	251.015	334.686	33.33%
0.003	292.850	390.467	33.33%

As indicated in Table 6 and Figure 11, at each deterioration rate, the total profit of the centralized system is always higher than the decentralized system by 33.33%. This is observed without IoT when the deterioration is 0.0067/hr, and also with the use of IoT to reduce the rate to several different values. Therefore, the system always benefits with increased profits through centralization.

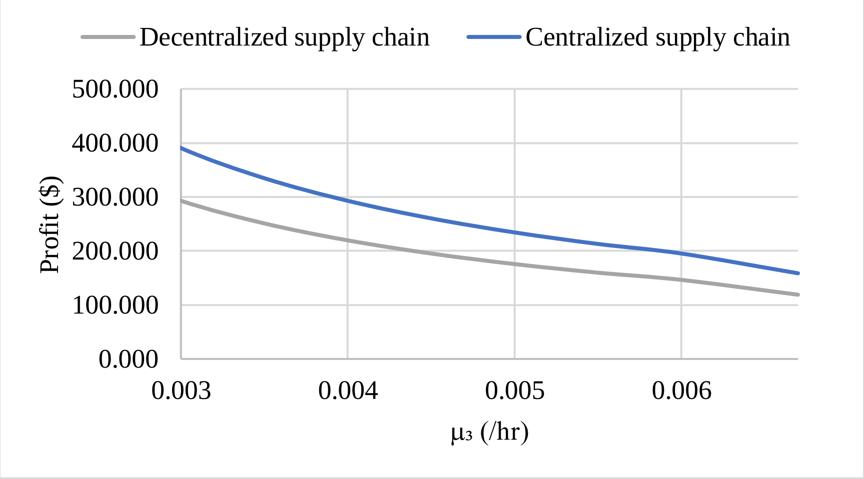

Figure 11: Decentralized and centralized supply chain profits at varying deterioration rates

3.4.4.2. Effect of quality deterioration rate on profit. As in the decentralized system, in order to examine the impact of reduced deterioration rates through IoT deployment on the centralized system, the supply chain profits, not inclusive of investment costs, are calculated for various deterioration rates. As exhibited in Table 7, the initial deterioration rate of 0.0067/hr is brought down to several rates between 0.006/hr and 0.003/hr, which is followed by computing the centralized profit $\prod_c$ and the percentage difference in profit $\Delta\prod_c$ comparative to the initial rate.

Table 7: Effect of reducing deterioration rate on centralized profit

μ_3 (/hr)	**π_c (\$)**	**$\Delta\pi_c$ (%)**
0.0067	158.628	0.00%
0.006	195.234	23.08%
0.0055	212.982	34.26%
0.005	234.280	47.69%
0.0045	260.312	64.10%
0.004	292.850	84.61%
0.0035	334.686	110.99%
0.003	390.467	146.15%

As illustrated in Table 7 and Figure 12, the supply chain earns higher profits when the deterioration rate is reduced, with the percentage increase in profits being the same as those of the decentralized system (refer to Table 5) at each deterioration rate.

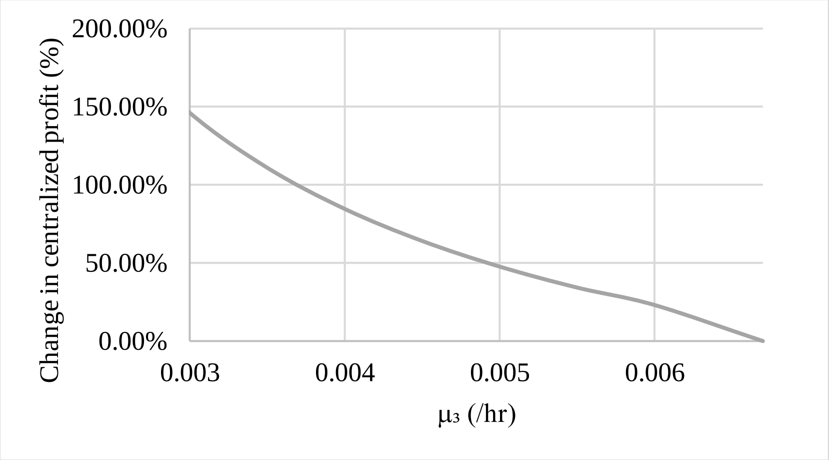

Figure 12: Effect of reducing deterioration rate on centralized profit

3.4.4.3. Effect of initial quality. As in the decentralized system, the effect of the initial quality level q_3 on the investment critical threshold I_C of the centralized system is analyzed by assuming initial and reduced deterioration rates μ_{31} and μ_{32} of 0.0067/hr and 0.004/hr, respectively, as used earlier.

As displayed in Figure 13, the critical investment threshold is computed for varying initial quality levels between 0.60 and 1.00, and it is observed that the investment threshold becomes higher as the initial quality increases. Therefore, the centralized supply chain is more likely to benefit from investing in IoT at higher levels of initial quality.

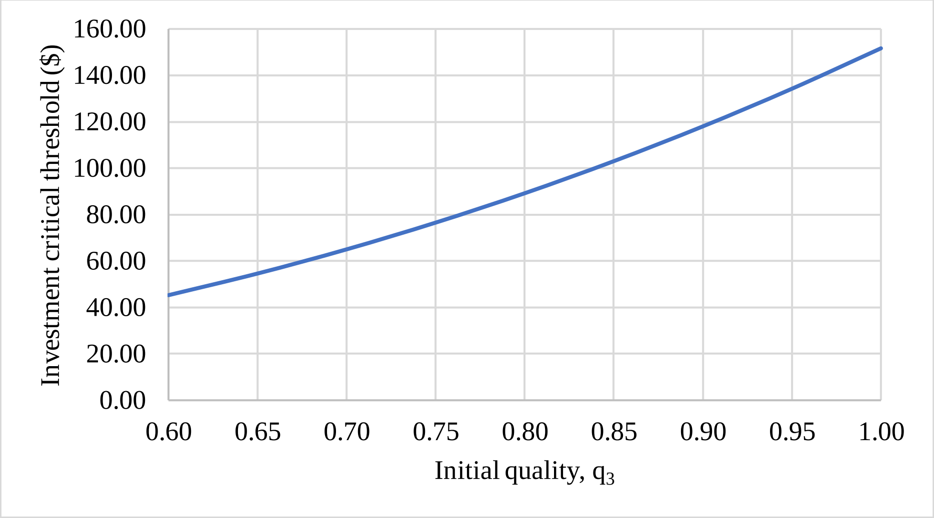

Figure 13: Effect of initial quality on investment threshold for centralized system

3.4.4.4. Effect of relative elasticity. As in the preceding system, the influence of the relative elasticity ratio α/β on the centralized system profit is studied, without including IoT cost, by varying the ratio from 0.001 to 0.01 at a reduced quality deterioration rate of 0.004/hr. Figure 14 reveals a trend similar to the decentralized system, wherein the supply chain earns higher profits when the elasticity ratio is substantially low, and it generates considerably lower profits as the ratio increases beyond 0.002. This implies that the centralized supply chain network reaps more profits when the consumer demand has a higher sensitivity to product quality relative to product price.

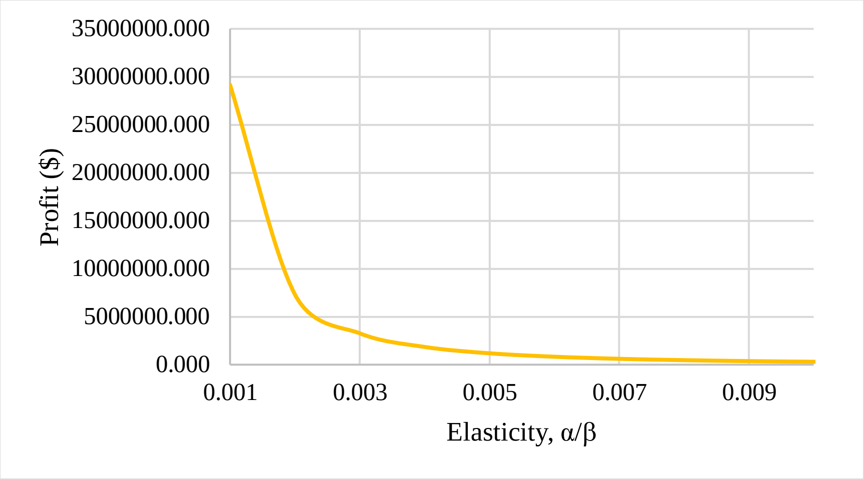

Figure 14: Effect of relative elasticity on centralized profit

Furthermore, the effect of relative elasticity on the centralized system's investment threshold is studied by varying it from 0.001 to 0.01 at the reduced rate of 0.004/hr as before. As observed in Figure 15, the critical threshold is much higher when the ratio is less than 0.002, deceasing considerably as the ratio increases beyond that. As a result, the system can invest higher amounts in IoT to earn higher profits in the former case where demand is more sensitive to quality. However, it is more likely to not invest in the latter case when demand's sensitivity to price begins to increase.

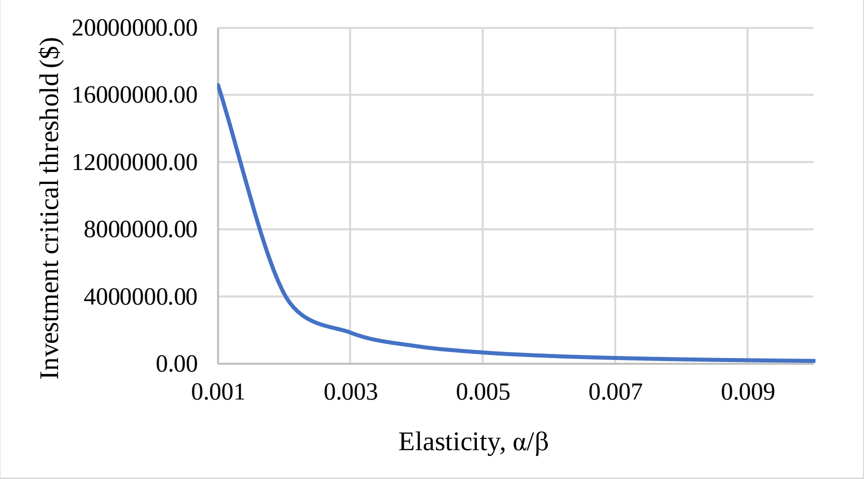

Figure 15: Effect of relative elasticity on investment threshold for centralized system

3.5. Single Price Model with Revenue-Sharing Coordination

As an attempt to enhance the performance of the supply chain network to resemble that of a centralized system, the single price model is explored within a coordinated system in which revenue-sharing contracts are employed as the coordination mechanism. Herein, the retail price p_1 is optimized in a manner similar to the centralized system, i.e. through maximization of the aggregated supply chain profit. Consequently, the retailer retains a fraction δ of the sales revenue and shares the remaining proportion with the supplier who offers a comparatively lower wholesale price w_1 in exchange for the shared revenue.

3.5.1. No investment in IoT. For a coordinated system that utilizes the single price policy without investing in IoT, the retailer's profit function π_r is simply his marginal profit with revenue-sharing multiplied by the consumer demand faced during the selling period as depicted below:

$$\pi_r = \left(\delta p_1 - w_1\right) D_1 \tag{87}$$

$$\pi_r = \frac{\left(\delta p_1 - w_1\right)}{\mu_3}\left\{-\frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_1 + \beta q_3\right)\left(q_3 - q_c\right)\right\} \tag{88}$$

Similarly, the supplier's profit function π_s within the aforementioned setting is a product of his marginal profit with the shared revenue and the customer demand for the sale period as expressed below:

$$\pi_s = \left[\left(1-\delta\right) p_1 + w_1 - c\right] D_1 \tag{89}$$

$$\pi_s = \frac{\left[\left(1-\delta\right) p_1 + w_1 - c\right]}{\mu_3}\left\{-\frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_1 + \beta q_3\right)\left(q_3 - q_c\right)\right\} \tag{90}$$

Moreover, the overall profit Π of the coordinated supply chain is identical to the that of the centralized system, which is merely an accumulation of the profits of the retailer and supplier as shown below:

$$\Pi = \pi_r + \pi_s \tag{91}$$

$$\Pi = \frac{\left(p_1 - c\right)}{\mu_3}\left\{-\frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_1 + \beta q_3\right)\left(q_3 - q_c\right)\right\} \tag{92}$$

Similar to the centralized system, the optimal retail price p_1^* for a system that follows the single price strategy coordinated with a revenue-sharing contract and does not improvise quality through the use of IoT is determined through maximization of the aggregated supply chain profit as follows:

$$p_1^* = \frac{-\beta\left[\left(q_3-q_h\right)^2+\left(q_3-q_c\right)^2\right]+2\left(D_0+\beta q_3\right)\left(q_3-q_c\right)}{4\alpha\left(q_3-q_c\right)}+\frac{c}{2} \tag{93}$$

3.5.2. Investment in IoT. Within a coordinated system that spends on IoT for visibility into product quality, the retailer's profit π_r is his marginal profit under the revenue-sharing scheme multiplied by the customer demand, along with the subtraction of a fixed cost I_r attributed to IoT deployment which is exhibited below:

$$\pi_r = \left(\delta p_1 - w_1\right)D_1 - I_r \tag{94}$$

$$\pi_r = \frac{\left(\delta p_1 - w_1\right)}{\mu_3}\left\{-\frac{1}{2}\beta\left(q_3-q_c\right)^2+\left(D_0-\alpha p_1+\beta q_3\right)\left(q_3-q_c\right)\right\}-I_r \tag{95}$$

In the same way, the supplier's profit function π_s within the aforesaid framework is a product of his marginal profit from his share of sales revenues and the consumer demand, including a fixed investment cost I_s for the IoT infrastructure as shown below:

$$\pi_s = \left[\left(1-\delta\right)p_1 + w_1 - c\right]D_1 - I_s \tag{96}$$

$$\pi_s = \frac{\left[\left(1-\delta\right)p_1 + w_1 - c\right]}{\mu_3}\left\{-\frac{1}{2}\beta\left(q_3-q_c\right)^2+\left(D_0-\alpha p_1+\beta q_3\right)\left(q_3-q_c\right)\right\}-I_s \tag{97}$$

Furthermore, the coordinated supply chain profit Π is an accrual of the retailer and supplier profits with their investment costs, which bears a resemblance to the profit of the centralized supply chain as displayed below:

$$\Pi = \pi_r + \pi_s \tag{98}$$

$$\Pi = \frac{\left(p_1 - c\right)}{\mu_3}\left\{-\frac{1}{2}\beta\left(q_3-q_c\right)^2+\left(D_0-\alpha p_1+\beta q_3\right)\left(q_3-q_c\right)\right\}-I \tag{99}$$

Similar to the preceding system without IoT costs, for system coordinating through revenue-sharing, implementing the single pricing method, and employing IoT to enhance quality, the optimal retail price p_1^* is discerned by maximizing the combined network profit as the following:

$$p_1^* = \frac{-\beta\left(q_3 - q_c\right)^2 + 2\left(D_0 + \beta q_3\right)\left(q_3 - q_c\right)}{4\alpha\left(q_3 - q_c\right)} + \frac{c}{2} \tag{100}$$

3.5.3. Critical thresholds for IoT investment. Similar to the prior supply chain systems, the financial performance of the coordinated network and its players is supposedly improved by investing in IoT through reduced deterioration rates, as long as the investment I does not exceed three specific investment critical thresholds.

To begin with, the retailer's IoT investment I_r must be lower than his critical investment threshold under the revenue-sharing coordination $I_{R,rs}$. This is found by computing the difference between the retailer's profits when the original deterioration rate of μ_{31} is decreased to μ_{32} through IoT and equating it to zero to get the following expression:

$$I_{R,rs} = \frac{\delta}{4}\left\{\begin{array}{l} \left(\frac{1}{\mu_{32}} - \frac{1}{\mu_{31}}\right)\left[\begin{array}{c} \frac{\beta^2\left(q_3 - q_c\right)^4 - 4\beta\left(D_0 + \beta q_3\right)\left(q_3 - q_c\right)^3 + 4\left(D_0 + \beta q_3\right)^2\left(q_3 - q_c\right)^2}{4\alpha\left(q_3 - q_c\right)} \\ + \frac{w_1\left[\beta\left(q_3 - q_c\right)^2 - 2\left(D_0 + \beta q_3 - \alpha c\right)\left(q_3 - q_c\right)\right]}{\delta} - \alpha c^2\left(q_3 - q_c\right) \end{array}\right] \\ - \left(\frac{\beta\left(q_3 - q_h\right)^2}{\mu_{31}}\right)\left[\frac{\beta\left(q_3 - q_h\right)^2 + 2\beta\left(q_3 - q_c\right)^2 - 4\left(D_0 + \beta q_3\right)\left(q_3 - q_c\right)}{4\alpha\left(q_3 - q_c\right)} + \frac{w_1}{\delta}\right] \end{array}\right\} \tag{101}$$

If the retailer's investment is within his critical threshold ($0 < I_r < I_{R,rs}$), the retailer earns additional profits with by investing in an IoT infrastructure under the revenue-sharing scheme. On the other hand, if his investment surpasses the critical investment threshold ($I_r > I_{R,rs}$), then investing in IoT is not validated for the retailer since it would cause him to incur losses.

