A Study on the Effect of New Technologies on Supply Chain Coordination

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Abstract

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Concordia University, 2019

In this globalized economy, the fierce competition in the market, added to the increasingly exigences from customers demanding products with more added value and lower prices, force organizations to be always at the vanguard to maintain their positioning in the market. One critical ingredient for maintaining the competitive advantage is the acquisition and implementation of new technologies for achieving process and product enhancement. This is specially the case for high-tech industries in sectors like aerospace, pharmaceutic and telecommunication, to name but a few. But investment in new technologies is a challenging decision due to their complexity for implementation and the cost involved. Therefore, it is of utmost importance to understand the effect of new technologies on the performance of the acquiring company and on its supply chain. Although the existence of an ample number of empirical studies in the current literature describing the relation between supply chain ($\mathcal{SC}$) operation and new technologies acquisition, analytical research on this matter is quite scarce. In this thesis, our objective is to model and analyze the effect of new technologies on the $\mathcal{SC}$ members performance. We propose two main directions of research: (1) impact of technology transfer among SC members; and (2) impact of technology investment in the $\mathcal{SC}$. In the first direction, we consider that an existing technology in the supply chain is transferred from its owner to a different member in the system. In the second direction, we assume that the new technology is independently acquired by an organization in the supply chain, i.e. obtained from a third-party or through internal R&D. Furthermore, we analyze the impact of new technologies on the performance of different system structures. On the first stream of research, we discuss the effect

of technology transfer on a one-supplier one-manufacturer supply chain system involving technology transfer and market sharing. We consider the technology transfer decision to be made by the manufacturer, the key technology owner, as the decision affects its market share. It is proposed three models for analyzing the system performance: (i) a supply chain without technology transfer, (ii) a supply chain with technology transfer but without supplier's market sharing, and (iii) a supply chain with technology transfer and supplier's market sharing. Findings show that the optimal profit of the manufacturer in a supply chain with technology transfer and market sharing is typically greater than those without technology transfer or market sharing. The analysis also provides the conditions for the manufacturer to enhance technology transfer when the supplier's market is open to the final products. On the second stream of research, we explore the impact of technology investment on supply chain coordination. We first investigate the optimal pricing and technology investment decisions in a system consisting of one manufacturer and two competing retailers. On one hand, the manufacturer is required to invest in new technologies in order to improve its performance. On the other hand, the retailers compete in the same market with different products. We determine the conditions at which the cost-revenue sharing contract and the two-part tariff contract are capable of coordinating the one-manufacturer two-retailer supply chain system. Lastly, we analyze a system consisting of multiple complementary suppliers and a single manufacturer. It is assumed that the suppliers are required to invest in new technologies in order to participate in the supply chain negotiations. While the manufacturer initially offers a wholesale price contract to the suppliers. We compare both the decentralized and centralized settings, and show that if the supply chain members decide to cooperate and coordinate the system, they could increase the overall expected profit by at least 1/3 compared to the non-cooperative scenario. We then find that although the cost-sharing contract is unable to coordinate the system, the cost-revenue sharing contract is capable of coordinating the multi-supplier and single-manufacturer supply chain. Moreover, we establish the conditions at which the cost-revenue sharing contract offers a win-win profit scenario to all parties of the negotiation and review how bargaining analysis can lead to the optimal negotiation ability of each member.

Dedication

To my beloved mother, Gladys E. Gallegos Carrasco, for all her love, hard work and self sacrifice that allowed me and my brothers to be the persons we are now. Gracias mamita, te amo.

To my beloved father, Fernando Rodriguez Comastri, for his constant support and care for me and my brothers to keep advancing and working hard. Gracias papi, te amo.

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Chapter 1

Introduction

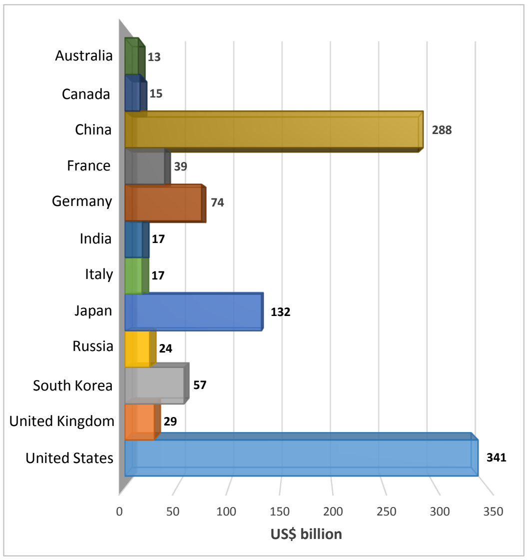
1.1 Overview and Problem statement

According to Forbes (2018), the manufacturing sector is fundamentally changing. Increasingly industries are turning their competitive advantage focus from a cost-reduction strategy to a more robust high-tech manufacturing. Cutting-edge technologies enable companies to develop advanced processes and products which offer higher levels of productivity and quality, and that are better perceived by the end customer. Recognizing the significance of this transition, a number of nations have already aligned their efforts to support their manufacturing sector on becoming global high-tech manufacturing leaders. We can mention examples like the China's Made in China 2025 Program, and the European Union's Industry 4.0 Program (Subcommittee on advanced manufacturing, 2018). As reported by McKinsey Global Institute (2017) the manufacturing sector in U.S. currently represents 35% of the productivity growth, 60% of exports, 70% of R&D in the private sector , 9% of employment and 12% of GDP. This report suggests that by 2025, with the contribution of state-of-the-art technology, U.S. manufacturing industry could augment their value up to US$530 billion which represents a 20% increase, in addition to add 2.4 million jobs to the economy. U.S.-based manufacturing companies have taken note on this potential benefits. A survey from The Boston Consulting Group (2015) reveals that 72% of the large-size companies interviewed have plans to invest in new advanced technologies in the next five years. Table 1.1 presents a summary of some of the exponential new technologies in manufacturing.

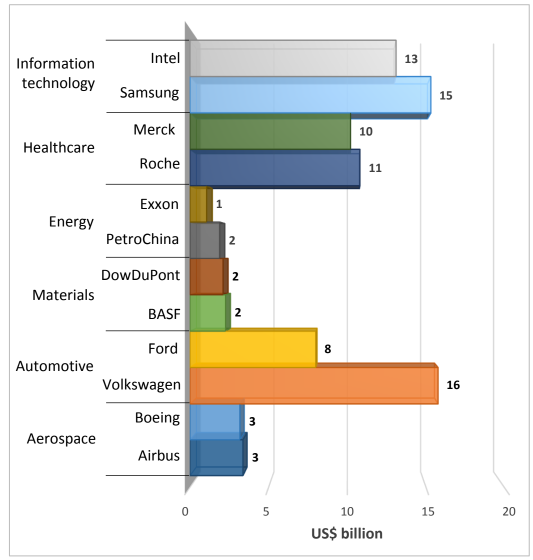
Table 1.1: Worldwide market of exponential new technologies (source: Deloitte (2018))

Technology	Sector	Investment 2016 (US$ billion)	Expected investment 2021 (US$ billion)
Additive manufacturing	Aerospace, automotive	13	36
Advanced materials	Aerospace, automotive	195	283
Advanced robotics and cognitive automation	Manufacturing, health care	92	225
Digital design, simulation, and integration	Computer-Aided Design	25	45
Energy storage	Electronics, transportation	37	54

We can consider different sources when referring to new technologies acquisition, i.e. external and internal sources of technology. Examples of external sources are the merge and acquisition of tech-companies, and the acquisition of avant-garde equipment or intellectual property. An example of internal sources is the development of new processes or products through internal R&D. According to Thomson Reuters (2016), from the 46,055 merger transactions taken place worldwide on 2016, 13% (US$487.63 billion) were acquisitions of high-tech companies. Value only surpassed by merges in the energy and power sector. We can mention cases like Qualcomm's US$39 billion purchase of NXP Semiconductors (The New York Times, 2017), Ulta acquisition of QM Scientific and GlamST (Digiday UK, 2019), and Intel's US$13.8 billion purchase of Mobileye (J.P. Morgan, 2018). Compared to latter case, purchase of new high-tech equipment or intellectual property requires smaller size investment, but could bring considerable benefits to the company. As example, when Airbus suffered a shortage of relatively inexpensive parts bought from a supplier, that caused potential production and revenue losses to the company, Airbus decided to invest on a 3D printer to manufacture the pieces in-house, saving the company at least 50 days of supply lead times (Strategy&, 2017). Lastly, investment on internal R&D is seen as critical in the manufacturing industry. Forbes (2018) reported that 86% of the top 100 companies investing into R&D worldwide belong to the manufacturing sector. Among them it is worth to mention General Electric efforts to build an engine piece using new technologies on additive manufacturing that decreases its weight by 25% and increases its durability by 5 times, and Ford investment on digital design, simulation, and integration technologies for developing aluminum castings used for engines, that had helped the company to save more than US$120 million and reduced the development time by 15%-25% (The Boston Consulting Group, 2015). To illustrate the magnitude of investment on R & D, Figure 1.1a shows the private-sector investment per country, and Figure 1.1b presents the investment per industry sector on 2018.



(a) Private-sector expenditure in R&D per country (source: Unesco (2018))



(b) Expenditure in R&D per company (source: Strategy& (2018))

Figure 1.1: Expenditure in R&D (2018)

Although acquisition of new technologies can become a critical factor of competitive advantage for industries in sectors like aerospace, pharmaceutic and telecommunication, investment on new technologies is a challenging decision due to its complexity for implementation and the cost involved. Hence, it is of utmost importance to understand the impact of new technologies on the performance of the acquiring company and on its supply chain. In order to investigate how technology can help the economy to increase efficiency and productivity across industries, we aim to answer the following questions through our research:

- Does new technologies acquisition offer benefits to supply chain members?
- Is it possible to coordinate a supply chain system in presence of technology acquisition decisions?

- What is the impact of the coordination contracts on the pricing and technology investment decisions of the system?
- Can the coordination contracts be designed to offer a win-win scenario for all agents of the negotiation?

1.2 Acquisition of new technologies in the supply chain

Traditionally, supply chain management has centered its attention in studying how materials, monetary funds and information influence the competitive advantage of the $\mathcal{SC}$ agents (Cerchione & Esposito, 2016); but a fourth dimension, knowledge, has become an increasingly important factor to be considered (Jiabin, Lili, & Dongmei, 2010; Kang & Jiang, 2011). The field of knowledge management makes a clear distinction between information and knowledge (Erickson & Rothberg, 2014). Information is seen as descriptions that support the understanding of a specific subject and that is explicit and easily transferred (Rowley, 2007). There exist a vast literature on analytical studies that tackle the impact of different types of information on $\mathcal{SC}$ performance and how its accessibility can be of benefit for the $\mathcal{SC}$ members. Table 1.2 summarizes some of these works.

Knowledge stands a step further from information as the accumulation of learning, expertise and know-how useful for the problem solving process but that at the same time poses more difficulties when being managed and shared (Rowley, 2007). Battistella, De Toni, and Pillon (2016) highlighted that the $\mathcal{SC}$ knowledge consists of four basic components, one of them been the technological component. This latter is the subject of our research. Technology is not limited to tangible elements like equipment or tools, but it could also refer to intangible aspects like experience and skills. Table 1.3 presents examples of different expressions of technology.

Global competition makes the acquisition of new technologies crucial for the success of any firm (Kumar, Luthra, & Haleem, 2015). Due to the increasingly technological complexity and shortened life-cycle of products, organizations are compelled to continually invest in new technologies to maintain their positioning in the market (Bhaskaran & Krishnan, 2009). Technology is seen as a key element for competitive advantage (Reisman, 2005) that can lead companies to access wider

Table 1.2: Literature on information in the supply chain

Information	Author
Demand forecast	Ha, Tong, and Zhang (2011) Leng and Parlar (2009) T. Li and Zhang (2015) Rached, Bahroun, and Campagne (2015)
Production plan	Huang, Lau, and Mak (2003)
Inventory level	Rached et al. (2015) H. Zhang, Nagarajan, and Sošić (2010)
Order quantity	Xue, Shen, Tan, Zhang, and Fan (2011)
Shipment information	Scott (2015) C. Zhang, Tan, Robb, and Zheng (2006)
Lead time	F. Chen and Yu (2005) Rached et al. (2015)
Quality level	H.-c. P. Choi, Blocher, and Gavirneni (2008) Wu, Zhai, Zhang, and Liu (2011) Xue et al. (2011)
Product return information	J. Chen (2011) R. Yan and Cao (2017)
Cost information	Güler, Körpeoğlu, and Şen (2018)

markets, sales increment, cost reduction, brand enhancement, to name but a few (da Silva, Kovaleski, & Pagani, 2019; Kumar et al., 2015). And its benefits are not limited only to the owner of the technology but they can be translated into the performance improvement of the $\mathcal{SC}$ as a whole (Kang & Jiang, 2011). On the other hand, management of new technologies can result challenging because of its complexity and high cost (Bhaskaran & Krishnan, 2009; Günsel, 2015), specially for high-tech industries (Battistella et al., 2016). In this thesis, we study the effect of technology acquisition in the $\mathcal{SC}$ performance. Specifically, we consider two main sources of new technologies: (1) the acquisition of a new technology through its transfer among $\mathcal{SC}$ members; and (2) the acquisition of a new technology through the investment on its own R&D or third-party source outside the $\mathcal{SC}$

system.

Table 1.3: Examples of different expressions of technology

Technology aspect	Example	Technology aspect	Example
Tangible	Materials Tools Equipment Machinery Product Prototype	Intangible	Skills Applied knowledge Methods Intellectual property Experience

1.2.1 Transfer of technology among supply chain members

As discussed by Tatikonda and Stock (2003), a $\mathcal{SC}$ can be categorized depending on the elements flowing in the system as either a: product/component $\mathcal{SC}$; or a technology $\mathcal{SC}$. In Chapter 2, we consider that the system under study not only involves the flow of products, but that a main objective is the transfer of technology between members. Due to the fact that the performance of a company is tied to that of its suppliers (Ishizaka & López, 2018), $\mathcal{OEM}$s are constantly motivated to improve its suppliers' capabilities (El Ouardighi & Kim, 2010; Niosi & Zhegu, 2010) so that they can obtain parts and components with higher quality and lower cost. Suppliers, in turn, are also encouraged by the $\mathcal{OEM}$ to invest and adopt new technologies. Technology transfer is an essential process in latter scenario because it favors the diffusion and implementation of new technologies between $\mathcal{SC}$ members in a fraction of the time and cost required by its original developer (Goldstein, 2006). In our research for Chapter 2 we define two main players in our analysis, a technology source entity (the $\mathcal{OEM}$) and a technology recipient entity (the Supplier) who are engaged into interfirm negotiations to attain the transfer of new technologies.

1.2.2 Investment on technology in the supply chain

Different from technology transfer, a $\mathcal{SC}$ under technology investment deals only with the flow of product/component among the members of the system. In this case, the technology is utilized as a tool to attain system enhancement, i.e. for meeting manufacturing regulations (Bai, Chen, & Xu, 2017), amelioration of the quality level (Bhaskaran & Krishnan, 2009; Chakraborty, Chauhan, & Ouhimmou, 2019), etc. Because the required technology is not part of the system, its acquisition is achieved either through its own R&D or through a third-party technology supplier outside the $\mathcal{SC}$. In Chapter 3 and 4 we study the impact of technology investment considering different features. Firstly, Chapter 3 reviews a downstream $\mathcal{SC}$ in which the $\mathcal{OEM}$ solely decides the level of investment in new technologies, as it interacts with an oligopoly formed by two Retailers. Secondly, Chapter 4 studies an upstream $\mathcal{SC}$ system where multiple Suppliers make decisions on the level of technology investment they will engage for the components manufactured for the $\mathcal{OEM}$.

Table 1.4 presents a summary of the features considered in the thesis.