Similarly, the supplier's investment in IoT would be justified only as long as it falls within his critical investment threshold $I_{S,rs}$. This is determined in a manner similar to the retailer, through a calculation of the difference between the supplier's profits with and without the use of IoT, as the following:

$$I_{S,rs}=\frac{1}{4}\left\{\begin{array}{l}\left(\frac{1}{\mu_{32}}-\frac{1}{\mu_{31}}\right)\left[\begin{array}{l}\frac{(1-\delta)\left[\beta^{2}(q_3-q_c)^{4}-4\beta(D_0+\beta q_3)(q_3-q_c)^{3}+4(D_0+\beta q_3)^{2}(q_3-q_c)^{2}\right]}{4\alpha(q_3-q_c)}\\ +c\left[\beta(q_3-q_c)^{2}-2(D_0+\beta q_3)(q_3-q_c)+\alpha c(1+\delta)(q_3-q_c)\right]\\ +w_1\left[-\beta(q_3-q_c)^{2}+2(D_0+\beta q_3-\alpha c)(q_3-q_c)\right]\end{array}\right]\\ -\left(\frac{\beta(q_3-q_h)^{2}}{\mu_{31}}\right)\left[\frac{(1-\delta)\left[\beta(q_3-q_h)^{2}+2\beta(q_3-q_c)^{2}\right]-4(D_0+\beta q_3)(q_3-q_c)}{4\alpha(q_3-q_c)}+c-w_1\right]\end{array}\right\} \tag{102}$$

Once again, the supplier's part in the investment under the revenue-sharing system is only rationalized if it is under his critical threshold ($0<I_s<I_{S,rs}$), whereas if it exceeds the critical threshold ($I_s>I_{S,rs}$), then the supplier is better off without investing in IoT.

Finally, the accumulated supply chain investment I is beneficial when it is lower than the critical threshold I_{RS} of overall revenue-sharing system. This is found through the difference between the total supply chain profits under the revenue-sharing system with and without IoT, and resembles that of the centralized supply chain as exhibited below:

$$I_{RS}=\frac{1}{16\alpha(q_3-q_c)}\left\{\begin{array}{l}\left(\frac{1}{\mu_{32}}-\frac{1}{\mu_{31}}\right)\left[\beta^{2}(q_3-q_c)^{4}-4\beta(D_0+\beta q_3-\alpha c)(q_3-q_c)^{3}+4(D_0+\beta q_3-\alpha c)^{2}(q_3-q_c)^{2}\right]\\ -\left(\frac{\beta(q_3-q_h)^{2}}{\mu_{31}}\right)\left[\beta(q_3-q_h)^{2}+2\beta(q_3-q_c)^{2}-4(D_0+\beta q_3-\alpha c)(q_3-q_c)\right]\end{array}\right\} \tag{103}$$

Therefore, if the combined investment of the coordinated system is within the critical threshold for the supply chain ($0<I<I_{RS}$), then the profits are higher with IoT. However, when the investment goes beyond the threshold ($I>I_{RS}$), the IoT investment is not substantiated for the supply chain.

3.5.4. Numerical analysis. The preceding numerical examples are extended to study the effect of the parameters on the single price system under revenue-sharing coordination. Similar values are assigned to the parameters as before (refer to Table 4), with additional input parameters of wholesale price w_1 and revenue-sharing factor δ assigned initially as 2.60 \$/unit and 60%, respectively.

3.5.4.1. Effect of quality deterioration rate on profits. The impact of reducing the product deterioration rate via IoT on the individual and overall system profits of the coordinated supply chain, excluding investment cost, is examined in the same manner as before. As shown in Table 8, the original deterioration rate of 0.0067/hr is reduced to numerous rates from 0.006/hr to 0.003/hr, and the supplier, retailer, and supply chain profits are computed for each rate. The percentage difference in each of the three profits owing to IoT is then calculated relative to the initial rate of 0.0067/hr.

Table 8: Effect of reducing deterioration rate on revenue-sharing profits

μ_3 (/hr)	π_s (\$)	$\Delta\pi_s$ (%)	π_r (\$)	$\Delta\pi_r$ (%)	π (\$)	$\Delta\pi$ (%)
0.0067	98.022	0.00%	60.607	0.00%	158.628	0.00%
0.006	118.621	21.02%	76.613	26.41%	195.234	23.08%
0.0055	129.405	63.15%	83.577	37.90%	212.982	34.26%
0.005	142.345	79.47%	91.935	51.69%	234.280	47.69%
0.0045	158.161	99.41%	102.150	68.55%	260.312	64.10%
0.004	177.932	124.34%	114.919	89.61%	292.850	84.61%
0.0035	203.350	156.39%	131.336	116.70%	334.686	110.99%
0.003	237.242	199.12%	153.225	152.82%	390.467	146.15%

As depicted in Table 8 and Figure 16, the retailer and supplier generate higher profits as the deterioration rate is reduced, and thus, the overall supply chain also earns more profits. Moreover, Figure 16 indicates that the percentage increase in profit margins is higher for the supplier than the retailer, which is faintly higher than that of the overall supply chain. This, however, is merely due to the initial assumption of values for the wholesale price and revenue-sharing factor, and thus, would differ if these contract conditions between the retailer and supplier are varied. Therefore, the cost to invest in IoT must be distributed equally between the two parties as established earlier.

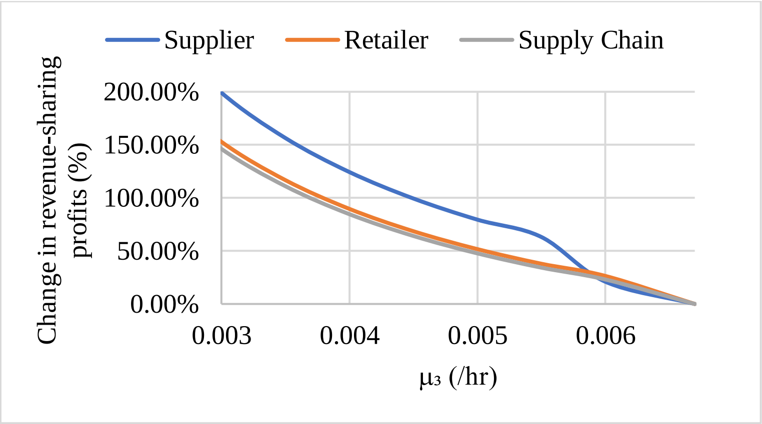

Figure 16: Effect of reducing deterioration rate on revenue-sharing profits

3.5.4.2. Effect of initial quality. Once again, presuming the initial and reduced deterioration rates μ_{31} and μ_{32} to be 0.0067/hr and 0.004/hr, respectively, the effect of initial quality q_3 is studied on the retailer, supplier and overall coordinated supply chain's critical investment thresholds $I_{R,rs}$, $I_{S,rs}$, and I_{RS} , respectively.

Varying the initial quality between 0.60 to 1.00, Figure 17 demonstrates that the three critical thresholds are found to be higher as the initial quality increases, implying that they can consider greater IoT investments when the initial quality is high. Additionally, it is also observed that the retailer's threshold with the assumed parameter values is lower than that of the supplier. However, unlike the decentralized system, the supplier and retailer's critical investment thresholds under revenue-sharing are functions of the wholesale price and revenue-sharing factor as well. Therefore, depending on these two additional parameters, the retailer's critical threshold may be higher or lower than that of the supplier.

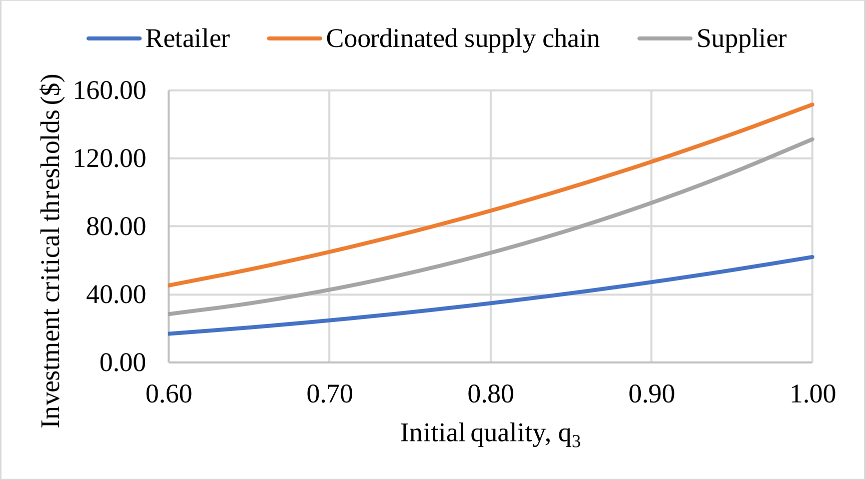

Figure 17: Effect of initial quality on investment thresholds for revenue-sharing system

3.5.4.3. Effect of relative elasticity. The impact of relative elasticity is evaluated on revenue-sharing profits, excluding IoT costs, at the reduced deterioration rate of 0.004/hr. When the ratio is varied from 0.001 to 0.01 as shown in Figure 18, a trend similar to the decentralized system is observed. The profits are much higher when the ratio is considerably low and demand is more sensitivity to quality than price, and much lower when the ratio goes above 0.002 and the demand becomes more sensitive to price.

Furthermore, unlike the decentralized system where the supplier always has higher profits than the retailer, Figure 18 reveals that the retailer gains higher profits than the supplier at the assumed values of w_1 and δ. As aforementioned, this may change when different values are assigned to these two parameters.

The effect of relative elasticity is also studied on the investment thresholds at varying ratios as illustrated in Figure 19. Like the decentralized system, the thresholds are much higher when the ratio is less than 0.002. Hence, the system can settle on higher investments and obtain more profits with IoT when the demand is highly sensitive to quality. However, the thresholds reduce greatly at ratios above 0.002, where price sensitivity begins to rise. Thus, the system becomes less willing to deploy IoT due to reduced benefits from investment.

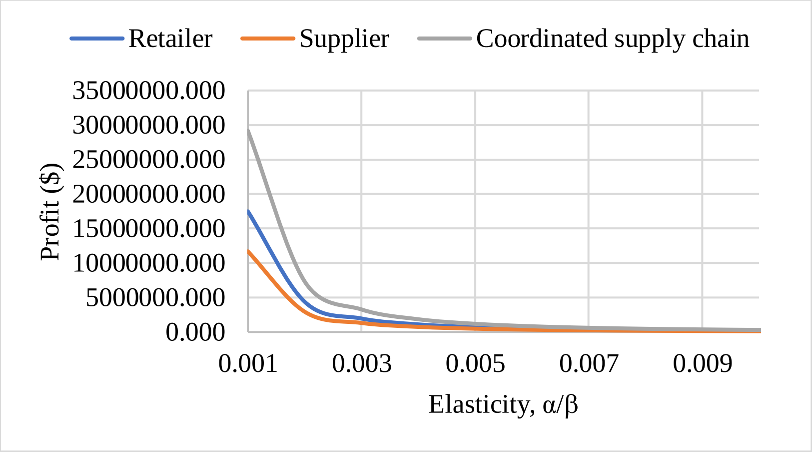

Figure 18: Effect of relative elasticity on revenue-sharing profits

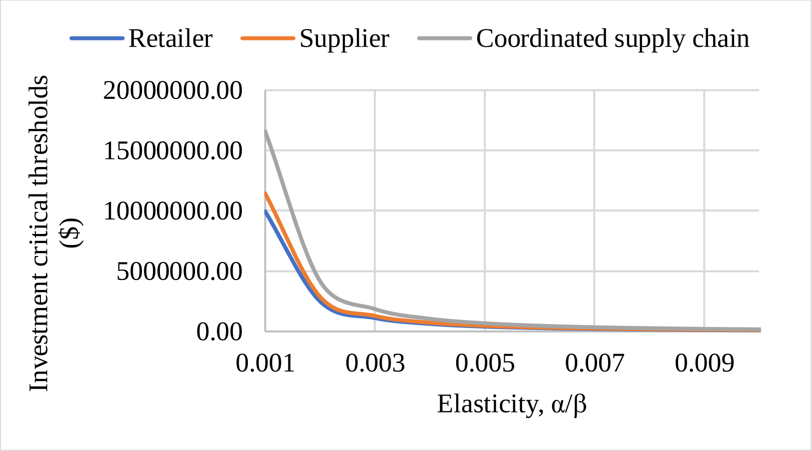

Figure 19: Effect of relative elasticity on investment thresholds for revenue-sharing system

3.5.4.4. Effect of revenue-sharing factor. As mentioned previously, the revenue-sharing factor δ measures the fraction of the system's sales revenue that is withheld by the retailer, whereas the remaining fraction $(1-\delta)$ is handed to the supplier. As established earlier, the system earns very low profits when the price sensitivity is high, therefore, the effect of the revenue-sharing factor on the system is analyzed at a lower elasticity ratio. Consequently, the quality sensitivity factor β is assumed to be 18.3 for a ratio of 0.1, while all the other parameters are the same as before with a reduced deterioration rate of 0.004/hr.

As expected, it is seen in Figure 20 that as δ increases, the retailer gains increasingly more profits with revenue-sharing as compared to decentralization, whereas the opposite is true for the supplier. However, the overall increase of the system's profits with coordination is always 33.33% as is expected for a centralized system. Ideally, it is desired to determine a value of δ such that the retailer and supplier have an identical percentage increase in profits, which is observed to be around 50% in this example.

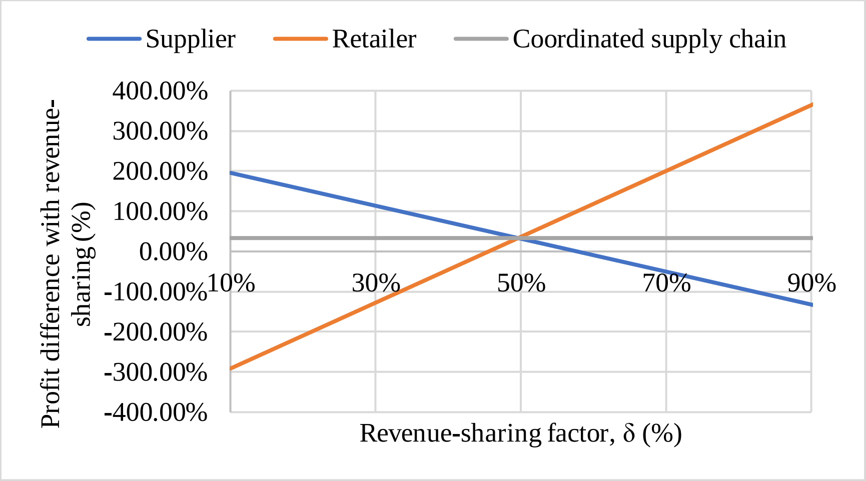

Figure 20: Effect of revenue-sharing factor on profits as compared to decentralized system

Similarly, Figure 21 demonstrates that as δ increases, the retailer's critical investment threshold $I_{R,rs}$ becomes higher whereas the supplier's threshold $I_{S,rs}$ becomes lower, which is as anticipated. Nevertheless, the overall system's threshold I_{RS} remains constant throughout, which resembles that for the centralized system and is independent of δ. Therefore, the retailer and supplier's individual contributions to investment must be lower than both $I_{R,rs}$ and $I_{S,rs}$ in order for them to benefit from IoT, which is the region under the two thresholds between 30% and 90% for this specific case (refer to Figure 21).

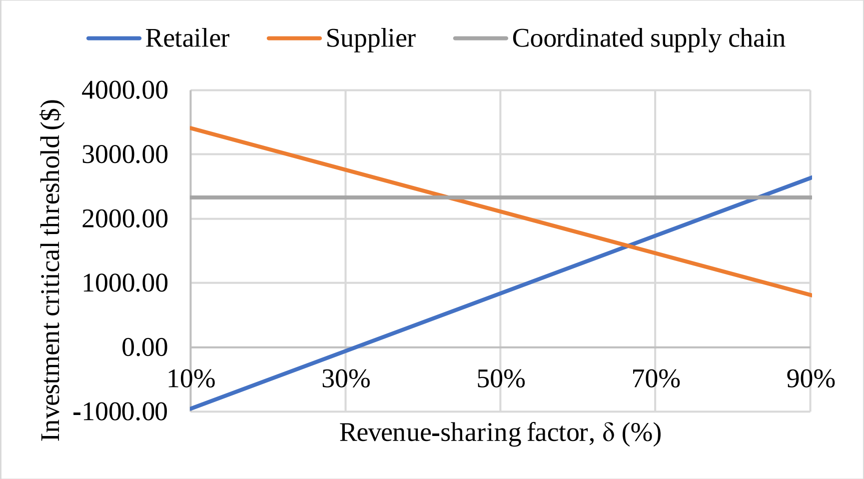

Figure 21: Effect of revenue-sharing factor on investment thresholds for revenue-sharing system

Based on the results derived above, the revenue-sharing factor must fall within lower and upper bounds in order for the coordination to be beneficial for the retailer and the supplier. Consequently, the lower bound is found based on the theory that the retailer's revenue-sharing profit must be higher than his decentralized profit as the following:

$$\delta > \frac{\left[\beta\left(q_3+q_c\right)+2\left(D_0-\alpha c\right)\right]+16\alpha w_1}{4\left[\beta\left(q_3+q_c\right)+2\left(D_0+\alpha c\right)\right]} \tag{104}$$

Likewise, the upper bound is determined based on the notion that the supplier's revenue-sharing profit must be higher than his profit in the decentralized system as expressed below:

$$\delta < \left[\frac{8\alpha w_1+\left[\beta\left(q_3+q_c\right)+2\left(D_0-\alpha c\right)\right]}{2\left[\beta\left(q_3+q_c\right)+2\left(D_0+\alpha c\right)\right]}\right] \tag{105}$$

3.5.4.5. Effect of wholesale price. To study the effect of the wholesale price w_1 offered to the retailer by the supplier, the β is considered as 18.3 for a relative elasticity of 0.1 as above, while the other parameters remain as before. As anticipated, Figure 22 illustrates that as w_1 increases, the supplier earns increasingly more profits with revenue-sharing relative to decentralization, whereas the opposite occurs for the retailer. The overall supply chain profit difference, however, remains unaffected as before, since it is not dependent on w_1.