1.3 Motivation and Research objectives

In this globalized economy, the fierce competence in the market, added to the increasingly exigences from customers demanding products with more added value and lower prices, force organizations to be always at the vanguard to maintain their positioning in the market. One critical ingredient for maintaining the competitive advantage is the acquisition and implementation of new technologies for achieving process and product enhancement. This is specially the case for high-tech industries in sectors like aerospace, pharmaceutic and telecommunication, to name but a few. But the acquisition of new technologies is a challenging decision due to its complexity for implementation and the cost involved. Therefore, it becomes critical for the industry sector to determine the effect of new technologies on the performance of the acquiring company and on its supply chain. There exist a vast literature that empirically describes the benefits of new technologies implementation on supply chain systems, but analytical research on this matter is quite scarce. In this thesis, our main objective is to model and analyze the impact of new technologies on the supply chain members performance and to demonstrate how it can lead to the coordination of the system. The specific research objectives of this thesis include:

- Study the effect of technology transfer in a supply chain influenced by market sharing. We introduce a one-supplier one-manufacturer system under production yield uncertainty and review the impact of technology transfer and market sharing on the order quantity decision.

Table 1.4: Summary of the features considered in the thesis

Feature		Chapter 2	Chapter 3	Chapter 4
Technology acquisition	Through transfer among SC members	✓		
	Through investment		✓	✓
Technology acquisition agents	Single agent	✓	✓	
	Multiple agents			✓
Supply chain decision	Technology level	✓	✓	✓
	Order quantity	✓		
	Retail price		✓	✓
	Wholesale price		✓	✓
Randomness	Demand		✓	✓
	Production yield	✓		
Supply chain category 1	$\mathcal{OEM}$'s upstream	✓		✓
	$\mathcal{OEM}$'s downstream		✓	
Supply chain category 2	Product / component	✓	✓	✓
	Technology	✓		
Supply chain structure	One-supplier one-manufacturer	✓		
	One-manufacturer two-retailer		✓	
	Multi-supplier single-manufacturer			✓
Market structure	Monopoly	✓		✓
	Oligopoly		✓	
Findings	Profit benefit	✓	✓	✓
	System coordination		✓	✓
	Win-win condition			✓
	Bargain analysis			✓

- Investigate the effect of a manufacturer's investment decision on new technology on a supply chain formed by one manufacturer and two retailers influenced by uncertain demand.

- Study the effect of multiple suppliers' investment decisions on new technologies on the performance of a two echelon supply chain. We consider a system affected by uncertain demand and analyze the behavior of the pricing decisions for both the manufacturer and suppliers.

1.4 Contributions

This thesis presents a number of main contributions in modeling and analyzing the effect of new technologies on $\mathcal{SC}$ performance that differentiate our research from the existing literature. The main contributions of this thesis are summarized as follows:

- We demonstrate that a supply chain system under technology acquisition decisions can achieve coordination, and we prove the specific conditions under which different contract agreements are capable of coordinating the system.
- We show that under particular conditions coordination of the supply chain can lead to a reduction on pricing decisions, and at the same time can lead to an increment on the level of technology acquisition.
- We prove that certain coordination contracts can be designed to reach a win-win state for all agents of the negotiation.

Specifically, the contributions from Chapter 2 are:

- We find that for each of the considered scenarios, there exists an optimal profit level which is a concave function on the optimal order quantity.
- We prove the required condition for finding the optimal order quantity, and also show the benefit for the manufacturer to include supplier's market sharing into the negotiation in setting up the supply chain.
- For the considered supply chain systems, we demonstrate that for any level of technology transfer, the optimal order quantity and therefore the optimal profit are always higher when the supplier is willing to share some of its market with the manufacturer than the case that market share is not part of the negotiation. In addition, we also notice certain behaviors of the proposed models with respect to technology transfer.
- We present the necessary conditions for reaching the optimal technology transfer level even when the supplier's market sharing is not included in the supply chain structure.

From our findings, the main contributions in Chapter 3 are:

- We demonstrate that a one-manufacturer two-retailer $\mathcal{SC}$ system under technology investment can achieve coordination, and we prove the specific conditions under which the CR contract and the TPT contract are capable of coordinating the system.

- We show that coordination of the supply chain can lead to a reduction on the pricing decisions, i.e. wholesale price and retail price, and at the same time can lead to an increment on the level of the technology acquisition decision.

- Through a numerical example we observe that both the CR and TPT contracts can reach a win-win state for all agents in the supply chain.

The main contributions from Chapter 4 are:

- We prove that if the $\mathcal{SC}$ members decide to cooperate and coordinate the system, they could increase the overall expected profit by at least 1/3 compared to the non-cooperative supply chain.

- We find that under particular conditions, coordination of the $\mathcal{SC}$ can lead to a reduction on the retail price, and also to an increment on the level of technology acquisition.

- We demonstrate that although the CS contract does not offer the necessary incentives to coordinate the $\mathcal{SC}$, the CR contract proves to reach perfect coordination of the system.

- We prove that there exist a feasible solution for $LB_{\phi_i} \leq \phi_i \leq UB_{\phi_i}$ that offers a win-win condition for both the manufacturer and the suppliers in the CR contract.

- We show that through bargaining analysis it is possible to determine the optimal negotiation ability of each SC member.

- The numerical example shows that as the number of suppliers involved in the negotiation increase, benefits on profit and level of technology acquisition further improve when compared to the decentralized scenario.

The results of the research shown in this thesis have been presented in the following conferences:

(a) 21st Conference of the International Federation of Operational Research Societies (IFORS) (Quebec city, Canada, July 2017).

(b) 2019 International Conference on Intelligent Transportation and Logistics with Big Data & the 7th International Forum on Decision Sciences (Windsor, Canada, July 2019), where it was nominated as a candidate for the best paper award.

(c) INFORMS Annual Meeting (Seattle, United States, October 2019).

In addition, three journal articles were used in the body of this thesis and are currently under review in the following research Journals:

(a) Computers & Industrial Engineering (August 2019).

(b) International Journal of Production Economics (September 2019).

(c) Production and Operations Management (September 2019).

1.5 Organization of the thesis

Chapter 1 provides an overview and a summary of the problem statement, objectives and contributions of this thesis. The remainder of the thesis is organized as follows:

In Chapter 2, we introduce a supply chain model consisting of one supplier and one manufacturer to study the impact of technology transfer and market sharing in the negotiation. We consider that the manufacturer is the owner of the key technology who decides whether or not to transfer it to the supplier depending on the openness of the supplier's market to the manufacturer's final products. In Section 2.1 we present a brief introduction, followed by a review in Section 2.2 of the literature relevant to technology transfer in one of the pillar high-technology industrial sectors, the aerospace sector. The problem description and model formulation is shown in Section 2.3, followed by a detailed analysis of the optimal decisions in Section 2.4. A numerical example is provided in Section 2.5 to illustrate the model and the analytical results. Summary and conclusions are drawn in Section 2.6.

In Chapter 3, we review the impact of new technologies on supply chain coordination by investigating the optimal pricing decisions and technology investment decision in a one-manufacturer two-retailer system. After the introduction in Section 3.1, a review of the literature relevant to technology investment and supply chain coordination is presented in Section 3.2. In section 3.3, we describe the base model and illustrate the supply chain structure. Section 3.4 is dedicated to the equilibrium analysis. In section 3.5, we set out the cost-revenue sharing contract and the two-part tariff contract, and determine the coordination conditions for the supply chain participants. In Section 3.6, we use a numerical example to discuss the impact of each contract on the supply chain performance. Lastly, the conclusions are given in section 3.7 followed by future research directions.

In Chapter 4, we analyze a multi-supplier single-manufacturer supply chain system impacted by technology investment decisions. We first give a brief introduction on Section 4.1, followed by review of the current research on technology acquisition in the supply chain and contract coordination mechanisms in Section 4.2. In section 4.3, we introduce the base model and explain the structure of the supply chain model proposed. Section 4.4 is dedicated to the comparison of the decentralized and centralized scenarios in this system. In sections 4.5 and 4.6, we present the cost-sharing contract and the cost-revenue sharing contract, respectively, and study the conditions at which the supply chain members can attain the system coordination. In Section 4.7, we develop a numerical example to discuss the managerial insight of our findings. Finally, the conclusions and future research directions are given in section 4.8.

Lastly, In Chapter 5, we summarize the main conclusions and future research directions of this thesis in Sections 5.1 and 5.2, respectively.

Chapter 2

Technology Transfer in a One-supplier One-manufacturer Supply Chain

Chapter 2 discusses the effect of technology transfer on a supplier-manufacturer relationship in a supply chain system involving technology transfer and market sharing. We consider the technology transfer decisions to be made by the original equipment manufacturer, the key technology owner, as they affect its market share. This chapter proposes three models for analyzing the effect of technology transfer: (i) a supply chain without technology transfer, (ii) a supply chain with technology transfer but without supplier's market sharing, and (iii) a supply chain with technology transfer and supplier's market sharing. A numerical example with sensitivity analysis is presented to illustrate the theoretical findings and analytical results. We show that the optimal profit of the original equipment manufacturer in a supply chain with technology transfer and market sharing is typically greater than those without technology transfer or market sharing. The analysis also provides the conditions for the original equipment manufacturer to enhance technology transfer when the supplier's market is open to the final products. The proposed supply chain model is illustrated with applications in aerospace industry and it can be extended for solving similar problems in other industries. Research findings from Chapter 2 are currently under review on the journal Computers & Industrial Engineering.

2.1 Introduction

The aerospace and defense industry is one of the main pillars of U.S. trade that in 2017 generated \$143 billion in sales representing alone 9 percent of American exports (SpaceNews, 2018). On 2018, Boeing sold \$101 billion and gave job to more than 150,000 employees worldwide (Boeing, 2018a). A fifth of the commercial aircrafts manufactured by Boeing on 2014 were sold to China, and it is forecasted that in twenty years Boeing fleet will triple in the country, with expected sales of \$950 billion (The Washington Post, 2015). With these considerations, in recent years Boeing has moved forward to strength its commercial relations with China. On 2018, Boeing opened its first 737s completion facility in the Asian country, a joint venture with the Chinese state-owned aerospace company COMAC (Reuters, 2018), as part of the requirements for a \$38 billion 300-plane order of 737 airplanes placed by Chinese airline companies (Bloomberg, 2015). This joint venture is an example of how Chinese companies can access Boeing technology in exchange of sharing a larger portion of its local aerospace market (The Washington Post, 2015). For the past ten years India has been considered as the world's largest importer of aerospace and defense equipment. Nowadays, the country is under negotiations with different companies worldwide for a \$20 billion 110-fighter aircraft order. Boeing has offered India to build a new facility in the country for manufacturing its F/A-18 Super Hornet if it obtains this order. In addition, Boeing has moved forward partnering with the Indian companies Mahindra & Mahindra Ltd. and Hindustan Aeronautics Ltd. as part of the agreement (Bloomberg, 2019). The decision of Boeing comes because of the requirement of the Indian government that the majority of the planes bought from this contract have to be assembled in the country, as a national effort to make foreign partners transfer state-of-the-art technology to their local counterparts (The New York Times, 2018). In the case of Airbus, this year China has decided to place an order of 290 A320 planes and 10 A350s aircrafts summing a total of US\$ 35 billion (South China Morning Post, 2019). For the last decade, Airbus has been assembling its A320s in China (Yahoo Finance, 2019), but this deal came thanks to an offer of Airbus to expand a production line in Tianjin that will include a completion center for its A330s (Bloomberg, 2018). All of these are some examples of how technology transfer can play a crucial role in supply chain negotiations as an effective tool for further accessing the market demand in foreign nations.

Although the existence of an ample number of empirical studies that describe the relation between supply chain performance and the transfer of new technologies between supply chain parties, analytical research on this matter is quite scarce. In this chapter, our aim is to model and analyze the impact of technology transfer on the supply chain members performance. Furthermore, this chapter intends to open the discussion on how technology transfer and market sharing interact at the time when supply chain actors engage into negotiation. More specifically, this chapter discusses how a original equipment manufacturer (OEM) is concerned with the impact of technology transfer on its profit and market share. While the supplier is more interested in accessing the OEM's technology through the contract. We propose a mathematical model to describe this supply chain system and present the sufficient conditions for a favorable scenario where technology transfer takes place in the negotiations.

The remainder of the chapter is organized as follows. After the introduction, a review of the literature relevant to technology transfer in the aerospace sector is presented in Section 2.2. The model formulation is shown in Section 2.3, followed by a detailed analysis of the optimal decisions in Section 2.4. A numerical example is provided in Section 2.5 to illustrate the model and the analytical results. Summary and conclusions are drawn in Section 2.6.

2.2 Literature review

In the past several decades, emerging economies have sought various ways to shift from labor-intensive manufacturing to more value-added functions in global supply chains for healthier and more economical development. Such changes, however, require advanced technological know-hows and avant-garde level of specializations (Eriksson, 2011; McGuire, 2011). Aerospace industry, for example, is often considered as one of the strategic and high value-added industry sectors for developing as well as developed countries (Dostaler, 2013). In the past 50 years, the world commercial aircraft manufacturing industry has been dominated by major competitors in the US and Western Europe. Economical benefits and technological advancement have motivated different nations to venture in the development of this industry (Goldstein, 2006) with new players arising in Asia, Eastern Europe and Latin America (McGuire, 2011).

Commercial airplanes are manufactured typically in low volumes and have long life cycles (Eriksson, 2011). State-of-the-art technology is crucial for success and it requires intensive expenses in research and development (Eriksson, 2011) with financial returns taking place after long time periods (McGuire, 2011). Demand is often volatile and purchasing decisions are frequently influenced by economical, financial and political considerations (Eriksson, 2010). In addition, aerospace product development and manufacturing are highly regulated by national and international authorities (McGuire, 2011) due to the rigorous quality requirements in the sector (Dietrich & Cudney, 2011), making the lead time from design to market much longer than that of non-aerospace products.

In today's world, only few nations have the necessary means to sustain the whole aircraft industry (Eriksson, 2010) with international aerospace supply chains dominated by very few original equipment manufacturers (OEMs). Similar to other supply chains, aerospace supply chains are organized in different tiers. OEMs are at the top of these chains such as Airbus and Boeing dominating the market of mainline and transcontinental commercial aircraft. Bombardier and Embraer are the main OEMs dominating the regional jet market. The OEMs outsource manufacturing and certain design functions to Tier 1 suppliers which provide aircraft subsystems and components. Tier 1 suppliers may in turn outsource certain activities to Tier 2 companies. Raw material suppliers are typically at the bottom of such supply chains (Eriksson, 2010).

Investment required for an aerospace project is often difficult to sustain by an OEM alone. To survive in this highly competitive industry, an OEM may follow an integrated low-cost strategy. Supplier's presence in the aerospace sector is becoming increasingly relevant (Morton, Dainty, Burns, Brookes, & Backhouse, 2006). It has been noticed that commercial aerospace industry is changing (Dostaler, 2013) from OEM dominated supply chains to more cooperative partnerships (Wagner, Ohlhausen, Vilsmeier, & Bennion, 1999) with risk and revenue sharing among the parties at different tiers (Rose-Anderssen, Baldwin, & Ridgway, 2011). As it evolves, higher level of technology and financial sharing among major project partners has been observed (Rose-Anderssen et al., 2009).

When an OEM decides to launch a new model or upgrade an existing one, product design, development, manufacturing, assembly and services may take place in different countries (Eriksson, 2011). Therefore, the OEM will mainly focus on core activities such as design, system integration and marketing, with manufacturing and other activities taking place around the globe (Monroy & Arto, 2010). On the other hand, this practice has been considered as an opportunity for suppliers in emerging economies to gain technology advancement (Monroy & Arto, 2010; Niosi & Zhegu, 2010). Similar to the OEMs, many aerospace suppliers also face challenges of high level competitions on safety, quality, performance, and cost-effectiveness in manufacturing aerospace parts and components (Dostaler, 2013). Due to the fact that the performance of a company is tied to that of its suppliers (Ishizaka & López, 2018), many OEMs have motivated to improve its suppliers' capabilities in all these aspects (El Ouardighi & Kim, 2010; Niosi & Zhegu, 2010) so that they can obtain parts and components with higher quality and lower cost. Suppliers, in turn, are also encouraged by the OEM to invest and adopt new technologies. If not successful, a supplier may be removed from the supply chain system (Dostaler, 2013).