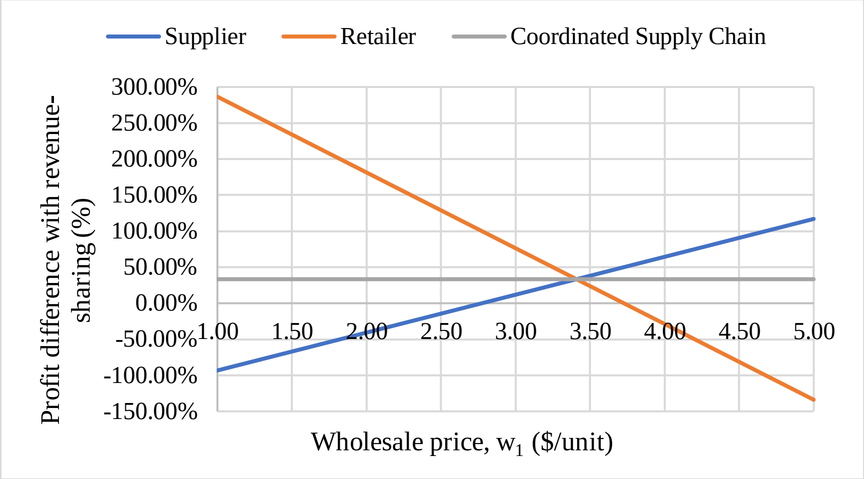

Figure 22: Effect of wholesale price on profits as compared to the decentralized system

Likewise, Figure 23 shows that as w_1 increases, the retailer's investment threshold $I_{R,rs}$ decreases while the supplier's threshold $I_{S,rs}$ increases, which is also as projected. However, the total supply chain threshold I_{RS} remains unchanged as before.

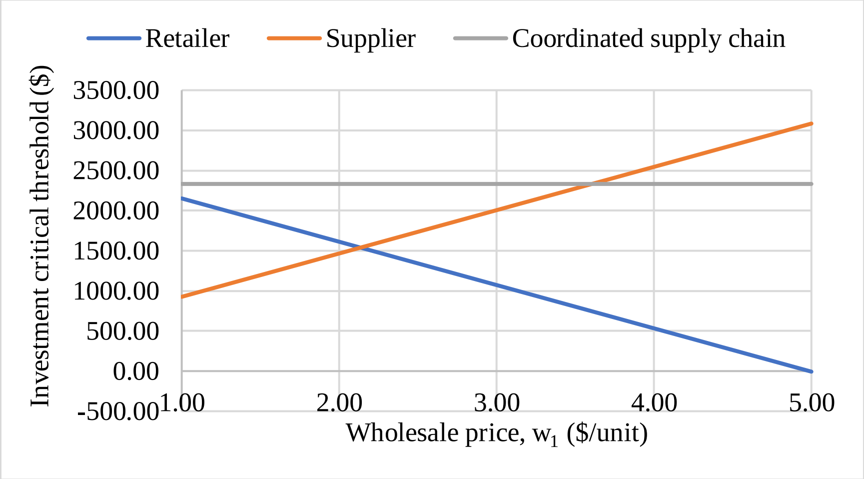

Figure 23: Effect of wholesale price on investment thresholds for revenue-sharing system

Finally, the impact of wholesale price is also examined on the revenue-sharing factor's bounds determined earlier. As shown in Figure 24, both the upper and the lower bounds for δ are directly proportional to w_1. This implies that at a higher wholesale price, the fraction of revenue retained by the retailer must be higher in order for the retailer to benefit from revenue-sharing. Similarly, at a lower wholesale price, the fraction withheld by the retailer must be lower so that the supplier earns enough to benefit from the coordination.

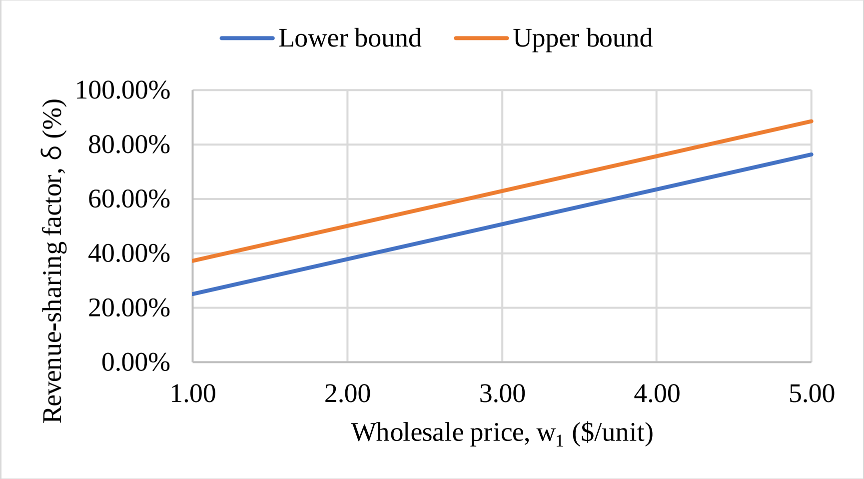

Figure 24: Effect of wholesale price on lower and upper bounds for revenue-sharing factor

3.6. Managerial Implications

The mathematical modelling and numerical analysis of the single price strategy presented in this work offer important managerial inferences to suppliers and retailers within the FSC. Foremost, the decision for grocery suppliers and retailers to implement real-time quality monitoring is dependent on the cost of investing in the required IoT technology and its relationship with the critical investment thresholds developed in this research. Identified for the retailer, supplier, and the collective supply chain, these three thresholds are influenced by parameters including the initial and reduced quality deterioration rates, initial, organoleptic, and critical quality levels, and the relative elasticity of the consumer demand. These factors need to be considered prior to implementing IoT for quality monitoring of perishable food products. Furthermore, it is identified that the retailer and supplier must split the investment costs equally because they both generate an identical percentage increase in their respective profits upon reducing the food quality deterioration rate.

Moreover, where IoT is more likely to enhance the fiscal performance of the retailer, supplier, and overall supply chain, the perishable food corporations should explore methods to lower the IoT investment costs and identify the most optimal logistical point for its implementation. Since the initial 24 to 48 hours after harvest are the most crucial in terms of food quality, it would be ideal to employ quality monitoring at these earlier points. On the contrary, where IoT benefits the supplier and the overall food supply chain but leads to decreased profits for the retailer, the supplier should either increase his individual contribution to the investment or offer incentives to motivate the retailer to implement IoT technology.

Additionally, the lower and upper bounds of the retailer's revenue-sharing factor for an optimal revenue-sharing coordination have been identified in this research. These bounds depend on the supplier's wholesale price, along with several other parameters. Within these bounds, both the retailer and supplier gain increased profits with revenue-sharing as compared to decentralization, which leads to an improved supply chain performance.

Chapter 4. Two-Stage Price Model

This chapter exhibits the various stages in the development of the two-stage price model for decentralized, centralized, and coordinated structures of two-echelon food supply chains. Similar to the preceding single price model, each system is developed with and without the utilization of IoT for constant monitoring of food quality. Subsequently, a numerical analysis is also presented to study the impact of certain parameters on the fiscal performance and decisions of the supply chain within each system.

4.1. Assumptions and Notations

The mathematical model for the two-stage pricing strategy is established based on assumptions that are similar those made for the single price strategy, which are the following:

1. The two-echelon perishable food supply chain consists of an upstream supplier and a downstream retailer.
2. The retail price and food quality have an impact on the customer demand, where the demand decreases as the price increases, and it increases as the product quality increases.
3. The sale period commences at the time t_3 wherein the food retailer receives the perishable products from the food supplier at quality q_3, and the selling period terminates at the time t_c when the food quality reaches the critical quality q_c.
4. The time t_h, which is the time when the sensory food quality changes begin to occur, is fixed, and it is also considered as the markdown time when the retail price is reduced.

The notations used in the development of the two-stage price model are presented in Table 3, which are similar to those used in the single price model. Additionally, the same food quality deterioration process followed for the single price model, which is illustrated in Figure 6, is also employed to develop the model for the two-price policy.

Table 9: Notations for two-stage price model

Notation	Description
D_0	Potential market size
α	Price sensitivity factor
β	Quality sensitivity factor
$p(t)$	Product price at time t
$q(t)$	Product quality at time t
$D(t)$	Demand function at time t
q_3	Initial quality level at retailer
q_h	Highest quality level beyond which organoleptic quality changes occur
q_c	Critical quality level below which the product is considered a waste
μ_3	Instantaneous deterioration rate of food quality at retailer
μ_{31}	Instantaneous deterioration rate at retailer without IoT
μ_{32}	Instantaneous deterioration rate at retailer with IoT
t_3	Time at which the product arrives at retailer
t_h	Time at which organoleptic quality changes begin to occur
t_c	Time beyond which the product is unsaleable due to poor quality
D_2	Demand rate at retailer for two-price strategy
c	Unit product cost to supplier
w_2	Unit wholesale price for two-price strategy
p_{21}	Unit initial retail price for two-price strategy
p_{22}	Unit markdown retail price for two-price strategy
I	Cost to invest in IoT to monitor product quality
I_r	Fixed cost to retailer for investment in IoT
I_s	Fixed cost to supplier for investment in IoT
π_r	Retailer’s profit
π_s	Supplier’s profit
Π	Total supply chain profit
Π_c	Centralized supply chain profit

4.2. Demand Function

As mentioned earlier, the rate of demand is negatively impacted by higher initial and markdown retail prices, and it is positively impacted by higher food quality.

Therefore, the demand function used to derive the two-stage price model is identical to that used for the single price model as demonstrated below:

$$D(t) = D_0 - \alpha p(t) + \beta q(t) \tag{106}$$

However, the price function differs from the preceding model wherein two retail prices are set by the retailer; an initial price p_{21} from the start of the selling season until the point where discernable changes in food quality begin to occur at t_h, beyond which the retail price is marked down to p_{22} until the end of the sale period. The piecewise function of price in the two-stage model is illustrated below:

$$p(t) = \begin{cases} p_{21}, t_3 < t < t_h \\ p_{22}, t_h < t < t_c \end{cases} \tag{107}$$

4.2.1. No investment in IoT. Similar to the single price model, when the supply chain does not invest in an IoT setup, changes in food quality can only be detected once they go beyond the organoleptic quality q_h and can be observed by the customer. Therefore, the quality is assumed to be stable at q_h until discernable changes begin to occur after which the quality decreases linearly with time. As aforementioned, the unit retail price is set to p_{21} from the beginning of the selling period at time t_3 up to the point t_h when the product quality falls below q_h and the a markdown retail price of p_{22} is set. Consequently, the deterministic customer demand for the two-stage price strategy without investment in IoT is expressed mathematically as follows:

$$D_2 = \int_0^{t_h - t_3} \left(D_0 - \alpha p_{21} + \beta q_h\right) dt + \int_{t_h - t_3}^{t_c - t_3} \left(D_0 - \alpha p_{22} + \beta\left(q_3 - \mu_3 t\right)\right) dt \tag{108}$$

$$D_2 = \frac{1}{\mu_3}\left\{\alpha\left(p_{22} - p_{21}\right)\left(q_3 - q_h\right) - \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_3 - q_c\right)\right\} \tag{109}$$

4.2.2. Investment in IoT. When the players in the supply chain invest in an IoT infrastructure to enhance quality visibility, the product quality can be measured throughout the demand period even when the changes are not apparent. Consequently, the quality is presumed to decrease linearly with time throughout the selling period with an initial retail price of p_{21} and a markdown price of p_{22} as mentioned previously.

Therefore, the deterministic customer demand for the two-price strategy with deployment of an IoT system is expressed as the following:

$$D_2 = \int_0^{t_h - t_3} \left(D_0 - \alpha p_{21} + \beta\left(q_3 - \mu_3 t\right)\right)dt + \int_{t_h - t_3}^{t_c - t_3} \left(D_0 - \alpha p_{22} + \beta\left(q_3 - \mu_3 t\right)\right)dt \qquad (110)$$

$$D_2 = \frac{1}{\mu_3}\left\{\alpha\left(p_{22} - p_{21}\right)\left(q_3 - q_h\right) + \left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_3 - q_c\right) - \frac{1}{2}\beta\left(q_3 - q_c\right)^2\right\} \qquad (111)$$

4.3. Two-Stage Price Model for a Decentralized System

Initially, the model is studied within the context of a decentralized system in which both the supplier and the retailer are the decision makers wherein both incentivize their individual gains. The retailer seeks to optimize the initial and markdown retail prices p_{21} and p_{22}, respectively, to maximize his profit. Subsequently, these optimized retail prices are used by the supplier to optimize the wholesale price w_2 to maximize his profit. Consequently, the supply chain profit is merely an aggregate of the maximized profits of the retailer and the supplier.

4.3.1. No investment in IoT. Within a decentralized system under the two-stage pricing scheme that does not invest in an IoT infrastructure, the retailer's profit function π_r is an addition of his revenue from the initial and markdown periods, from which the amount paid to the supplier for the customer demand is deducted as shown below:

$$\pi_r = p_{21}\int_0^{t_h - t_3} \left(D_0 - \alpha p_{21} + \beta q_h\right)dt + p_{22}\int_{t_h - t_3}^{t_c - t_3} \left(D_0 - \alpha p_{22} + \beta\left(q_3 - \mu_3 t\right)\right)dt - w_2 D_2 \qquad (112)$$

$$\pi_r = \frac{1}{\mu_3}\left\{\begin{array}{l} p_{21}\left(D_0 - \alpha p_{21} + \beta q_h\right)\left(q_3 - q_h\right) + p_{22}\left[\left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_h - q_c\right) + \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 - \left(q_3 - q_c\right)^2\right]\right] \\ -w_2\left[\alpha\left(p_{22} - p_{21}\right)\left(q_3 - q_h\right) - \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_3 - q_c\right)\right] \end{array}\right\} \qquad (113)$$

Under the same setting, the supplier's profit function π_s is a multiplication of his marginal profit and the customer demand as demonstrated below:

$$\pi_s = \left(w_2 - c\right)D_2 \qquad (114)$$

$$\pi_s = \frac{\left(w_2 - c\right)}{\mu_3}\left[\alpha\left(p_{22} - p_{21}\right)\left(q_3 - q_h\right) - \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_3 - q_c\right)\right] \qquad (115)$$

Lastly, the overall profit Π of the decentralized supply chain is found by adding up the profits of the retailer and the supplier as the following:

$$\Pi = \pi_r + \pi_s \tag{116}$$

Upon maximizing the profits of the retailer and supplier, the optimal initial and markdown retail prices p_{21}^* and p_{22}^*, respectively, and the optimal wholesale price w_2^* for a decentralized system under the two-price strategy that does not invest in IoT are obtained as exhibited below:

$$p_{21}^* = \frac{6D_0\left(q_3 - q_c\right) + \beta\left(6q_3q_h - 4q_hq_c - q_h^2 - q_c^2\right)}{8\alpha\left(q_3 - q_c\right)} + \frac{c}{4} \tag{117}$$

$$p_{22}^* = \frac{6D_0\left(q_3 - q_c\right) + \beta\left(4q_3q_h - 2q_hq_c + 2q_3q_c - q_h^2 - 3q_c^2\right)}{8\alpha\left(q_3 - q_c\right)} + \frac{c}{4} \tag{118}$$

$$w_2^* = \frac{\beta\left(2q_3q_h - {q_h}^2 - {q_c}^2\right) + 2D_0\left(q_3 - q_c\right)}{4\alpha\left(q_3 - q_c\right)} + \frac{c}{2} \tag{119}$$

This illustrates that the retailer's optimal initial price p_{21}^* and optimal markdown price p_{22}^*, and the supplier's optimal wholesale price w_2^* exist uniquely within this setting. Furthermore, it is observed that these optimal prices are not influenced by the quality deterioration rate.