In this type of supply chains, Tier I suppliers can be less interested in building under license, but desire to participate in more active ways for accessing the state-of-the-art technology (Niosi & Zhegu, 2010). In other sectors, it is possible to acquire advanced technology by starting with lower quality components and moving to higher level products. In aerospace industry, however, this approach can be difficult or impossible due to extensive regulatory and certification procedures required for aerospace design, manufacturing and testing processes (McGuire, 2011). A common strategy used by Tier I suppliers to acquire advanced technology from OEMs is through political influence (Rose-Anderssen et al., 2011). Supplier's country may decide to buy significant number of an OEM's aircraft if certain important parts and components are designed and manufactured in the supplier's country (Buzacott & Peng, 2012). This will not only generate local jobs but also help local suppliers to absorb foreign technologies (Eriksson, 2010). A local government may also demand that the OEM transfer some part of the technology to the suppliers in exchange for further opening the local market to the OEM (McGuire, 2011; Rose-Anderssen et al., 2009). After the project is complete, the local suppliers may implement the more advanced foreign technology for subsequent understanding and assimilating to make it own with much reduced time and cost of research and development (Goldstein, 2006). But in addition outsourcing has proven to be a fundamental strategy for the manufacturing firms worldwide (Kaur, Singh, & Majumdar, 2018), and this is not exception for the OEM. Outsourcing design and manufacturing with technology transfer may also help the OEM to capture a larger portion of the market outside the supplier's country since the final product will have its cost reduced and quality improved as the supplier progresses with the transferred technology (Aamer, 2018; Niosi & Zhegu, 2010). Therefore, OEM's outsource to the supplier results in a mutually beneficial approach for both members of the supply chain (Gunasekaran & Irani, 2010).

Partnership with suppliers involving technology transfer, however, can be a risky approach for the OEM in the global competition as technology transfer can also lead to the loss of its competitive advantage over the supplier which may have plan to becoming a new OEM in the near future (Buzacott & Peng, 2012; Dolgui & Proth, 2013; McGuire, 2011). In addition, technology of one OEM transferred to a supplier may be used by the latter in producing parts for other OEMs competing in the same market (Nasr, Kilgour, & Noori, 2015). Consequently, an OEM may safeguard its sensitive information from competitors by investing in just few high qualified supply chain partners (Rose-Anderssen et al., 2009). In certain situations, instead of monitoring the supplier, trust and commitment are necessary in this type of supply chain partnership to avoid opportunistic behavior (Monroy & Arto, 2010; Rose-Anderssen et al., 2011). Risk and revenue sharing is another way to obtain commitment of the links in the supply chain (Cooper, Lambert, & Pagh, 1997). Risk and revenue sharing partnership can be seen as a win-win model as the OEM can increase sells while the supplier has access to its cutting edge technology (Eriksson, 2010).

2.3 Problem Description and Model Formulation

This chapter considers a two level supply chain consisting of an OEM and a supplier. We assume that there is no forced compliance required on the supplier in the considered supply chain (Cachon, 2003). In such supply chains, both supplier and OEM are subject to the risk caused by product quality variations and hence have more opportunities for various forms of sharing, such as revenue sharing (Cachon & Lariviere, 2005), risk sharing (Chick, Mamani, & Simchi-Levi, 2008), or information sharing (Ren, Cohen, Ho, & Terwiesch, 2010). Technology transfer discussed in this chapter is one of these cooperation mechanisms. In this section, we first consider a simple case and assume that there is no technology transfer from the OEM to the supplier. Then it is presented two extended models considering technology transfer from the OEM to the supplier.

2.3.1 *Supply Chain without Technology Transfer*

In presenting the first model, the primary focus will be on the OEM. Let w be the wholesale price of the products from the supplier, r be the retail price of the products the OEM will charge to its end customers. Let X be a random variable representing the quality level of the products delivered by the supplier, and $f(x)$ be its probability density function with $\mu = \mathbb{E}X$. Let T be the size of the entire market for the products and s be the OEM's share of the market. Hence the OEM's market demand is sT. Finally let q be the quantity of the products that the OEM decides to order from the supplier so that the OEM's profit $\Pi_{\mathcal{OEM}}$ will be maximized.

$$\Pi_{\mathcal{OEM}} = \mathbb{E}_X \left(r \min\{sT, qX\} - wqX \right). \tag{1}$$

2.3.2 *Technology Transfer without Supplier's Market Sharing*

This chapter now assumes that the OEM owns certain special technology, which, if fully transferred to the supplier, would improve supplier's capability in product quality and production cost. It is further assumed that the OEM may not transfer the whole technology to the supplier for different reasons, however, decides to transfer part of the technology to the supplier. Let α $(0 \leq \alpha \leq 1)$ denote the percentage of the technology that will be transferred. As results the transferred technology will improve the quality level X as well as lower the wholesale and retail prices of the end product. Let $w(\alpha)$ and $r(\alpha)$ be the new wholesale price and retail price, respectively. Let X_α be the random variable representing the new quality level, and $f_\alpha(x)$ be its probability density function with $\mu(\alpha) = \mathbb{E}X_\alpha$. From the above mentioned assumptions, we have $\mu(\alpha) \geq \mu$. Due to the lowered product cost and higher product quality, the total market size should be improved. Let $T(\alpha)$ be the new total market and $s(\alpha)$ be the OEM's new share of the market. Hence the OEM's new market demand is $s(\alpha)T(\alpha)$ with $s(\alpha)T(\alpha) \geq sT$. Finally, let Q_1 be the OEM's new order quantity. Then the OEM chooses the optimal Q_1 to maximize its profit $\Pi^1_{\mathcal{OEM}}$ corresponding to the level α of technology transferred to the supplier.

$$\Pi^1_{\mathcal{OEM}} = \mathbb{E}_{X_\alpha}\left(r(\alpha)\min\{s(\alpha)T(\alpha), Q_1X_\alpha\} - w(\alpha)Q_1X_\alpha\right). \tag{2}$$

Clearly, the optimal order quantity depends on α, denoted by $Q_1(\alpha)$.

2.3.3 *Technology Transfer with Supplier's Market Sharing*

We further assume that the supplier's local governments have influences on the local market that the OEM has targeted. Due to the OEM's technology transfer to the local supplier, the local market now is open to the OEM's end products. Assume that the size of the local market is H and the OEM's portion of H can be expected at Y_α as the result of its technology transfer. In other words, this influenced market share is not strictly bonded and Y_α is a random variable. Let $g_\alpha(y)$ be the probability density function of Y_α and $\mathbb{E}Y_\alpha = \lambda(\alpha)$. This chapter also assumes that $\lambda(\alpha)$ is an increasing function of α. In this case, the market demand for the OEM is $s(\alpha)T(\alpha) + HY_\alpha$. Finally, let Q_2 be the OEM's order quantity in this supply chain system. Then the OEM will choose the optimal Q_2 for the given level α of technology transfer and the given supplier's market share Y_α to maximize its profit $\Pi^2_{\mathcal{OEM}}$.

$$\Pi^2_{\mathcal{OEM}} = \mathbb{E}_{X_\alpha,Y_\alpha}\left(r(\alpha)\min\{s(\alpha)T(\alpha) + HY_\alpha, Q_2X_\alpha\} - w(\alpha)Q_2X_\alpha\right). \tag{3}$$

Similarly to that in Section 2.2, $Q_2(\alpha)$ is used to denote the optimal order quantity, which is a function of α.

2.4 Analysis of Optimal Decisions

In this section we derive several basic properties of the three models introduced in the previous section. For notation simplicity, the next two functions are sometimes used: $k(\alpha) := \frac{w(\alpha)\mu(\alpha)}{r(\alpha)}$ and $h(\alpha) := s(\alpha)T(\alpha)$. The notation $k := k(0) = \frac{w\mu}{r}$ and $h := h(0) = sT$ are also used when appropriate.

2.4.1 *The Optimal Order Quantities and Profits*

Proposition 1. *We have the following properties concerning to the optimal order quantities and profits:*

(1) $\Pi_{\mathcal{OEM}}$ *is concave on q, and the optimal order quantity that maximizes* $\Pi_{\mathcal{OEM}}$ *satisfies*

$$\int_0^{\frac{h}{q}} xf(x)dx = k. \tag{4}$$

(2) For any given $0 \leq \alpha \leq 1$*, with quality level being a random variable* X_α*,* $\Pi^1_{\mathcal{OEM}}$ *is concave on* Q_1 *and the optimal order quantity* $Q_1(\alpha)$ *satisfies*

$$\int_0^{\frac{h(\alpha)}{Q_1(\alpha)}} xf_\alpha(x)dx = k(\alpha). \tag{5}$$

(3) For any given $0 \leq \alpha \leq 1$*, with quality level being a random variable,* X_α *and supplier's market share* Y_α*,* $\Pi^2_{\mathcal{OEM}}$ *is concave on* Q_2 *and the optimal order quantity* $Q_2(\alpha)$ *satisfies*

$$\int_0^1 \int_0^{\frac{h(\alpha)+Hy}{Q_2(\alpha)}} xf_\alpha(x)g_\alpha(y)dxdy = k(\alpha). \tag{6}$$

Proof. Below we prove Point (3) as an example. Proofs for the first two points are similar.