4.3.2. Investment in IoT. For a decentralized two-price system that invests in IoT for an improved visibility of product quality, the retailer's profit π_r is again an aggregate of the revenue earned from the initial and markdown selling periods. However, this profit function includes a deduction of the amount paid out to the supplier with an additional deduction of the fixed investment cost I_r that the retailer expends on IoT as illustrated below:

$$\pi_r = p_{21}\int_0^{t_h - t_3}\left(D_0 - \alpha p_{21} + \beta\left(q_3 - \mu_3 t\right)\right)dt + p_{22}\int_{t_h - t_3}^{t_c - t_3}\left(D_0 - \alpha p_{22} + \beta\left(q_3 - \mu_3 t\right)\right)dt - w_2 D_2 - I_r \tag{120}$$

$$\pi_r = \frac{1}{\mu_3}\left\{\begin{array}{l} p_{21}\left[\left(D_0 - \alpha p_{21} + \beta q_3\right)\left(q_3 - q_h\right) - \frac{1}{2}\beta\left(q_3 - q_h\right)^2\right] \\ + p_{22}\left[\left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_h - q_c\right) + \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 - \left(q_3 - q_c\right)^2\right]\right] \\ - w_2\left[\alpha\left(p_{22} - p_{21}\right)\left(q_3 - q_h\right) + \left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_3 - q_c\right) - \frac{1}{2}\beta\left(q_3 - q_c\right)^2\right] \end{array}\right\} - I_r \tag{121}$$

Under the same situation as aforementioned, the supplier's profit function π_s is a product of his marginal profit with consumer demand along with the subtraction of a fixed investment cost I_s for IoT deployment as displayed below:

$$\pi_s = \left(w_2 - c\right) D_2 - I_s \tag{122}$$

$$\pi_s = \frac{\left(w_2 - c\right)}{\mu_3}\left[\alpha\left(p_{22} - p_{21}\right)\left(q_3 - q_h\right) + \left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_3 - q_c\right) - \frac{1}{2}\beta\left(q_3 - q_c\right)^2\right] - I_s \tag{123}$$

Finally, the overall supply chain profit Π for this decentralized system is as an addition of the retailer and supplier profits which presented as follows:

$$\Pi = \pi_r + \pi_s \tag{124}$$

Similar to the preceding system without IoT investment, the optimal initial retail price p_{21}^*, the optimal markdown price p_{22}^*, and the optimal wholesale price w_2^* for a decentralized system following the two-price policy with IoT implementation are obtained via maximization of the individual profits as the following:

$$p_{21}^* = \frac{6D_0 + \beta\left(3q_3 + 2q_h + q_c\right)}{8\alpha} + \frac{c}{4} \tag{125}$$

$$p_{22}^* = \frac{6D_0 + \beta(q_3 + 2q_h + 3q_c)}{8\alpha} + \frac{c}{4} \tag{126}$$

$$w_2^* = \frac{2D_0 + \beta(q_3 + q_c)}{4\alpha} + \frac{c}{2} \tag{127}$$

As within the preceding setting, the retailer's optimal prices p_{21}^* and p_{22}^*, and the supplier's optimal wholesale price w_2^* exist uniquely and are not influenced by the quality deterioration rate.

4.3.3. Critical thresholds for IoT investment. As mentioned earlier, investing in an IoT infrastructure provides enhanced visibility and better control over product quality, which would result in a reduced product deterioration rate. Consequently, this would also theoretically lead to a superior financial performance for the supply chain and its players. However, in order to analyze the impact of IoT on the supply chain's performance, three critical investment thresholds – I_R for the retailer, I_S for the supplier, and I_T for the overall supply chain – are determined as done in the preceding single price system.

To begin with, IoT investment would be beneficial for the retailer if his profits are higher when IoT is employed for real-time monitoring of food quality. Therefore, the critical investment threshold I_R is established through the difference between the retailer's profit without IoT at the initial deterioration rate of μ_{31} and his profit with IoT when the deterioration rate is reduced to μ_{32}. This difference in retailer's profits is equated to zero in order to obtain a simplified expression for the retailer's critical investment threshold as the following:

$$I_R = \frac{1}{64\alpha\left(q_3 - q_c\right)^2}\left\{\begin{array}{l} \left(q_3 - q_c\right)^3\left(\dfrac{1}{\mu_{32}} - \dfrac{1}{\mu_{31}}\right)\left(4D_0^{\ 2} - 8D_0\alpha c + 4\alpha^2 c^2\right) \\ +\left(q_3 - q_c\right)\left[\begin{array}{l} \dfrac{1}{\mu_{32}}\left[\beta\left[D_0\left(4q_3^3 - 4q_3q_c^2 - 4q_3^2q_c + 4q_c^3\right) + \alpha c\left(-4q_3^3 + 4q_3q_c^2 + 4q_3^2q_c - 4q_c^3\right)\right]\right] \\ -\dfrac{1}{\mu_{31}}\left[\beta\left[\begin{array}{l} D_0\left(8q_3^2q_h - 8q_3q_hq_c - 4q_3q_h^2 - 4q_3q_c^2 + 4q_h^2q_c + 4q_c^3\right) \\ +\alpha c\left(-8q_3^2q_h + 4q_3q_h^2 + 4q_3q_c^2 + 8q_3q_hq_c - 4q_h^2q_c - 4q_c^3\right) \end{array}\right]\right] \end{array}\right] \\ +\beta^2\left[\begin{array}{l} \dfrac{1}{\mu_{32}}\left(\begin{array}{l} q_3^5 + 4q_3^4q_h - 5q_3^4q_c - 4q_3^3q_h^2 + 10q_3^3q_c^2 + 12q_3^2q_h^2q_c - 10q_3^2q_c^3 \\ -8q_3^3q_hq_c + 8q_3q_hq_c^3 - 12q_3q_h^2q_c^2 + 5q_3q_c^4 - 4q_hq_c^4 + 4q_h^2q_c^3 - q_c^5 \end{array}\right) \\ -\dfrac{1}{\mu_{31}}\left(\begin{array}{l} 4q_3^3q_h^2 - 16q_3^2q_h^2q_c + 8q_3^2q_hq_c^2 + 2q_3q_h^2q_c^2 - 3q_3q_h^4 + 5q_3q_c^4 + 12q_3q_h^3q_c \\ -12q_h^3q_c^2 - 4q_hq_c^4 + 10q_h^2q_c^3 - 4q_3q_hq_c^3 - 4q_3^2q_c^3 + 3q_h^4q_c - q_c^5 \end{array}\right) \end{array}\right] \end{array}\right\} \qquad (128)$$

When the retailer's investment amount is lower than his critical investment threshold ($0 < I_r < I_R$), he gains more profits using IoT to improve product quality. On the other hand, if his investment goes above the critical threshold ($I_r > I_R$), the retailer's investment in IoT is not validated since it does not generate any additional profits for him.

Similarly, the investment in product quality monitoring would be helpful to the supplier only if his profits are higher using the IoT technology required for it. Determined in a manner similar to the retailer by computing the difference in the supplier's profits without and with the use of IoT at initial and reduced quality deterioration rates of μ_{31} and μ_{32}, respectively, the supplier's critical investment threshold is found as follows:

$$I_S = \frac{1}{32\alpha\left(q_3-q_c\right)^2}\left\{\begin{array}{l} \left(\frac{1}{\mu_{32}}-\frac{1}{\mu_{31}}\right)\left(q_3-q_c\right)^3\left(2D_0-2\alpha c\right)^2 \\ +\left(q_3-q_c\right)\left[\begin{array}{l} \frac{1}{\mu_{32}}\left[\left(q_3-q_c\right)^2\beta\left[D_0\left(4q_3+4q_c\right)-\alpha c\left(4q_3+4q_c\right)\right]\right] \\ -\frac{1}{\mu_{31}}\left[\beta\left(\begin{array}{l} D_0\left(8q_3^2q_h-4q_3q_h^2-4q_3q_c^2-8q_3q_hq_c+4q_h^2q_c+4q_c^3\right) \\ -\alpha c\left(8q_3^2q_h-4q_3{q_h}^2-4q_3q_c^2-8q_3q_hq_c+4{q_h}^2q_c+4{q_c}^3\right) \end{array}\right)\right] \end{array}\right] \\ +\left[\begin{array}{l} \frac{1}{\mu_{32}}\left[\beta^2\left(q_3+q_c\right)^2\left(q_3-q_c\right)^3\right] \\ -\frac{1}{\mu_{31}}\left[\beta^2\left(\begin{array}{l} 4q_3^3q_h^2-4q_3^2q_h^2q_c-4q_3^2q_hq_c^2-4q_3^2q_h^3+4q_3q_h^3q_c+4q_3q_hq_c^3 \\ +2q_3q_h^2q_c^2+q_3q_h^4-q_h^4q_c-2q_h^2q_c^3+q_3q_c^4-q_c^5 \end{array}\right)\right] \end{array}\right] \end{array}\right\} \tag{129}$$

When the supplier contributes an amount less than the critical threshold to the IoT investment ($0 < I_s < I_S$), he makes higher profits with IoT. On the contrary, if the amount invested exceeds the threshold ($I_s > I_S$), then the IoT investment is not justified for the supplier since he receives lower profits with it.

Finally, the cumulative investment of the retailer and supplier would only be effective if it falls below the critical investment threshold I_T for the whole supply chain. This is found by adding up the retailer and supplier's individual thresholds, or by computing the difference between the aggregated supply profits for the system with and without IoT, as the following:

$$I_T = \left(\frac{1}{64\alpha\left(q_3-q_c\right)^2}\right)\left\{\begin{array}{l} \left(\frac{1}{\mu_{32}}-\frac{1}{\mu_{31}}\right)\left(q_3-q_c\right)^3\left(12{D_0}^2-24D_0\alpha c+12\alpha^2c^2\right) \\ +\beta\left(q_3-q_c\right)\left[\begin{array}{l} \frac{1}{\mu_{32}}\left[12D_0\left(q_3^3-q_3q_c^2-q_3^2q_c+q_c^3\right)-12\alpha c\left(q_3^3-q_3q_c^2-q_3^2q_c+q_c^3\right)\right] \\ -\frac{1}{\mu_{31}}\left[\begin{array}{l} D_0\left(24q_3^2q_h-24q_3q_hq_c-12q_3q_h^2-12q_3q_c^2+12q_h^2q_c+12q_c^3\right) \\ +\alpha c\left(-24q_3^2q_h+12q_3q_h^2+12q_3q_c^2+24q_3q_hq_c-12q_h^2q_c-12q_c^3\right) \end{array}\right] \end{array}\right] \\ +\beta^2\left[\begin{array}{l} \frac{1}{\mu_{32}}\left(\begin{array}{l} 3q_3^5+4q_3^4q_h-7q_3^4q_c-4q_3^3q_h^2+6q_3^3q_c^2+12q_3^2q_h^2q_c-6q_3^2q_c^3 \\ -8q_3^3q_hq_c+8q_3q_hq_c^3-12q_3q_h^2q_c^2+7q_3q_c^4-4q_hq_c^4+4q_h^2q_c^3-3q_c^5 \end{array}\right) \\ -\frac{1}{\mu_{31}}\left(\begin{array}{l} 12q_3^3q_h^2-24q_3^2q_h^2q_c+6q_3q_h^2q_c^2-q_3q_h^4+7q_3q_c^4+20q_3q_h^3q_c-12q_h^3q_c^2 \\ -4q_hq_c^4+6q_h^2q_c^3+4q_3q_hq_c^3-4q_3^2q_c^3+q_h^4q_c-3q_c^5-8q_3^2q_h^3 \end{array}\right) \end{array}\right] \end{array}\right\} \tag{130}$$

If the total IoT investment of the decentralized system is less than its critical threshold ($0 < I < I_T$), the supply chain reaps more profits when deploying IoT. However, if it surpasses the threshold ($I > I_T$), the investment is not rationalized as the supply chain does not benefit from spending on IoT.

4.3.4. Numerical analysis. In order to assess the effect of the different parameters on the investments of the decentralized system within the two-stage pricing strategy, a numerical example is demonstrated. The values assigned to the parameters are identical to those used in the single price model (refer to Table 4).

4.3.4.1. Effect of quality deterioration rate on profits. As done earlier, the impact of slowing down the quality deterioration process of food products through utilization of IoT is analyzed on the two-price decentralized profits. This is done by computing the supplier, retailer, and aggregated supply chain profits, excluding the IoT investment cost, for quality deterioration that is reduced from the initial rate of 0.0067/hr to rates varying between 0.006/hr and 0.003/hr (refer to Table 10). The percentage difference for each of the individual and collective profits, with reference to the initial deterioration rate of 0.0067/hr, is also computed and shown in Table 10.

Table 10: Effect of reducing deterioration rate on decentralized profits for two-price system

μ_3 (/hr)	π_s (\$)	$\Delta\pi_s$ (%)	π_r (\$)	$\Delta\pi_r$ (%)	π (\$)	$\Delta\pi$ (%)
0.0067	79.314	0.00%	39.905	0.00%	119.220	0.00%
0.006	97.617	23.08%	50.109	25.57%	147.726	23.91%
0.0055	106.491	34.26%	54.665	36.99%	161.156	35.18%
0.005	117.140	47.69%	60.131	50.69%	177.271	48.69%
0.0045	130.156	64.10%	66.813	67.43%	196.968	65.21%
0.004	146.425	84.61%	75.164	88.36%	221.589	85.87%
0.0035	167.343	110.99%	85.902	115.26%	253.245	112.42%
0.003	195.234	146.15%	100.219	151.14%	295.452	147.82%

As depicted in Table 10 and Figure 25, when the food deterioration is slowed down, the retailer, supplier, and the overall supply chain generate greater profits. Moreover, it can be observed that the retailer’s percentage increase in profits is slightly higher than that of the supplier. However, since the difference is insignificant, the percentage increase is almost identical for the two players, and thus, the investment must be distributed equally between the two as shown below:

$$I_r = I_s = 0.5I \tag{131}$$

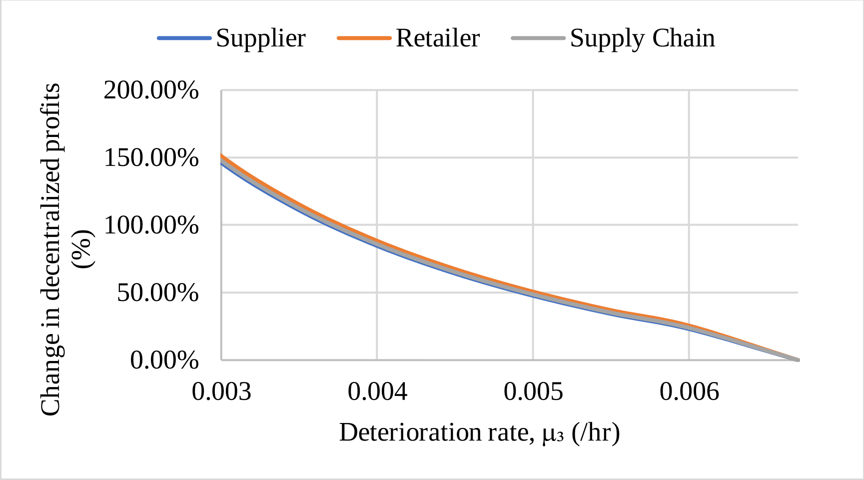

Figure 25: Effect of reducing deterioration rate on decentralized profits for two-price system

4.3.4.2. Effect of initial quality. Assuming the same initial deterioration rate μ_{31} of 0.0067/hr as before and a reduced deterioration rate μ_{32} of 0.004/hr, the influence of the initial quality level q_3 on the critical investment thresholds determined earlier – retailer's investment threshold I_R, supplier's investment threshold I_S, and supply chain's investment threshold I_T – is examined.

As exhibited in Figure 26, the three critical thresholds are computed for initial quality levels varying from 0.60 to 1.00. It is noticed that the three thresholds I_R, I_S, and I_T become higher with increase in initial quality of the perishable products. Additionally, it is also observed that the supplier has a higher threshold than the retailer at each quality level, whereas the overall system threshold is the highest as expected since it is a sum of the other two thresholds.

Therefore, as displayed in Figure 26, both the retailer and the supplier will benefit from investing in IoT if their equal contributions to the investment are below I_R, since the retailer has a lower threshold than the supplier. However, if the investment contribution falls between I_R and I_S, investing in IoT will be favorable for the supplier but not for the retailer. On the other hand, if the individual investment amounts surpass I_S, investing in IoT will not be beneficial for the supplier or the retailer.

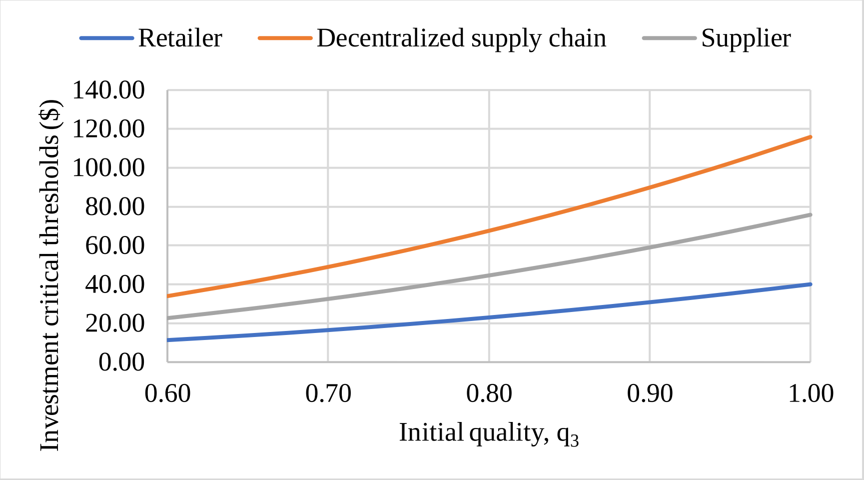

Figure 26: Effect of initial quality on investment thresholds for two-price decentralized system

4.3.4.3. Effect of relative elasticity. The influence of the relative elasticity, α/β, is studied on the two-price decentralized system's profits at the reduced deterioration rate of 0.004/hr. This is done by varying the relative elasticity ratio from 0.001 up to 0.01. As shown in Figure 27, the effect is identical to that observed in the single price system. All three profits are comparatively higher when the ratio is considerably low, which implies that the retailer and supplier gain higher profits with a more quality-sensitive demand, while profits decline significantly as the ratio and sensitivity to price increase.

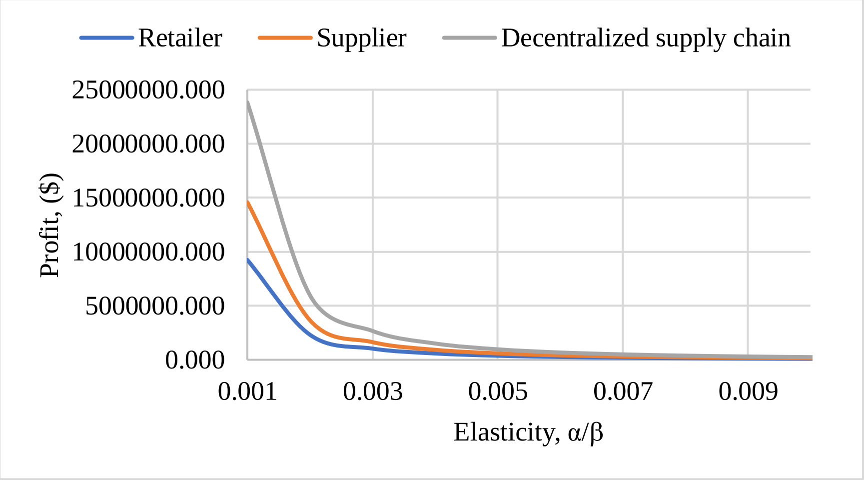

Figure 27: Effect of relative elasticity on two-price decentralized profits

The relative elasticity's effect on the investment thresholds is also analyzed at the same reduced deterioration rate of 0.004/hr, with the ratio varying between 0.001 and 0.01. Figure 28 exhibits that both the retailer and supplier have higher thresholds when the ratio is less than 0.002. This indicates that when the demand is significantly more sensitive to quality than price, the system can benefit from using IoT even if the investment is not low. However, when the ratio goes above 0.002 and price sensitivity begins to increase, there is a considerable decline in both thresholds. As a result, investing in IoT is not favorable for the supply chain when the demand has higher sensitivity to price than quality.

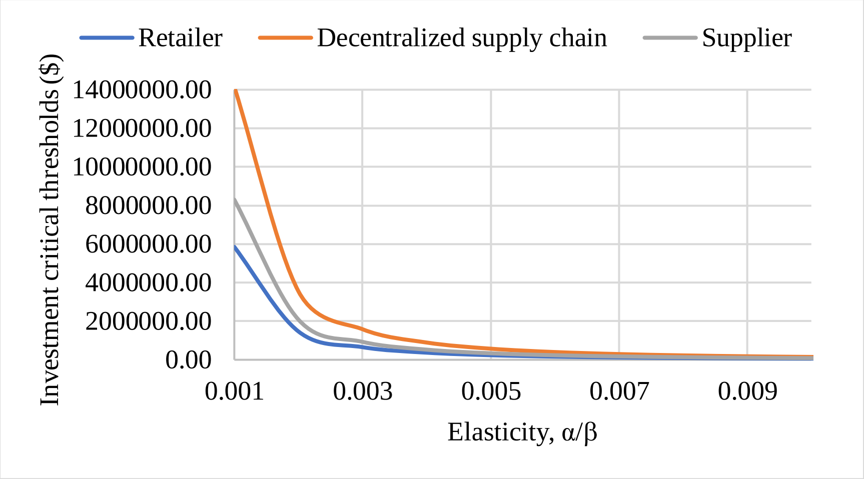

Figure 28: Effect of relative elasticity on investment thresholds for two-price decentralized system

4.4. Two-Stage Price Model for a Centralized System

For an optimized supply chain performance, the two-price model is also explored within a centralized system which incentivizes the integrated supply chain objectives. This unified network optimizes the initial unit retail price p_{21} and the markdown unit retail price p_{22} to maximize the overall supply chain profit.

4.4.1. No investment in IoT. For a centralized system that follows the two-price strategy and does not deploy IoT to monitor quality, the integrated supply chain profit Π_c is the sum of the revenues earned from the initial and markdown selling periods, from which the total product cost for customer demand is deducted as follows:

$$\Pi_c = p_{21}\int_0^{\frac{(q_3-q_h)}{\mu_3}} \left(D_0 - \alpha p_{21} + \beta q_h\right)dt + p_{22}\int_{\frac{(q_3-q_h)}{\mu_3}}^{\frac{(q_3-q_c)}{\mu_3}} \left(D_0 - \alpha p_{22} + \beta\left(q_3 - \mu_3 t\right)\right)dt - cD_2 \tag{132}$$

$$\Pi_c = \frac{1}{\mu_3}\left\{\begin{array}{l} p_{21}\left(D_0 - \alpha p_{21} + \beta q_h\right)\left(q_3 - q_h\right) + p_{22}\left[\left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_h - q_c\right) + \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 - \left(q_3 - q_c\right)^2\right]\right] \\ -c\left[\alpha\left(p_{22} - p_{21}\right)\left(q_3 - q_h\right) - \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_3 - q_c\right)\right] \end{array}\right\} \tag{133}$$

As opposed to the preceding decentralized network, the optimal retail prices p_{21}^* and p_{22}^* for a centralized two-price system that does not utilize IoT are attained through maximization of the total supply chain profit and are determined as the following:

$$p_{21}^* = \frac{D_0 + \beta q_h}{2\alpha} + \frac{c}{2} \tag{134}$$

$$p_{22}^* = \frac{2D_0 + \beta(q_h + q_c)}{4\alpha} + \frac{c}{2} \tag{135}$$

This reveals that the retailer's optimal initial price p_{21}^* and optimal markdown price p_{22}^* exist within the centralized setting and are unique. Additionally, it is discerned that these optimal retail prices are not influenced by the quality deterioration rate.

4.4.2. Investment in IoT. The overall profit Π_c for a centralized supply chain that utilizes IoT for enhanced food quality is an accumulation of the sales revenue from the initial and markdown periods as before. Nevertheless, this profit function also includes an additional deduction of the fixed cost I_c for investment in IoT as follows:

$$\Pi_c = p_{21}\int_0^{\frac{(q_3-q_h)}{\mu_3}} \left(D_0 - \alpha p_{21} + \beta\left(q_3 - \mu_3 t\right)\right)dt + p_{22}\int_{\frac{(q_3-q_h)}{\mu_3}}^{\frac{(q_3-q_c)}{\mu_3}} \left(D_0 - \alpha p_{22} + \beta\left(q_3 - \mu_3 t\right)\right)dt - cD_2 - I_c \tag{136}$$

$$\Pi_c = \frac{1}{\mu_3}\left\{\begin{array}{l} p_{21}\left[\left(D_0 - \alpha p_{21} + \beta q_3\right)\left(q_3 - q_h\right) - \frac{1}{2}\beta\left(q_3 - q_h\right)^2\right] \\ +p_{22}\left[\left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_h - q_c\right) + \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 - \left(q_3 - q_c\right)^2\right]\right] \\ -c\left[\alpha\left(p_{22} - p_{21}\right)\left(q_3 - q_h\right) + \left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_3 - q_c\right) - \frac{1}{2}\beta\left(q_3 - q_c\right)^2\right] \end{array}\right\} - I_c \tag{137}$$

Like the previous system without IoT, the optimal retail prices p_{21}^* and p_{22}^* for a centralized two-price system employing IoT are determined by maximizing the collective profit of the supply chain as follows:

$$p_{21}^{*} = \frac{2D_0 + \beta\left(q_3 + q_h\right)}{4\alpha} + \frac{c}{2} \tag{138}$$

$$p_{22}^{*} = \frac{2D_0 + \beta(q_h + q_c)}{4\alpha} + \frac{c}{2} \tag{139}$$

As mentioned earlier, this indicates that the retailer's optimal prices p_{21}^{*} and p_{22}^{*} exist uniquely within this setting and are not influenced by the deterioration rate.

4.4.3. Critical thresholds for IoT investment. Just as in the previous systems, the financial performance of a centralized two-stage system can hypothetically be enhanced by capitalizing on IoT for improved product quality. However, the investment cost I must be below the critical threshold I_C, which is found through the difference between the centralized profits at the original deterioration rate of μ_{31} without IoT and at the decreased rate of μ_{32} with the use of IoT. As a result, the following critical threshold is established:

$$I_C = \left\{ \begin{array}{l} \dfrac{\left(q_3 - q_h\right)}{16\alpha}\left[\dfrac{\left(2D_0 + \beta\left(q_3 + q_h\right)\right)^2 - \left(2\alpha c\right)^2}{\mu_{32}} - \dfrac{\left(2D_0 + 2\beta q_h\right)^2 - \left(2\alpha c\right)^2}{\mu_{31}}\right] \\ + \dfrac{\left(q_h - q_c\right)}{16\alpha}\left(\dfrac{1}{\mu_{32}} - \dfrac{1}{\mu_{31}}\right)\left[\left(2D_0 + \beta(q_h + q_c)\right)^2 - \left(2\alpha c\right)^2\right] \\ - \dfrac{c}{4}\left\{ \begin{array}{l} \left(q_3 - q_c\right)\left[\dfrac{\left(2D_0 + \beta(q_3 + q_c) - 2\alpha c\right)}{\mu_{32}} - \dfrac{\left(2D_0 + \beta(4q_3 - q_h - q_c) - 2\alpha c\right)}{\mu_{31}}\right] \\ - \dfrac{\beta\left(3q_3 - q_h - 2q_c\right)\left(q_h - q_c\right)}{\mu_{31}} \end{array} \right\} \end{array} \right\} \tag{140}$$

When the centralized system's investment is less than the aforementioned critical threshold ($0 < I < I_C$), it earns more profit with the use of IoT. On the other hand, the system does not benefit from IoT if the investment exceeds the critical threshold ($I > I_C$).

4.4.4. Numerical analysis. The effect of specific parameters on the decisions and performance of the centralized two-price approach is analyzed through a numerical example, wherein the same parameter assignment as the previous examples is used (refer to Table 4).

4.4.4.1. Effect of centralization. In order to study the impact of centralization, the overall profits of the decentralized and centralized supply chain, excluding the fixed IoT investment, are compared at several deterioration rates. As shown in Table 11, the rate is varied from the initial value of 0.0067/hr to several lower rates down to 0.003/hr. The decentralized supply chain profit $\prod$, centralized profit $\prod_c$, and the percentage difference between profits $\Delta\prod$ are also computed at each rate, as shown in Table 11.

Table 11: Difference between decentralized and centralized two-price supply chain profits at varying deterioration rates

μ_3 (/hr)	**π ($)**	**π_c ($)**	**Δπ (%)**
0.0067	119.220	158.877	33.26%
0.006	147.726	170.113	15.15%
0.0055	161.156	185.578	15.15%
0.005	177.271	204.136	15.15%
0.0045	196.968	226.818	15.15%
0.004	221.589	255.170	15.15%
0.0035	253.245	291.623	15.15%
0.003	295.452	340.227	15.15%

As presented in Table 11 and Figure 29, the total profit of the centralized system is higher than the decentralized system at each deterioration rate. This percentage increase is found to be higher at 33.26% at the initial rate of 0.0067/hr without IoT, while it is lower at 15.15% at each of the reduced rates with IoT. Hence, centralization always results in an enhanced supply chain performance within the two-price strategy.

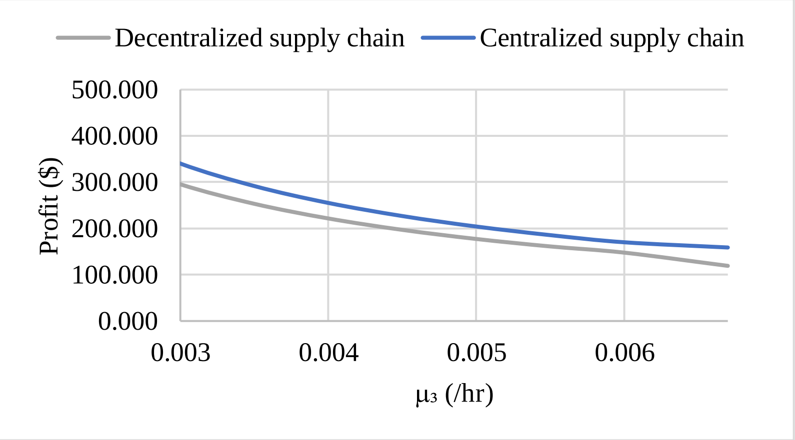

Figure 29: Decentralized and centralized two-price supply chain profits at varying deterioration rates

4.4.4.2. Effect of quality deterioration rate on profit. The effect of quality deterioration rate using IoT is examined by determining the centralized supply chain profit, excluding investment costs, at varying deterioration rates. As shown in Table 12, the initial rate of 0.0067/hr is lowered to several rates between 0.006/hr and 0.003/hr. The centralized profit $\prod_c$ and the percentage difference in profit $\Delta\prod_c$ relative to the initial rate of 0.0067/hr are then computed.

Table 12: Effect of reducing deterioration rate on two-price centralized profit

μ_3 (/hr)	π_c (\$)	$\Delta\pi_c$ (%)	$\Delta\pi$ (%)
0.0067	158.877	0%	0.00%
0.006	170.113	7%	23.91%
0.0055	185.578	17%	35.18%
0.005	204.136	28%	48.69%
0.0045	226.818	43%	65.21%
0.004	255.170	61%	85.87%
0.0035	291.623	84%	112.42%
0.003	340.227	114%	147.82%

As displayed in Table 12 and Figure 30, the centralized system earns higher profits at lower deterioration rates, while the percentage increases as the deterioration rate decreases. Additionally, the percentage increase in profit is comparatively lower than that of the decentralized two-price system (refer to Table 10) at each decay rate.

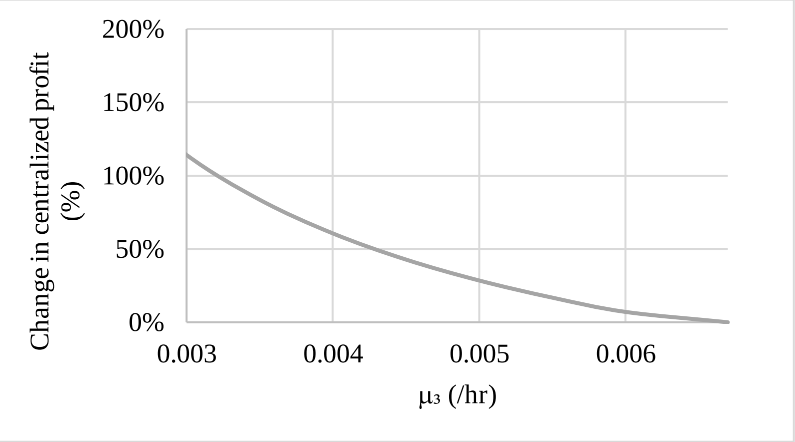

Figure 30: Effect of reducing deterioration rate on two-price centralized profit

4.4.4.3. Effect of initial quality. The effect of initial quality q_3 is studied on the critical investment threshold I_C for the centralized system, with the initial and reduced quality deterioration rates μ_{31} and μ_{32} as 0.0067/hr and 0.004/hr, respectively.

As depicted in Figure 31, the critical threshold, found for initial quality varying from 0.60 to 1.00, is observed to be higher at a higher initial quality level. Thus, the centralized system can gain more benefits from IoT investment at higher initial quality.

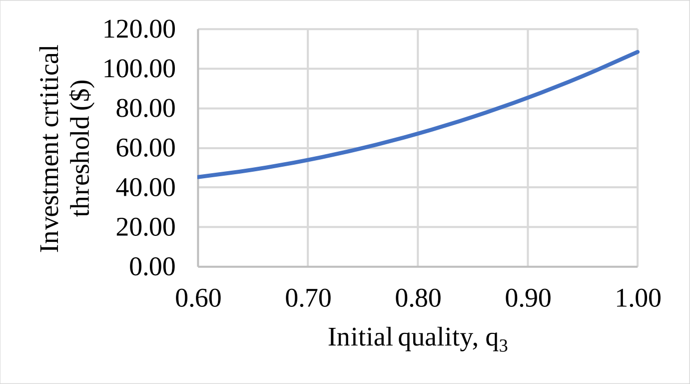

Figure 31: Effect of initial quality on investment threshold for two-price centralized system

4.4.4.4. Effect of relative elasticity. The impact of the relative elasticity α/β is studied on the centralized two-price system's profit, excluding IoT cost, at the reduced deterioration rate of 0.004/hr with the ratio varying from 0.001 to 0.01. As established earlier, Figure 32 reveals that the profit is much higher at a substantially low ratio, with the profit becoming considerably lower beyond 0.002. Therefore, the system would benefit more from a demand that has a much higher sensitivity to quality than price.