The first partial derivative of $\Pi^2_{\mathcal{OEM}}$ with respect to Q_2 is

$$r(\alpha)\int_0^1 \int_0^{\frac{h(\alpha)+Hy}{Q_2}} xf_\alpha(x)g_\alpha(y)dxdy - w(\alpha)\mu(\alpha).$$

By setting this partial derivative to 0, (6) is obtained.

The second partial derivative of $\Pi^2_{\mathcal{OEM}}$ with respect to Q_2 is

$$\frac{\partial^2\Pi^2_{\mathcal{OEM}}}{\partial Q_2^2} = -\frac{r(\alpha)}{Q_2^3}\int_0^1 (h(\alpha)+Hy)^2 f_\alpha\left(\frac{h(\alpha)+Hy}{Q_2}\right) g_\alpha(y)dy < 0,$$

This implies that $\Pi^2_{\mathcal{OEM}}$ is concave on Q_2. □

Let q denote the optimal order quantity that satisfies (4), this chapter next study the relationship between $Q_1(\alpha)$ and q. Naturally, it is expected that Q_1 is greater than or equal to q if the OEM transfers some of its technology to the supplier. In addition, $Q_1(\alpha)$ should increase as α increases in a certain range.

Proposition 2. *For any given $0 \leq \alpha \leq 1$, the optimal order quantity $Q_1(\alpha)$ will increase if the following condition is satisfied,*

$$h(\alpha) f_\alpha \left(\frac{h(\alpha)}{Q_1(\alpha)} \right) h'(\alpha) \geq Q_1^2(\alpha) k'(\alpha). \tag{7}$$

In particular letting $\alpha = 0$, we get $Q_1(0+) > q$ if

$$h f_\alpha \left(\frac{h}{q} \right) h'(0) > q^2 k'(0). \tag{8}$$

Proof. From (5), by implicit differentiation of $Q_1(\alpha)$ with respect to α, it is obtained

$$Q_1'(\alpha) = \frac{1}{h(\alpha)} \left[h'(\alpha) Q_1(\alpha) - \frac{k'(\alpha) Q_1^3(\alpha)}{h(\alpha) f_\alpha\left(\frac{h(\alpha)}{Q_1(\alpha)}\right)} \right],$$

This provides the result by letting $Q_1'(\alpha) \geq 0$. □

The condition (7) can easily be satisfied when $h'(\alpha) \geq 0$ and $k'(\alpha) \leq 0$ hold simultaneously. In the numerical example presented in the next section, we can see that this indeed is the case. In general, $h(\alpha)$ is concave and first increasing then decreasing, while $k(\alpha)$ is convex and decreasing. Hence in most practical applications, the condition (7) should naturally be satisfied. Since the profits $\Pi^1_{\mathcal{OEM}}$ and $\Pi^2_{\mathcal{OEM}}$ are also functions of α, they are denoted by $\Pi^1_{\mathcal{OEM}}(\alpha)$ and $\Pi^2_{\mathcal{OEM}}(\alpha)$, respectively.

It is interesting to mention that Proposition 2 shows to the participants of the negotiation that i) with the given α the highest possible optimal order quantity is not reached, but at the same time that ii) there exist a positive incremental tendency of the optimal order quantity with that given α. All this will encourage participants of the supply chain to further increase the percentage of technology transfer in the negotiation.

Proposition 3. *For any given $0 \leq \alpha \leq 1$,* *(1)* $Q_2(\alpha) > Q_1(\alpha)$*;*

(2) $\Pi^2_{\mathcal{OEM}}(\alpha) > \Pi^1_{\mathcal{OEM}}(\alpha)$.

Proof. (1) Given α, by (5) and (6), we have $\int_0^1 F(y)dy = 0$, where

$$F(y) = \int_{\frac{h(\alpha)+Hy}{Q_2(\alpha)}}^{\frac{h(\alpha)}{Q_1(\alpha)}} x f_\alpha(x) g_\alpha(y) dx.$$

Applying the mean value theorem, there exists a $0 < \xi < 1$, such that $F(\xi) = \int_0^1 F(y)dy$, hence

$$\int_{\frac{h(\alpha)+H\xi}{Q_2(\alpha)}}^{\frac{h(\alpha)}{Q_1(\alpha)}} x f_\alpha(x) g_\alpha(\xi) dx = 0.$$

Since $x f_\alpha(x) g_\alpha(\xi) > 0$, it is obtained $\frac{h(\alpha)}{Q_1(\alpha)} = \frac{h(\alpha)+H\xi}{Q_2(\alpha)} > \frac{h(\alpha)}{Q_2(\alpha)}$, hence $Q_2(\alpha) > Q_1(\alpha)$.
(2) Given α, since $Q_2(\alpha)$ is the optimal order quantity that maximizes OEM's profit when supplier shares some market Y_α and $Q_1(\alpha) \neq Q_2(\alpha)$, hence $\Pi^2_{\mathcal{OEM}}(Q_2(\alpha), \alpha) > \Pi^2_{\mathcal{OEM}}(Q_1(\alpha), \alpha)$, where

$$\Pi^2_{\mathcal{OEM}}(Q_1(\alpha), \alpha) = \mathbb{E}_{X_\alpha, Y_\alpha} \left(r(\alpha) \min\{h(\alpha) + HY_\alpha, Q_1(\alpha)X_\alpha\} - w(\alpha)Q_1(\alpha)X_\alpha \right).$$

Since $HY_\alpha \geq 0$, we have that $\min\{h(\alpha) + HY_\alpha, Q_1(\alpha)X_\alpha\} \geq \min\{h(\alpha), Q_1(\alpha)X_\alpha\}$, hence $\Pi^2_{\mathcal{OEM}}(Q_1(\alpha), \alpha) \geq \Pi^1_{\mathcal{OEM}}(Q_1(\alpha), \alpha)$, therefore $\Pi^2_{\mathcal{OEM}}(Q_2(\alpha), \alpha) > \Pi^1_{\mathcal{OEM}}(Q_1(\alpha), \alpha)$, as desired. $\square$

As a simple summary of the above analysis, it is shown that $Q_2(\alpha) > Q_1(\alpha) > q$ and $\Pi^2_{\mathcal{OEM}}(Q_2(\alpha), \alpha) > \Pi^1_{\mathcal{OEM}}(Q_1(\alpha), \alpha) > \Pi_{\mathcal{OEM}}$ for every $0 \leq \alpha \leq 1$ in most cases. Proposition 3 evidences to the OEM that any level of technology transfer is of benefit for the negotiation. But it is important to remark that when designing the contract, the OEM should seek for the scenario in which the supplier agrees on an increment of the market share, as this will be translated into higher benefits.

2.4.2 *The Behavior of the Technology Transfer Models*

As discussed in the previous section, both OEM and supplier are interested in knowing the values of α_i that maximizes $\Pi^i_{\mathcal{OEM}}(\alpha)$ for $i = 1, 2$, respectively. In the following analysis we assume that $Q_i(\alpha), \Pi^i_{\mathcal{OEM}}(\alpha)$ are concave. Hence there exists α_1, α_2 that maximize $\Pi^1_{\mathcal{OEM}}(\alpha), \Pi^2_{\mathcal{OEM}}(\alpha)$, respectively. By the nature of the considered problem, $\Pi^i_{\mathcal{OEM}}(\alpha)$ can achieve its maximal value whenever $Q_i(\alpha)$ does so, hence to analyze $\Pi^i_{\mathcal{OEM}}(\alpha)$, it is sufficient to analyze $Q_i(\alpha)$. This simplification enables us to be able to gain certain insightful understanding on the behavior of α_1 and α_2 depending on other functions in the proposed models.