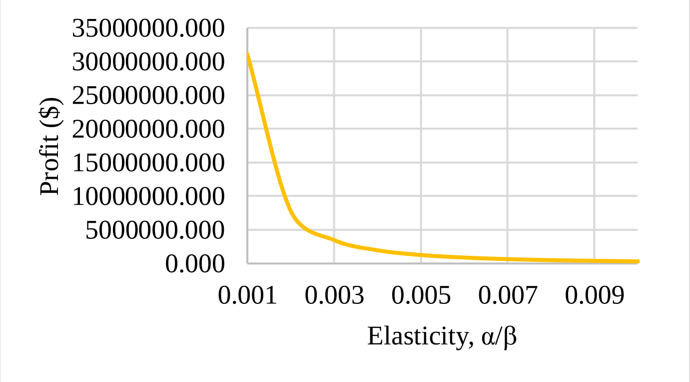

Figure 32: Effect of relative elasticity on two-price centralized profit

Moreover, the effect of relative elasticity on the investment threshold is also analyzed in a similar manner. Figure 33 demonstrates that the threshold is significantly higher when the relative elasticity is less than 0.002, and it decreases noticeably as it rises above 0.002. Thus, the system can invest more in IoT for increased profits when the consumer demand has higher sensitivity to quality. However, as the demand's sensitivity to price increases, it becomes less likely for the system to invest in IoT.

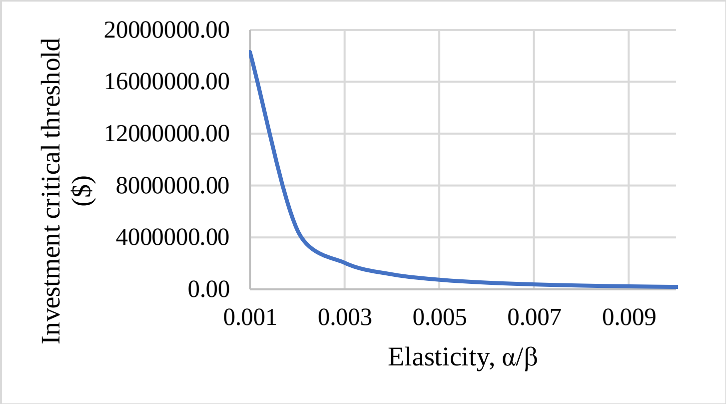

Figure 33: Effect of relative elasticity on investment threshold for two-price centralized system

4.5. Two-Stage Price Model with Revenue-Sharing Coordination

Similar to the single price model, the two-price model is analyzed within a system coordinated through revenue-sharing as an attempt to resemble the centralized network for an enhanced supply chain performance. Under this setting, the initial and marked down retail prices p_{21}^* and p_{22}^* are optimized by maximization of the total supply chain profit in the same way as the centralized system. Furthermore, the retailer holds on to a fraction δ of the revenue earned and hands over the rest to the supplier, who offers a relatively lower wholesale price w_2 in return.

4.5.1. No investment in IoT. For a coordinated two-price system without IoT, the retailer's profit function π_r is merely his fraction of the revenue earned from the initial and markdown selling periods, with the wholesale cost reduced as depicted below:

$$\pi_r = \delta p_{21} \int_0^{\frac{(q_3-q_h)}{\mu_3}} \left(D_0 - \alpha p_{21} + \beta q_h\right) dt + \delta p_{22} \int_{\frac{(q_3-q_h)}{\mu_3}}^{\frac{(q_3-q_c)}{\mu_3}} \left(D_0 - \alpha p_{22} + \beta\left(q_3 - \mu_3 t\right)\right) dt - w_2 D_2 \qquad (141)$$

$$\pi_r = \frac{1}{\mu_3}\left\{\begin{array}{l} \delta p_{21}\left(D_0 - \alpha p_{21} + \beta q_h\right)\left(q_3 - q_h\right) + \delta p_{22}\left[\left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_h - q_c\right) + \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 - \left(q_3 - q_c\right)^2\right]\right] \\ -w_2\left[\alpha\left(p_{22} - p_{21}\right)\left(q_3 - q_h\right) - \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_3 - q_c\right)\right] \end{array}\right\} \tag{142}$$

Likewise, the supplier’s profit function π_s is the sum of his portion of the shared revenue from the initial and markdown sale periods along with the wholesale amount received from the retailer, with the product cost deducted as expressed below:

$$\pi_s = \left(1-\delta\right) p_{21}\int_0^{\frac{(q_3-q_h)}{\mu_3}} \left(D_0 - \alpha p_{21} + \beta q_h\right)dt + \left(1-\delta\right) p_{22}\int_{\frac{(q_3-q_h)}{\mu_3}}^{\frac{(q_3-q_c)}{\mu_3}} \left(D_0 - \alpha p_{22} + \beta\left(q_3 - \mu_3 t\right)\right)dt + \left(w_2 - c\right)D_2 \tag{143}$$

$$\pi_s = \frac{1}{\mu_3}\left\{\begin{array}{l} \left(1-\delta\right) p_{21}\left(D_0 - \alpha p_{21} + \beta q_h\right)\left(q_3 - q_h\right) + \left(1-\delta\right) p_{22}\left[\left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_h - q_c\right) + \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 - \left(q_3 - q_c\right)^2\right]\right] \\ +\left(w_2 - c\right)\left[\alpha\left(p_{22} - p_{21}\right)\left(q_3 - q_h\right) - \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_3 - q_c\right)\right] \end{array}\right\} \tag{144}$$

Additionally, the collective profit Π of the coordinated supply chain is the same as the centralized system profit, which is simply an aggregate of the retailer and supplier’s profits. This is illustrated as the following:

$$\Pi = \pi_r + \pi_s \tag{145}$$

$$\Pi = \frac{1}{\mu_3}\left\{\begin{array}{l} p_{21}\left(D_0 - \alpha p_{21} + \beta q_h\right)\left(q_3 - q_h\right) + p_{22}\left[\left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_h - q_c\right) + \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 - \left(q_3 - q_c\right)^2\right]\right] \\ -c\left[\alpha\left(p_{22} - p_{21}\right)\left(q_3 - q_h\right) - \frac{1}{2}\beta\left[\left(q_3 - q_h\right)^2 + \left(q_3 - q_c\right)^2\right] + \left(D_0 - \alpha p_{22} + \beta q_3\right)\left(q_3 - q_c\right)\right] \end{array}\right\} \tag{146}$$

Finally, the optimal initial and markdown retail prices p_{21}^* and p_{22}^* for a two-price supply chain that coordinates through revenue-sharing and does not deploy IoT are ascertained in the same way as the centralized system as the following:

$$p_{21}^* = \frac{D_0 + \beta q_h}{2\alpha} + \frac{c}{2} \tag{147}$$

$$p_{22}^* = \frac{2D_0 + \beta(q_h + q_c)}{4\alpha} + \frac{c}{2} \tag{148}$$

4.5.2. Investment in IoT. Within a coordinated supply chain network that invests in IoT, the retailer’s profit π_r is again his portion of the revenue from the initial and markdown selling periods while reducing the wholesale cost, with an additional deduction of a fixed investment cost I_r for IoT deployment as exhibited:

$$\pi_r = \left\{ \begin{array}{l} \delta p_{21} \int_0^{\frac{(q_3 - q_h)}{\mu_3}} \left(D_0 - \alpha p_{21} + \beta \left(q_3 - \mu_3 t \right) \right) dt \\ + \delta p_{22} \int_{\frac{(q_3 - q_h)}{\mu_3}}^{\frac{(q_3 - q_c)}{\mu_3}} \left(D_0 - \alpha p_{22} + \beta \left(q_3 - \mu_3 t \right) \right) dt - w_2 D_2 - I_r \end{array} \right\} \tag{149}$$

$$\pi_r = \frac{1}{\mu_3} \left\{ \begin{array}{l} \delta p_{21} \left[\left(D_0 - \alpha p_{21} + \beta q_3 \right) \left(q_3 - q_h \right) - \frac{1}{2} \beta \left(q_3 - q_h \right)^2 \right] \\ + \delta p_{22} \left[\left(D_0 - \alpha p_{22} + \beta q_3 \right) \left(q_h - q_c \right) + \frac{1}{2} \beta \left[\left(q_3 - q_h \right)^2 - \left(q_3 - q_c \right)^2 \right] \right] \\ - w_2 \left[\alpha \left(p_{22} - p_{21} \right) \left(q_3 - q_h \right) + \left(D_0 - \alpha p_{22} + \beta q_3 \right) \left(q_3 - q_c \right) - \frac{1}{2} \beta \left(q_3 - q_c \right)^2 \right] \end{array} \right\} - I_r \tag{150}$$

Similarly, the supplier's profit function π_s is an accumulation of his proportion of the shared revenues and the wholesale payment from the retailer, with the product cost and a fixed cost I_s for the IoT investment as shown below:

$$\pi_s = \left\{ \begin{array}{l} \left(1 - \delta \right) p_{21} \int_0^{\frac{(q_3 - q_h)}{\mu_3}} \left(D_0 - \alpha p_{21} + \beta \left(q_3 - \mu_3 t \right) \right) dt \\ + \left(1 - \delta \right) p_{22} \int_{\frac{(q_3 - q_h)}{\mu_3}}^{\frac{(q_3 - q_c)}{\mu_3}} \left(D_0 - \alpha p_{22} + \beta \left(q_3 - \mu_3 t \right) \right) dt + \left(w_2 - c \right) D_2 - I_s \end{array} \right\} \tag{151}$$

$$\pi_s = \frac{1}{\mu_3} \left\{ \begin{array}{l} \left(1 - \delta \right) p_{21} \left[\left(D_0 - \alpha p_{21} + \beta q_3 \right) \left(q_3 - q_h \right) - \frac{1}{2} \beta \left(q_3 - q_h \right)^2 \right] \\ + \left(1 - \delta \right) p_{22} \left[\left(D_0 - \alpha p_{22} + \beta q_3 \right) \left(q_h - q_c \right) + \frac{1}{2} \beta \left[\left(q_3 - q_h \right)^2 - \left(q_3 - q_c \right)^2 \right] \right] \\ + \left(w_2 - c \right) \left[\alpha \left(p_{22} - p_{21} \right) \left(q_3 - q_h \right) + \left(D_0 - \alpha p_{22} + \beta q_3 \right) \left(q_3 - q_c \right) - \frac{1}{2} \beta \left(q_3 - q_c \right)^2 \right] \end{array} \right\} - I_s \tag{152}$$

Moreover, the coordinated supply chain profit Π is the combination of the retailer and supplier profits along with their fixed investment costs, which resembles the profit of the centralized system as illustrated below:

$$\Pi = \pi_r + \pi_s \tag{153}$$

$$\Pi = \frac{1}{\mu_3} \left\{ \begin{array}{l} p_{21} \left[\left(D_0 - \alpha p_{21} + \beta q_3 \right) \left(q_3 - q_h \right) - \frac{1}{2} \beta \left(q_3 - q_h \right)^2 \right] \\ + p_{22} \left[\left(D_0 - \alpha p_{22} + \beta q_3 \right) \left(q_h - q_c \right) + \frac{1}{2} \beta \left[\left(q_3 - q_h \right)^2 - \left(q_3 - q_c \right)^2 \right] \right] \\ - c \left[\alpha \left(p_{22} - p_{21} \right) \left(q_3 - q_h \right) + \left(D_0 - \alpha p_{22} + \beta q_3 \right) \left(q_3 - q_c \right) - \frac{1}{2} \beta \left(q_3 - q_c \right)^2 \right] \end{array} \right\} - I \tag{154}$$

Similar to the preceding system, for a two-price revenue-sharing system implementing IoT, the optimal initial and markdown retail prices p_{21}^{*} and p_{22}^{*} are determined in the same manner as before through overall profit maximization as follows:

$$p_{21}^{*} = \frac{2D_0 + \beta\left(q_3 + q_h\right)}{4\alpha} + \frac{c}{2} \tag{155}$$

$$p_{22}^{*} = \frac{2D_0 + \beta(q_h + q_c)}{4\alpha} + \frac{c}{2} \tag{156}$$

4.5.3. Critical thresholds for IoT investment. As in the prior supply chain systems, the performance of the supply chain can be enhanced through IoT, but only as long as the investment does not surpass three particular critical investment thresholds for the retailer, supplier, and supply chain.

First of all, the retailer's contribution to the investment I_r must be less than his critical threshold $I_{R,rs}$ within the revenue-sharing system. This is determined by finding the difference between the retailer's profit without IoT at the initial deterioration rate μ_{31} and his profit with IoT at the reduced rate μ_{32}, and then equating it to zero to obtain the following expression:

$$I_{R,rs} = \left\{ \begin{array}{l} \dfrac{\delta\left(q_3 - q_h\right)}{16\alpha}\left[\dfrac{\left(2D_0 + \beta\left(q_3 + q_h\right)\right)^2 - \left(2\alpha c\right)^2}{\mu_{32}} - \dfrac{\left(2D_0 + 2\beta q_h\right)^2 - \left(2\alpha c\right)^2}{\mu_{31}}\right] \\ + \dfrac{\delta\left(q_h - q_c\right)}{16\alpha}\left(\dfrac{1}{\mu_{32}} - \dfrac{1}{\mu_{31}}\right)\left[\left(2D_0 + \beta(q_h + q_c)\right)^2 - \left(2\alpha c\right)^2\right] \\ - \dfrac{w_2}{4}\left\{ \begin{array}{l} \left(q_3 - q_c\right)\left[\dfrac{\left(2D_0 + \beta(q_3 + q_c) - 2\alpha c\right)}{\mu_{32}} - \dfrac{\left(2D_0 + \beta(4q_3 - q_h - q_c) - 2\alpha c\right)}{\mu_{31}}\right] \\ - \dfrac{\beta\left(3q_3 - q_h - 2q_c\right)\left(q_h - q_c\right)}{\mu_{31}} \end{array} \right\} \end{array} \right\} \tag{157}$$

In order for the retailer to earn additional profits with IoT when coordinating through revenue-sharing, his investment must be less than the aforementioned critical threshold ($0 < I_r < I_{R,rs}$). However, the investment is not justified for the retailer if his contribution exceeds the threshold ($I_r > I_{R,rs}$).

Likewise, the supplier’s critical investment threshold $I_{S,rs}$ within the same system is found in a similar manner through his difference in profits with and without the use of IoT as the following:

$$I_{S,rs} = \left\{ \begin{array}{l} \frac{(1-\delta)(q_3-q_h)}{16\alpha}\left[\frac{(2D_0+\beta(q_3+q_h))^2-(2\alpha c)^2}{\mu_{32}}-\frac{(2D_0+2\beta q_h)^2-(2\alpha c)^2}{\mu_{31}}\right] \\ +\frac{(1-\delta)(q_h-q_c)}{16\alpha}\left(\frac{1}{\mu_{32}}-\frac{1}{\mu_{31}}\right)\left[(2D_0+\beta(q_h+q_c))^2-(2\alpha c)^2\right] \\ +\frac{(w_2-c)}{4}\left\{ \begin{array}{l} (q_3-q_c)\left[\frac{(2D_0+\beta(q_3+q_c)-2\alpha c)}{\mu_{32}}-\frac{(2D_0+\beta(4q_3-q_h-q_c)-2\alpha c)}{\mu_{31}}\right] \\ -\frac{\beta(3q_3-q_h-2q_c)(q_h-q_c)}{\mu_{31}} \end{array} \right\} \end{array} \right\} \tag{158}$$

The supplier’s investment under the revenue-sharing system is validated if it is within his critical investment threshold ($0 < I_s < I_{S,rs}$), whereas it is not favorable if it goes above the threshold ($I_s > I_{S,rs}$).

Finally, the critical investment threshold I_{RS} for the overall two-price supply chain under revenue-sharing coordination is ascertained through the difference in the overall profits with and without IoT. This threshold is the same as that of the centralized network and it is as exhibited as follows:

$$I_{RS} = \left\{ \begin{array}{l} \frac{(q_3-q_h)}{16\alpha}\left[\frac{(2D_0+\beta(q_3+q_h))^2-(2\alpha c)^2}{\mu_{32}}-\frac{(2D_0+2\beta q_h)^2-(2\alpha c)^2}{\mu_{31}}\right] \\ +\frac{(q_h-q_c)}{16\alpha}\left(\frac{1}{\mu_{32}}-\frac{1}{\mu_{31}}\right)\left[(2D_0+\beta(q_h+q_c))^2-(2\alpha c)^2\right] \\ -\frac{c}{4}\left\{ \begin{array}{l} (q_3-q_c)\left[\frac{(2D_0+\beta(q_3+q_c)-2\alpha c)}{\mu_{32}}-\frac{(2D_0+\beta(4q_3-q_h-q_c)-2\alpha c)}{\mu_{31}}\right] \\ -\frac{\beta(3q_3-q_h-2q_c)(q_h-q_c)}{\mu_{31}} \end{array} \right\} \end{array} \right\} \tag{159}$$

As a result, if the cumulative supply chain investment falls within the aforementioned critical threshold ($0 < I < I_{RS}$), then the system will gain more profits with IoT. Conversely, if the investment exceeds the threshold ($I > I_{RS}$), then investing in IoT is not rational for the coordinated supply chain.

4.5.4. Numerical analysis. An extension of the previous numerical examples is presented to analyze the effect of the parameters on the two-price revenue-sharing supply chain. The same values are assigned to the input parameters as before (see Table 4). Two additional parameters of wholesale price w_2 and revenue-sharing factor δ are initially assumed as 2.60 $/unit and 60%, respectively, keeping the values consistent with the single price revenue-sharing model.

4.5.4.1. Effect of quality deterioration rate on profits. The impact of reducing the quality deterioration rate using IoT on the coordinated system profits, excluding the fixed cost of investment, is studied in the same way as the previous systems. As illustrated in Table 13, the initial rate of 0.0067/hr is reduced to rates varying between 0.006/hr and 0.003/hr, and the supplier, retailer, and total supply chain profits are found at each rate. Then, the percentage difference in the profits due to IoT, as compared to the initial rate of 0.0067/hr without IoT, is computed.

Table 13: Effect of reducing deterioration rate on two-price revenue-sharing profits

μ_3 (/hr)	π_s ($)	$\Delta\pi_s$ (%)	π_r ($)	$\Delta\pi_r$ (%)	π ($)	$\Delta\pi$ (%)
0.0067	98.121	0.000	60.756	0.00%	158.877	0.00%
0.006	119.513	21.392	50.600	-16.72%	170.113	7.07%
0.0055	130.378	32.257	55.200	-9.14%	185.578	16.81%
0.005	143.416	45.295	60.720	-0.06%	204.136	28.49%
0.0045	159.351	61.230	67.467	11.05%	226.818	42.76%
0.004	179.270	81.149	75.900	24.93%	255.170	60.61%
0.0035	204.880	106.759	86.743	42.77%	291.623	83.55%
0.003	239.026	140.906	101.200	66.57%	340.227	114.15%

As presented in Table 13 and Figure 34, the retailer, supplier, and thus, the entire supply chain, generate greater profits as the deteriorate rate is lowered. Figure 34 also shows that the supplier's increase in profit margins is considerably higher than the retailer's, which is even lower than the percentage profit increase of the overall supply chain. However, this is due to the initial values assumed for the wholesale price and revenue-sharing factor, and would vary if these contract conditions are altered. Therefore, as established earlier, the supplier and retailer's contribution towards the IoT investment cost must still be equal.

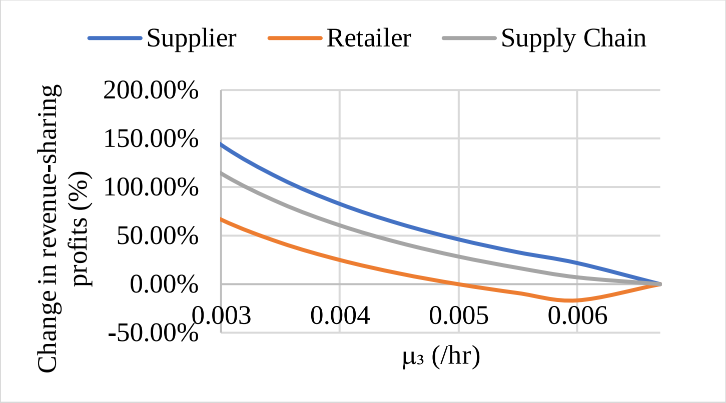

Figure 34: Effect of reducing deterioration rate on two-price revenue-sharing profits

4.5.4.2. Effect of initial quality. Assuming once again the original and reduced deterioration rates μ_{31} and μ_{32} as 0.0067/hr and 0.004/hr, respectively, the effect of initial quality level q_3 on the critical investment thresholds of the retailer, supplier and overall coordinated supply chain – $I_{R,rs}$, $I_{S,rs}$, and I_{RS} , respectively – is studied.

At initial quality levels varying from 0.60 to 1.00, Figure 35 shows that the three critical investment thresholds become higher as q_3 increases, which implies that higher investments in IoT can be made at a higher initial quality. Furthermore, at the assumed parameter values, the retailer's threshold is much lower than the supplier's threshold. Nevertheless, unlike the decentralized supply chain, the retailer and supplier's thresholds under the revenue-sharing system are also dependent on the wholesale price and revenue-sharing factor. Consequently, the retailer's threshold may be higher or lower than that of the supplier based on these two additional parameter values.

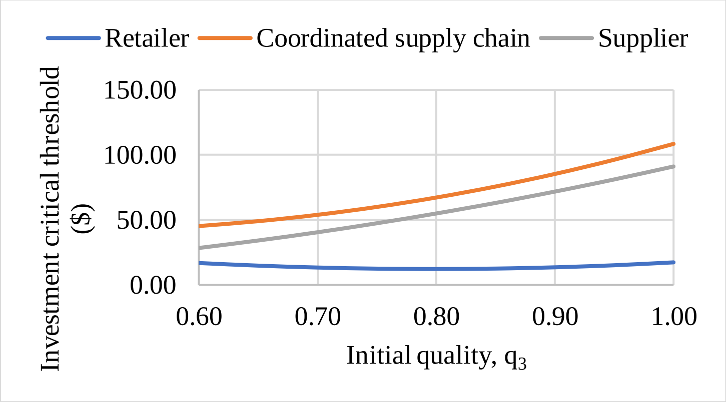

Figure 35: Effect of initial quality on investment thresholds for two-price revenue-sharing system

4.5.4.3. Effect of relative elasticity. The impact of relative elasticity on the two-price revenue-sharing profits, excluding IoT investment costs, is analyzed at the reduced quality deterioration rate of 0.004/hr. As shown in Figure 36, varying the ratio from 0.001 to 0.01 reveals that the profits are substantially higher at a very low ratio and the demand has a much higher sensitivity to quality than price. However, as the ratio increases above 0.002 and the demand becomes more sensitive to price, both the supplier and retailer profits become much lower.

Moreover, Figure 36 demonstrates that the retailer generates greater profits than the supplier at the specified values of w_1 and δ, whereas the opposite was observed for the decentralized system. However, as mentioned earlier, this may vary based on the values assumed for these two parameters.

Additionally, Figure 37 illustrates the effect of the relative elasticity on the investment critical thresholds at ratios varying between 0.001 and 0.01. Similar to the decentralized system, the three investment thresholds are considerably higher when the ratio is below 0.002. This permits the supply chain to invest higher amounts in IoT when the demand is highly sensitive to quality. However, the thresholds become significantly lower at ratios above 0.002 as price sensitivity increases, which indicates that the willingness to invest in IoT decreases.

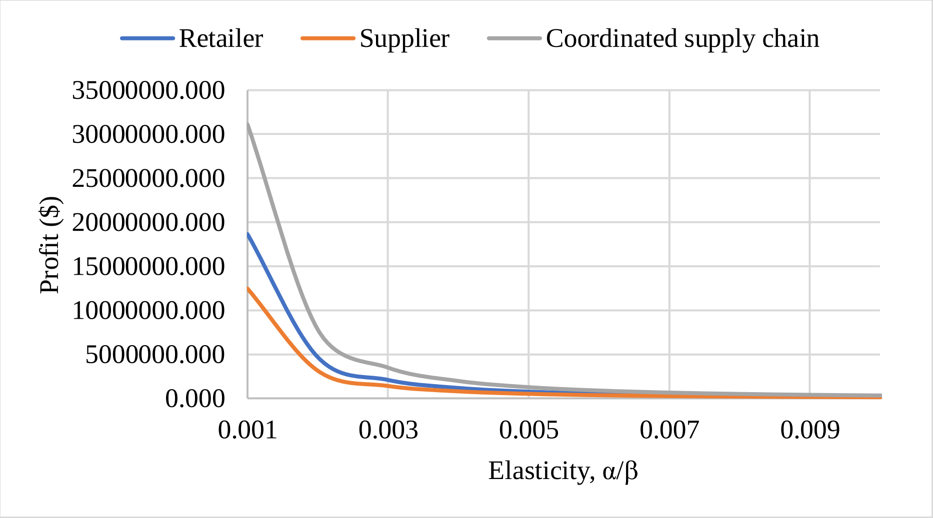

Figure 36: Effect of relative elasticity on two-price revenue-sharing profits

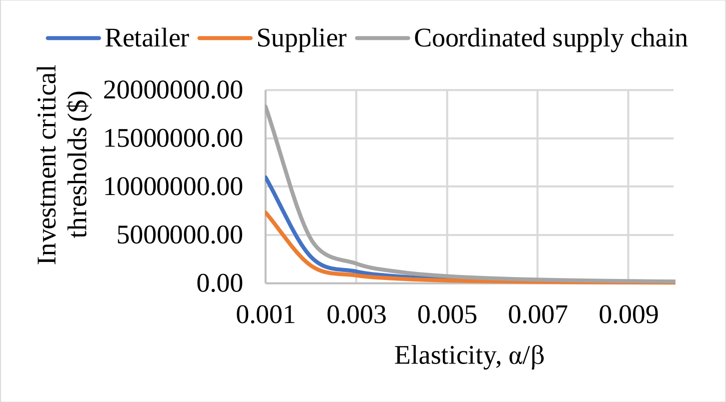

Figure 37: Effect of relative elasticity on investment thresholds for two-price revenue-sharing system

4.5.4.4. Effect of revenue-sharing factor. As determined earlier, since very low profits are generated when the demand has a high price sensitivity, a lower relative elasticity is used to analyze the effect of the revenue-sharing factor δ on the network. A quality sensitivity factor β of 18.3 is assumed for a ratio of 0.1, while the other parameters have the same values as before with a reduced deterioration rate of 0.004/hr.

As anticipated, Figure 38 shows that as δ increases, the retailer's percentage increase in profits due to revenue-sharing coordination increases, while a reverse trend is observed for the supplier. However, the increase in total supply chain profit remains constant at 27.24%, which is also the percentage increase in overall profits due to centralization. It is usually preferred to identify a value of δ that results in an equal percentage increase in profits for both the retailer and supplier, which is discerned to be a little over 50% in this specific example.

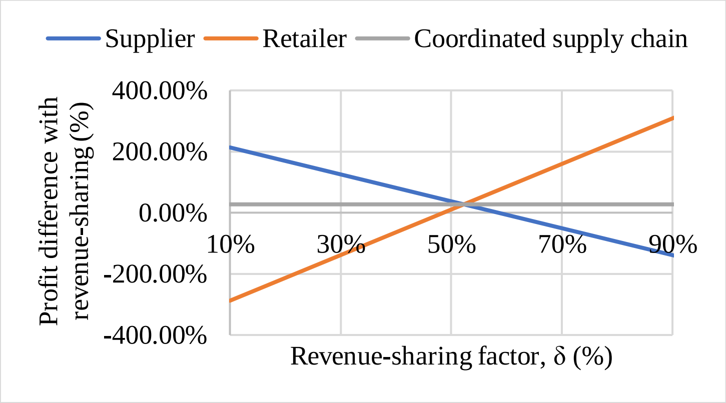

Figure 38: Effect of two-price revenue-sharing factor on profits as compared to decentralized system

Similarly, Figure 39 depicts that as expected, the retailer's critical investment threshold $I_{R,rs}$ increases and the supplier's critical investment threshold $I_{S,rs}$ decreases with increasing δ. However, the overall investment threshold of the coordinated system I_{RS} remains constant, since it is the same as the investment threshold for the centralized system, which is independent of the revenue-sharing factor δ. Due to the equal distribution of investment costs between the retailer and supplier, their individual investment contributions must be less than both $I_{R,rs}$ and $I_{S,rs}$ for IoT to prove beneficial for both of them. This is identified as the region under these two critical thresholds with a range of δ values from a little over 30% to around 80% for this particular case (see Figure 39).

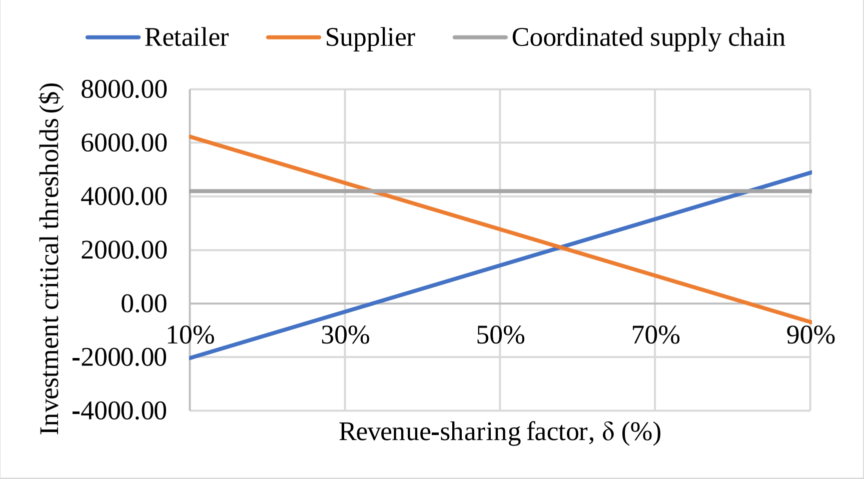

Figure 39: Effect of revenue-sharing factor on investment thresholds for two-price revenue-sharing system

Based on the above, the lower and upper bounds for the revenue-sharing factor are determined to find a region where both the players benefit from coordination. Based on the logic that the retailer's revenue-sharing profit must be greater than his decentralized profit, the lower bound is found as the following:

$$\delta > \frac{1}{4}\left\{\frac{\begin{bmatrix}\left(4D_0{}^2 - 8D_0\alpha c + 4\alpha^2 c^2\right) + 4\beta\left[D_0\left(q_3 + q_c\right) - \alpha c\left(q_3 + q_c\right)\right] \\ +\beta^2\left[q_3^2 - 2q_3 q_c + q_c^2 + 4q_h\left(q_3 + q_c\right) - 4q_h^2\right] + 16\alpha w_2\left(2D_0 + \beta(q_3 + q_c) - 2\alpha c\right)\end{bmatrix}}{\left(4D_0{}^2 - 4\alpha^2 c^2\right) + 4\beta\left[D_0\left(q_3 + q_c\right)\right] + \beta^2\left[q_3^2 + q_3 q_c + q_c^2 + q_h\left(q_3 + q_c\right) - q_h^2\right]}\right\} \tag{160}$$

Similarly, based on the theory that the supplier's revenue-sharing profit must be greater than his decentralized profit, the upper bound is determined as expressed below:

$$\delta < \frac{1}{2}\left\{\frac{\left[\begin{array}{l}\left(4D_0^{\,2}+8D_0\alpha c-12\alpha^2c^2\right)+4\beta\left[D_0\left(q_3+q_c\right)+\alpha c\left(q_3+q_c\right)\right]\\ +\beta^2\left(q_3^2+q_c^2+2q_h\left(q_3+q_c\right)-2q_h^2\right)+8\alpha\left(w_2-c\right)\left(2D_0+\beta(q_3+q_c)-2\alpha c\right)\end{array}\right]}{\left(4D_0^{\,2}-4\alpha^2c^2\right)+4\beta\left[D_0\left(q_3+q_c\right)\right]+\beta^2\left[q_3^2+q_3q_c+q_c^2+q_h\left(q_3+q_c\right)-q_h^2\right]}\right\} \tag{161}$$

4.5.4.5. *Effect of wholesale price.* The influence of the wholesale price w_2 is studied using β as 18.3 for a lower relative elasticity of 0.1 as above, with the same values for the other parameters as before. As expected, Figure 40 shows that as w_2 increases, the supplier's revenue-sharing profit becomes increasingly higher relative to his decentralized profit, whereas the opposite takes place for the retailer. However, as before, the overall supply chain's percentage increase in profit remains unchanged at 27.24% since it is independent of the wholesale price w_2.

Figure 40: Effect of wholesale price on two-price profits as compared to the decentralized system

Likewise, Figure 41 illustrates that the retailer's critical investment threshold $I_{R,rs}$ decreases while the supplier's critical investment threshold $I_{S,rs}$ increases with increase in w_2, as anticipated. The total supply chain threshold I_{RS}, however, remains the same as before.

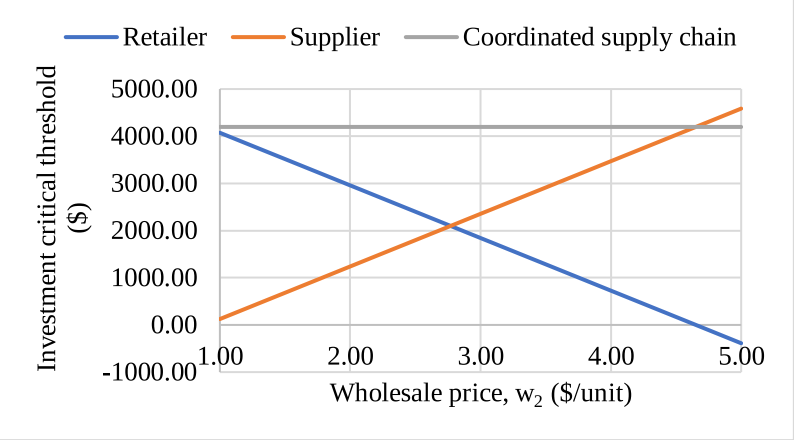

Figure 41: Effect of wholesale price on investment thresholds for two-price revenue-sharing system

Finally, the effect of w_2 on the bounds of the revenue-sharing factor is also examined. As illustrated in Figure 42, the upper and lower bounds for δ are directly proportional to w_2. This signifies that the fraction of the revenue δ retained by the retailer must be higher at a greater wholesale price for the retailer to benefit from revenue-sharing. Likewise, δ must be lower when the wholesale price is smaller for revenue-sharing to be beneficial for the supplier.