Proposition 4. *If there exits one $\alpha_0 \in (0, 1]$ such that $k'(\alpha_0) = 0$ and $h'(\alpha_0) = 0$ hold simultaneously, then $\alpha_2 = \alpha_1 = \alpha_0$.*

Proof. By implicit differentiation of (5) and (6), it is obtained

$$\frac{h(\alpha)}{Q_1(\alpha)} f_\alpha\left(\frac{h(\alpha)}{Q_1(\alpha)}\right) \frac{h'(\alpha)Q_1(\alpha) - h(\alpha)Q_1'(\alpha)}{Q_1(\alpha)^2} = k'(\alpha),$$

and

$$\int_0^1 \frac{h(\alpha) + Hy}{Q_2(\alpha)} f_\alpha\left(\frac{h(\alpha) + Hy}{Q_2(\alpha)}\right) \frac{h'(\alpha)Q_2(\alpha) - (h(\alpha) + Hy)Q_2'(\alpha)}{Q_2(\alpha)^2} g_\alpha(y)dy = k'(\alpha).$$

Applying the condition that $k'(\alpha_0) = h'(\alpha_0) = 0$, gives as result that $Q_1'(\alpha_0) = 0$ and $Q_2'(\alpha_0) = 0$, the concavity assumption then implies the assertion. $\square$

The condition in Proposition 4 may have slight chance to happen in certain situations while it should be avoided by the supply chain parties in the negotiation for technology transfer in exchange of market opening. The reason for this is that under this scenario, designing a contract with or without an increment in the market share, will lead in both cases that the highest optimal profit is obtained with the same level of technology transfer. And by knowing this, the supplier will not have an incentive to increase the market share to the OEM.

Proposition 5. *If $\frac{d}{d\alpha}\left(\frac{\lambda(\alpha)}{\mu(\alpha)}\right) > 0$ for all $0 \le \alpha \le 1$, then $\alpha_2 > \alpha_1$.*

Proof. If we consider the extreme case that the random variables take their expectation values with full probability, it is obtained

$$\Pi^1_{\mathcal{OEM}} = r(\alpha)\min\{h(\alpha), \mu(\alpha)Q_1(\alpha)\} - \mu(\alpha)w(\alpha)Q_1(\alpha),$$

and

$$\Pi^2_{\mathcal{OEM}} = r(\alpha)\min\{h(\alpha) + H\lambda(\alpha), \mu(\alpha)Q_2(\alpha)\} - \mu(\alpha)w(\alpha)Q_2(\alpha).$$

Hence we obtain $Q_1(\alpha) = \frac{h(\alpha)}{\mu(\alpha)}$ and $Q_2(\alpha) = \frac{h(\alpha)}{\mu(\alpha)} + H\frac{\lambda(\alpha)}{\mu(\alpha)} = Q_1(\alpha) + H\frac{\lambda(\alpha)}{\mu(\alpha)}$. By the assumption that $Q_i(\alpha)$ are concave and α_i maximizes $Q_i(\alpha)$ for $i = 1, 2$, we know that $Q_1'(\alpha_1) = 0$ and $Q_2'(\alpha_2) = 0$. But we have $Q_2'(\alpha_1) > 0$ as long as $\frac{d}{d\alpha}|_{\alpha=\alpha_1}\left(\frac{\lambda(\alpha)}{\mu(\alpha)}\right) > 0$, hence it is demonstrated that $\alpha_2 > \alpha_1$ by the concavity of $Q_2(\alpha)$. □

The condition $\frac{d}{d\alpha}\left(\frac{\lambda(\alpha)}{\mu(\alpha)}\right) > 0$ for all $0 \leq \alpha \leq 1$ has an intuitive interpretation. It in fact requires that the supplier's market sharing percentage Y_α be increased faster than the increase of the quality improvement resulted from the technology transfer. In contrast to Proposition 4, clearly this is a desirable situation for the OEM. The above proposition states that under this situation the OEM would be willing to transfer more technology to the supplier. This in turn, provides the incentive for the supplier side to share more of its market for this increase level of technology transfer. Therefore, this proposition gives us a simple description of the "win-win" situation. For example, the condition in this proposition is satisfied in the numerical example in Section 2.5, hence it is expected by this proposition that $\alpha_2 \geq \alpha_1$, which is indeed verified there.

The above two propositions, as a whole, indicate certain conditions to be avoided and parameter values to seek for in their negotiations to reach a "win-win" situation between the OEM and supplier in the supply chain.

2.5 Numerical Example

In this numerical example it is assumed the following forms of the related functions.

$$c(\alpha) = c\Big(1 - \frac{\alpha^i}{h}\Big), (0 < i < 1), \qquad w(\alpha) = w - \frac{\widetilde{w}}{d}\alpha^p, (0 < p < 1);$$

$$r(\alpha) = r - \frac{r-w}{m}\alpha^q, (0 < q < 1), \qquad s(\alpha) = -u\alpha^2 + v\alpha + s;$$

$$T(\alpha) = T(1 + \frac{\alpha^e}{n}), (0 < e < 1), \qquad l(\alpha) = a + (b-a)\sqrt{\alpha};$$

$$\lambda_\alpha = \lambda\alpha^2, \qquad \mathbb{E}X_\alpha = \mu(\alpha) = \frac{l(\alpha)+1}{2};$$

$$\mathbb{E}Y_\alpha = \lambda(\alpha) = \frac{\lambda_\alpha}{2}, \qquad f(x) = 6(x-a)(x-1)(a-1)^{-3};$$

$$f_\alpha(x) = 6[x - l(\alpha)][x-1][l(\alpha)-1]^{-3}, \qquad g_\alpha(y) = -6\lambda_\alpha^{-2}y(\lambda_\alpha^{-1}y - 1).$$

Some interpretation of these functions are given below.

- $\widetilde{w}$: This can be viewed as the difference between unit wholesale price and unit production cost;
- s: This the OEM's market share before technology sharing;
- $s(\alpha)$: Assume that $s(\alpha)$ is concave, for simplicity, in this chapter, a quadratic function is used;
- $l(\alpha)$: Assume that the OEM requires that the products delivered from the supplier satisfy a minimal quality level, denoted by this $l(\alpha)$. Hence $l(\alpha) \leq f_\alpha(x) \leq 1$;
- a, b: They are the bounds of supplier's quality level corresponding to no technology transfer ($\alpha = 0$) and full technology transfer ($\alpha = 1$), respectively. Naturally, $a < b$ with b close to 1.0;
- λ: This is the upper bound of the market that the supplier can share when full technology transfer is realized (i.e., $\alpha = 1$);
- $f(x), f_\alpha(x), g_\alpha(y)$: It is assumed that they are all quadratic functions which are used to approximate the normal distribution density functions;

- $d, h, m, n, p, q, e, i, u, v$: These are constants. Their values determine the shape of the corresponding functions.

Where the expected value of $f_\alpha(x)$ ($\mathbb{E}X_\alpha$) and $g_\alpha(y)$ ($\mathbb{E}Y_\alpha$) increase with respect to α. Meaning that an increment of technology transfer will lead to the improvement of quality and more willingness from the Supplier's country to open her market to the OEM respectively. $c(\alpha)$, $w(\alpha)$ and $r(\alpha)$ reduce with respect to α. This behavior is expected because the improvement in technology leads to quality enhancement and this latter to a reduction in scrap and rework. All of this being translated into pricing discounts. On the other hand, $T(\alpha)$ and $s(\alpha)$ increase with respect to α. This can be understood as the effect of pricing discount into the market. Where lower prices bring the attention of more possible buyers and in addition better place the retailer in the market.

The quality lower bound a may vary for different industries. For example, in aerospace industry, it can usually be high, say $a = 90\%$. The value of λ is also industry specific and depends on the supplier's influencing power on his country's market. If the supplier has strong influence on the local market (e.g., when the supplier is directly related to the country's government), λ can be quite large. On the other hand, it could be very small if the supplier has only very limited influence on the decisions regarding the country's market. In particular, this chapter has assumed that the supplier's wholesale price changes according to a convex function, and the supplier's market sharing uncertainty follows a quadratic distribution to approximate the normal distribution. Since in this example we have $\mu(\alpha) = \frac{a+(b-a)\sqrt{\alpha}+1}{2}$ and $\lambda(\alpha) = \frac{\lambda\alpha^2}{2}$, hence

$$\frac{d}{d\alpha}\left(\frac{\lambda(\alpha)}{\mu(\alpha)}\right) = \frac{3\lambda(b-a)\alpha^{3/2} + \lambda(1+a)\alpha}{8} > 0, \quad 0 \le \alpha \le 1,$$

hence by proposition 5, we expect $\alpha_2 > \alpha_1$, which will be verified shortly.