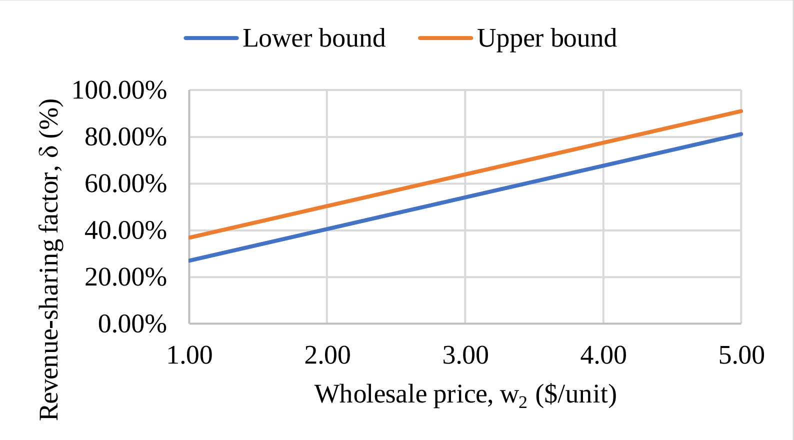

Figure 42: Effect of wholesale price on lower and upper bounds for two-price revenue-sharing factor

4.6. Managerial Implications

Similar to the single price strategy, the modelling and analysis of the two-stage price strategy provide essential managerial implications to food suppliers and retailers in a supply chain. As mentioned before, the decision for suppliers and retailers to employ real-time quality monitoring relies on the investment cost for the IoT setup and its correlation with the critical investment thresholds for the retailer, supplier, and overall supply chain established in this research. These thresholds are dependent on multiple parameters including the initial, organoleptic, and critical quality levels, the initial and reduced quality deterioration rates, and the relative demand elasticity. These factors must be taken into consideration before implementing IoT. Additionally, it is recognized that the retailer and supplier have a similar percentage increase in profits from decreasing the quality deterioration rate, therefore, the investment cost must be distributed equally between them.

Furthermore, where IoT quality monitoring is more likely to improve the financial performance of the retailer and supplier, methods should be explored by food companies to lessen the investment costs. Moreover, the optimal logistical points to deploy IoT must also be identified, which would ideally be found post-harvest within the first 24 to 48 hours since this duration is the most important for food quality. On the other hand, where IoT benefits the overall supply chain and one supply chain member but decreases profits of the other, the former should either increase his share of the investment costs or provide some incentives to the latter to encourage him to implement real-time quality monitoring.

Lastly, in order to acquire an optimal revenue-sharing mechanism, the retailer’s revenue-sharing factor must fall within specific lower and upper bounds, which are ascertained in this research. These bounds are dependent on the wholesale price set by the supplier, in addition to other parameters. Within these two bounds, both the retailer and supplier generate more profits with revenue-sharing than with decentralization, and therefore, the overall supply chain performance is enhanced.

Chapter 5. Conclusion and Future Work

In this research, mathematical models were developed and analyzed for multiple settings of a perishable food supply chain under two pricing strategies – the single price model and the two-stage price model. For each pricing strategy, the model was developed within the context of a two-echelon decentralized, centralized, and revenue-sharing structure. Additionally, each supply chain structure was modelled to depict a system with and without the use of IoT technology for real-time quality monitoring of the perishable food products. The optimal points were derived for each model variation, which were used to analyze the individual and joint performance and decisions of the supply chain members within each pricing strategy.

The key insight generated was that while the use of IoT enhanced the performance, there is a trade-off between the increased customer demand and the investment costs incurred. Whether the retailer, supplier and overall supply chain benefit from it depends on their respective critical investment thresholds, which are determined through a combination of parameters including the unit product cost, potential market size, quality deterioration rate, price and quality sensitivity factors, and initial, organoleptic and critical quality levels. Interestingly, the supplier's critical threshold is always found to be higher than that of the retailer within the decentralized structure; whereas their thresholds in the revenue-sharing structure vary depending on the revenue-sharing factor and wholesale price. Finally, for an effective coordination contract, the lower and upper bounds for the retailer's revenue-sharing factor are determined as functions of the wholesale price and the abovementioned parameters. Within these bounds, both the retailer and the supplier benefit from the revenue-sharing coordination mechanism.

While this research made progress in incorporating the impact of real-time quality monitoring and revenue-sharing coordination in single and two-stage pricing strategies, further studies can be undertaken to overcome the limitations of this modelling approach. First of all, since the quality degradation form varies depending on the type of perishable food product, this study can be developed using other forms of quality deterioration. Furthermore, these models can be extended to include a stochastic consumer demand as opposed to the deterministic demand used within this research. Since this research assumed a fixed time for price markdown, further research can be conducted to include the markdown time as a variable parameter. Further work can also include exploring the models with additional supply chain members as compared to the setting considered in this study with one retailer and one supplier. Moreover, this study can be extended by considering additional multiperiod pricing strategies. Finally, since this research only considered the revenue-sharing coordination, another future extension would be to investigate other supply chain coordination mechanisms.

References

[1] J. Gustavsson, C. Cederberg, U. Sonesson, R. van Otterdijk, and A. Meybeck, *Global Food Losses and Food Waste*. Rome: FAO, 2011.

[2] M. Rezaei and B. Liu, "Food Loss and Waste in the Food Supply Chain," 2017. [Online]. Available: http://theplate.nationalgeographic.com/2016/01/22/kenyan-farmers--ght-food-loss-by-drying-selling-mangoes/. [Accessed: May 11, 2019].

[3] E. Hegnsholt, S. Unnikrishnan, M. Pollmann-Larsen, B. Askelsdottir, and M. Gerard, "Tackling the 1.6-Billion-Ton Food Loss and Waste Crisis," 2018. [Online]. Available: http://image-src.bcg.com/Images/BCG-Tackling-the-1.6-Billion-Ton-Food-Waste-Crisis-Aug-2018 %281%29_tcm9-200324.pdf. [Accessed: May 11, 2019].

[4] Food and Agriculture Organization of the United Nations, *Food Wastage Footprint: Impacts on Natural Resources*. FAO, 2013.

[5] S. T. Foster, "Towards an Understanding of Supply Chain Quality Management," *Journal of Operations Management*, vol. 26, no. 4, pp. 461–467, 2008.

[6] A. C. Fernandes, H. Truong, P. Sampaio, and M. S. Carvalho, "Literature Review of Quality Management and Supply Chain Management: A Perspective of Integration," in *International Conference on Quality Engineering and Management*, 2014, pp. 103–114.

[7] L. A. Fish, "Supply Chain Quality Management," in *Supply Chain Management - Pathways for Research and Practice*, D. Onkal, Ed. InTech, 2011, pp. 25–42.

[8] E. Soltani, A. Azadegan, Y. Y. Liao, and P. Phillips, "Quality Performance in a Global Supply Chain: Finding Out the Weak Link," *International Journal of Production Research*, vol. 49, no. 1, pp. 269–293, 2010.

[9] C. J. Robinson and M. K. Malhotra, "Defining the Concept of Supply Chain Quality Management and its Relevance to Academic and Industrial Practice," *International Journal of Production Economics*, vol. 96, no. 3, pp. 315–337, 2005.

[10] A. J. Chaghooshi, M. Soltani-Neshan, and M. Moradi-Moghadam, "Canonical Correlation Analysis Between Supply Chain Quality Management and Competitive Advantages," *Foundations of Management*, vol. 7, no. 1, pp. 83–92, 2015.

[11] A. Soares, E. Soltani, and Y. Y. Liao, "The Influence of Supply Chain Quality Management Practices on Quality Performance: An Empirical Investigation," *Supply Chain Management*, vol. 22, no. 2, pp. 122–144, 2017.

[12] H. Kaynak and J. L. Hartley, "A Replication and Extension of Quality Management into the Supply Chain," *Journal of Operations Management*, vol. 26, no. 4, pp. 468–489, 2008.

[13] L. Da Xu, "Information Architecture for Supply Chain Quality Management," *International Journal of Production Research*, vol. 49, no. 1, pp. 183–198, 2011.

[14] R. Anupindi and Y. Bassok, "Supply Contracts with Quantity Commitments and Stochastic Demand," in *Quantitative Models for Supply Chain Management*, Boston, MA: Springer, 2011, pp. 197–232.

[15] M. I. Höhn, "Literature Review on Supply Chain Contracts," in *Relational Supply Contracts*, Berlin, Heidelberg: Springer, 2010, pp. 19–34.

[16] I. Giannoccaro and P. Pontrandolfo, "Supply Chain Coordination by Revenue Sharing Contracts," *International Journal of Production Economics*, vol. 89, no. 2, pp. 131–139, 2004.

[17] C. X. Wang, "A General Framework of Supply Chain Contract Models," *Supply Chain Management*, vol. 7, no. 5, pp. 302–310, 2002.

[18] K. Govindan and M. N. Popiuc, "Overview and Classification of Coordination Contracts within Forward and Reverse Supply Chains," 2011.

[19] Arshinder, A. Kanda, and S. G. Deshmukh, "Supply Chain Coordination: Perspectives, Empirical Studies and Research Directions," *International Journal of Production Economics*, vol. 115, no. 2, pp. 316–335, 2008.

[20] G. P. Cachon, "Supply Chain Coordination with Contracts," *Handbooks in Operations Research and Management Science*, vol. 11, pp. 227–339, 2003.

[21] A. A. Tsay, S. Nahmias, and N. Agrawal, "Modeling Supply Chain Contracts: A Review," in *Quantitative Models for Supply Chain Management*, Boston, MA: Springer, 1999, pp. 299–336.

[22] Z. K. Weng, "Coordinating Order Quantities Between the Manufacturer and the Buyer: A Generalized Newsvendor Model," *European Journal of Operational Research*, vol. 156, no. 1, pp. 148–161, 2004.

[23] S. Nahmias, *Production and Operations Analysis*, 5th ed. Boston, MA: McGraw-Hill Irwin, 2005.

[24] E. L. Porteus, "The Newsvendor Problem," in *Building Intuition*, Boston, MA: Springer, 2008, pp. 115–134.

[25] K. Govindan, M. N. Popiuc, and A. Diabat, "Overview of Coordination Contracts within Forward and Reverse Supply Chains," *Journal of Cleaner Production*, vol. 47, pp. 319–334, 2013.

[26] M. A. Lariviere and E. L. Porteus, "Selling to the Newsvendor: An Analysis of Price-Only Contracts," *Manufacturing and Service Operations Management*, vol. 3, no. 4, pp. 293–305, 2001.

[27] K. Govindan, A. Diabat, and M. N. Popiuc, "Contract Analysis: A Performance Measures and Profit Evaluation within Two-Echelon Supply Chains," *Computers and Industrial Engineering*, vol. 63, no. 1, pp. 58–74, 2012.

[28] Arshinder, A. Kanda, and S. G. Deshmukh, "A Framework for Evaluation of Coordination by Contracts: A Case of Two-Level Supply Chains," *Computers and Industrial Engineering*, vol. 56, no. 4, pp. 1177–1191, 2009.

[29] M. Tsiros and C. M. Heilman, "The Effect of Expiration Dates and Perceived Risk on Purchasing Behavior in Grocery Store Perishable Categories," *Journal of Marketing*, vol. 69, no. 2, pp. 114–129, 2005.

[30] X. Wang and D. Li, "A Dynamic Product Quality Evaluation Based Pricing Model for Perishable Food Supply Chains," *Omega*, vol. 40, no. 6, pp. 906–917, 2012.

[31] X. Chen, S. Wu, X. Wang, and D. Li, "Optimal Pricing Strategy for the Perishable Food Supply Chain," *International Journal of Production Research*, vol. 57, no. 9, pp. 2755–2768, 2019.

[32] P. S. Taoukis, T. P. Labuza, and I. S. Saguy, "Kinetics of Food Deterioration and Shelf-Life Prediction," in *Handbook of Food Engineering Practice*, New York: CRC Press LLC, 1997, pp. 361–403.

[33] T. P. Labuza, "Application of Chemical Kinetics to Deterioration of Foods," *Journal of Chemical Education*, vol. 61, no. 4, pp. 348–358, 1984.

[34] M. Achour, “A New Method to Assess the Quality Degradation of Food Products During Storage,” *Journal of Food Engineering*, vol. 75, no. 4, pp. 560–564, 2006.

[35] M. A. J. S. Van Boekel, “Kinetic Modeling of Food Quality: A Critical Review,” *Comprehensive Reviews in Food Science and Food Safety*, vol. 7, pp. 144–158, 2008.

[36] P. S. Taoukis, K. Koutsoumanis, and G. J. E. Nychas, “Use of Time-Temperature Integrators and Predictive Modelling for Shelf Life Control of Chilled Fish under Dynamic Storage Conditions,” *International Journal of Food Microbiology*, vol. 53, no. 1, pp. 21–31, 1999.

[37] S. D. Shim, S. W. Jung, and S. J. Lee, “Mathematical Evaluation of Prediction Accuracy for Food Quality by Time Temperature Integrator of Intelligent Food Packaging through Virtual Experiments,” *Mathematical Problems in Engineering*, vol. 2013, pp. 1–9, 2013.

[38] J. Baranyi and T. A. Roberts, “A Dynamic Approach to Predicting Bacterial Growth in Food,” *International Journal of Food Microbiology*, vol. 23, no. 3–4, pp. 277–294, 1994.

[39] K. Xanthiakos, D. Simos, A. S. Angelidis, G. J. E. Nychas, and K. Koutsoumanis, “Dynamic Modeling of Listeria Monocytogenes Growth in Pasteurized Milk,” *Journal of Applied Microbiology*, vol. 100, no. 6, pp. 1289–1298, 2006.

[40] M. R. Ansorena, M. G. Goñi, M. V. Aguëro, S. I. Roura, and K. C. Di Scala, “Application of the General Stability Index Method to Assess the Quality of Butter Lettuce during Postharvest Storage using a Multi-Quality Indices Analysis,” *Journal of Food Engineering*, vol. 92, no. 3, pp. 317–323, 2009.

[41] H. Hong, Y. Luo, S. Zhu, and H. Shen, “Application of the General Stability Index Method to Predict Quality Deterioration in Bighead Carp (Aristichthys Nobilis) Heads during Storage at Different Temperatures,” *Journal of Food Engineering*, vol. 113, no. 4, pp. 554–558, 2012.

[42] R. Badia-Melis, P. Mishra, and L. Ruiz-García, “Food Traceability: New Trends and Recent Advances. A Review,” *Food Control*, vol. 57, pp. 393–401, 2015.

[43] R. Y. Chen, “Autonomous Tracing System for Backward Design in Food Supply Chain,” *Food Control*, vol. 51, pp. 70–84, 2015.

[44] A. Osvald and L. Z. Stirn, “A Vehicle Routing Algorithm for the Distribution of Fresh Vegetables and Similar Perishable Food,” *Journal of Food Engineering*, vol. 85, no. 2, pp. 285–295, 2008.

[45] P. Bowman, J. Ng, M. Harrison, T. S. Lopez, and A. Illic, “Sensor Based Condition Monitoring,” 2009. [Online]. Available: www.bridge-project.eu. [Accessed: May 11, 2019].

[46] G. Alfian *et al.*, “Integration of RFID, Wireless Sensor Networks, and Data Mining in an E-Pedigree Food Traceability System,” *Journal of Food Engineering*, vol. 212, pp. 65–75, 2017.

[47] M. Ghaani, C. A. Cozzolino, G. Castelli, and S. Farris, “An Overview of the Intelligent Packaging Technologies in the Food Sector,” *Trends in Food Science and Technology*, vol. 51, pp. 1–11, 2016.

[48] K. Óskarsdóttir and G. V. Oddsson, “Towards a Decision Support Framework for Technologies used in Cold Supply Chain Traceability,” *Journal of Food Engineering*, vol. 240, pp. 153–159, 2019.

[49] K. L. Yam, P. T. Takhistov, and J. Miltz, “Intelligent Packaging: Concepts and Applications,” *Journal of Food Science*, vol. 70, no. 1, pp. R1–R10, 2006.

[50] G. Fuertes, I. Soto, R. Carrasco, M. Vargas, J. Sabattin, and C. Lagos, “Intelligent Packaging Systems: Sensors and Nanosensors to Monitor Food Quality and Safety,” *Journal of Sensors*, vol. 2016, 2016.

[51] Z. Fang, Y. Zhao, R. D. Warner, and S. K. Johnson, “Active and Intelligent Packaging in Meat Industry,” *Trends in Food Science and Technology*, vol. 61, pp. 60–71, 2017.

[52] K. B. Biji, C. N. Ravishankar, C. O. Mohan, and T. K. Srinivasa Gopal, “Smart Packaging Systems for Food Applications: A Review,” *Journal of Food Science and Technology*, vol. 52, pp. 6125–6135, 2015.

[53] Zest Labs, “Food Freshness Management,” 2019. [Online]. Available: https://www.zestlabs.com/food-freshness-management/. [Accessed: Nov. 25, 2020].

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