2.5.1 *Numerical data and Results*

The data shown in Table 2.1 are used in the numerical example as parameters for the selected functions.

In order to build a more realistic numerical example, it is considered as reference the information available from one of the well-known aircraft manufacturers, i.e. Boeing company. The Earnings

Table 2.1: Numerical Example Data - Function Parameters

Parameter	a	b	d	h	m	n	p	q	e	i	u	v
Value	90%	95%	2	3	3	8	1/2	1/2	1/2	3/4	0.20	0.26

release report from Boeing (Boeing, 2018b) showed that on the first half of 2018 the company delivered worldwide a total of 378 commercial airplanes. This represented to Boeing \$ 28,133 millions in revenue (\$74,425,926/airplane). The Current market outlook report from Boeing (Boeing, 2017) forecasted that in the next 20 years (2017 - 2036) the global demand of aircrafts will reach to 41,030 deliveries (2,052 deliveries/year), representing a total of \$ 6.1 trillions in market value. For the same period, this report forecasted that China alone will demand 7,240 aircrafts (362 aircrafts/year) representing \$ 1,085 billions. Additionally, a publication of Bidness Etc (Bidness Etc, 2015), mentioned that on 2014 Boeing owned 47% of the global commercial aircraft revenues. And according to Crucial Perspective (Crucial Perspective, 2018), on 2018 45% of all aircraft owned by China buyers will be built by Boeing.

Considering this information, the numeric example is modeled as follows. It is assumed that an OEM and a Supplier engage into negotiation. On one side, the OEM is a powerful participant in the aerospace market who is responsible of s= 45% of the T=2,500 aircraft sold yearly worldwide. On the other side, the Supplier is considered as a champion manufacturer in her country and that possess considerable influence about the strategic decisions done by her government in the aerospace sector. Knowing that the Supplier's country is a critical customer that alone demands H=450 airplanes/yearly, the OEM decides to partially transfer his technology to the Supplier. In exchange the Supplier agrees to support an increase of at most λ= 30% of the OEM's sales in her country. Furthermore, it is assumed that the unit retail price is r= \$75,000,000 and unit wholesale price is w=\$45,000,000. The decision for the OEM now is to decide which is the percentage of technology α that should be transferred in order to maximize the benefits. A summary of this data is shown in Table 2.2.

Table 2.2: Numerical Example Data - OEM & Supplier information

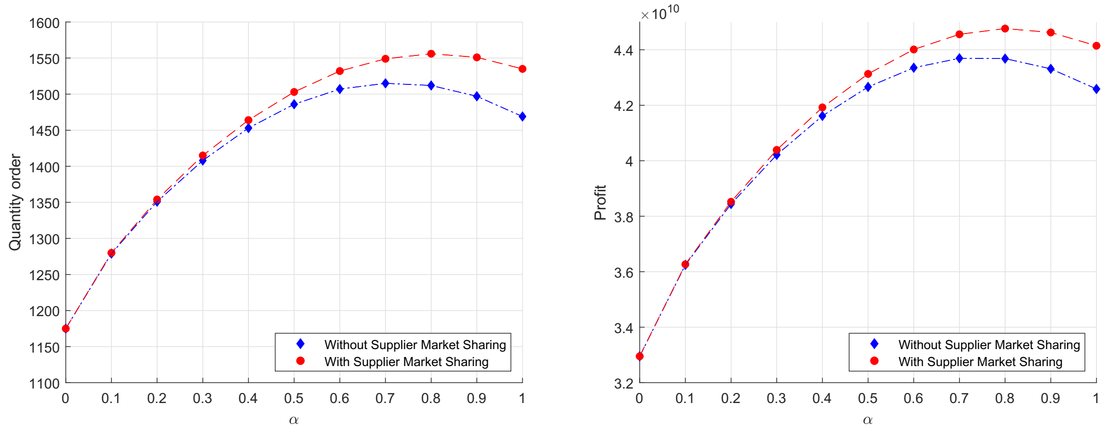
Parameter	r	w	$\widetilde{w}$	T	H	s	λ
Value	\$75,000,000	\$45,000,000	\$25,000,000	2,500	450	45.00%	30.00%

After solving the model without technology transfer, i.e., with $\alpha = 0$, the results are: $q = 1,175$, and $\Pi_{\mathcal{OEM}} = 32.95$. Results presented in Table 2.3 are optimal order quantities $Q_i(\alpha)$ and optimal profits $\Pi^i_{\mathcal{OEM}}(\alpha)$, $i = 1, 2$, corresponding to different levels of technology transfer, i.e., for different values of α with $0 < \alpha \leq 1$.

Table 2.3: Optimal Order Quantities and Profits

α	$Q_1(\alpha)$	$Q_2(\alpha)$	$\Pi^1_{\mathcal{OEM}}(\alpha)$ (billion dollars)	$\Pi^2_{\mathcal{OEM}}(\alpha)$ (billion dollars)
0.0	1,175	1,175	32.95	32.95
0.1	1,279	1,280	36.25	36.27
0.2	1,351	1,354	38.44	38.52
0.3	1,408	1,415	40.21	40.39
0.4	1,453	1,464	41.61	41.92
0.5	1,486	1,503	42.66	43.13
0.6	1,507	1,532	43.35	44.01
0.7	**1,515**	1,549	**43.69**	44.56
0.8	1,512	**1,556**	43.68	**44.76**
0.9	1,497	1,551	43.31	44.62
1.0	1,469	1,535	42.59	44.14

The results in Table 2.3 are also plotted to graphically compare optimal order quantities and optimal profits as shown in Figures 2.1a and 2.1b, respectively. As can be seen from Figures 2.1a and 2.1b, we have $\alpha_1 = 0.7 < \alpha_2 = 0.8$, for $Q_1(\alpha_1) = 1,515 < Q_2(\alpha_2) = 1,556$, and for $\Pi^1_{\mathcal{OEM}}(\alpha_1) = 43.69 < \Pi^2_{\mathcal{OEM}}(\alpha_2) = 44.76$. The large values of profit obtained from this numerical example result from considering only the cost of bought-out components (wholesale price of the supplier) at the moment of calculating the optimal profit for the OEM. The other cost terms, detailed in the work of S. G. Sturmey Sturmey (1964), are ignored from the analysis as they do not affect the relation between the OEM and Supplier. From our results we show that by engaging into a technology transfer agreement, the OEM could increase at most 28.94% of his aircraft orders to obtain the maximum profit. And with the addition of the market shared by the Supplier, this increase could reach to 32.43%. Furthermore, These results have in particular verified Proposition 3 and Proposition 5. They showed the benefits for both the OEM and the supplier to engage in a technology and market sharing win-win cooperation.



(a) Comparison of Optimal Order Quantities

(b) Comparison of Optimal Profits

Figure 2.1: Optimal results for Q^* and Π^*

2.5.2 *Sensitivity Analysis*

Due to complexity of the proposed models, some of the analytical properties are difficult to demonstrate on a general basis. The analysis below is intended to clarify some interesting phenomena and insights through numerical analysis.

Results Sensitivity on Probability Density Functions

Both of the model of technology transfer without supplier's market sharing (TS-1) and the model of technology transfer with supplier's market sharing (TS-2) have two random variables, X_α, the product quality level, and Y_α, the portion of the supplier's home market offered to the OEM. Their probability density functions are $f_\alpha(x)$ and $g_\alpha(y)$, respectively. In this analysis, we further use another group of density functions with larger mean values to analyze their effects on the results of the proposed models. These specific functions are given below.

$$f_\alpha^1(x) = 6[x-1][l(\alpha)-1]^{-3}[4[x-l(\alpha)]+[l(\alpha)-1]],$$

$$g_\alpha^1(y) = -6.2\lambda_\alpha^{-1}[(2\lambda_\alpha^{-1}y-1)^2-\lambda_\alpha^{-1}y],$$

where $X_\alpha \in \left[\frac{1+3l(\alpha)}{4}, 1\right]$ and $Y_\alpha \in \left[\frac{\lambda_\alpha}{4}, \lambda_\alpha\right]$. The results using these function values are summarized in Table 2.4.

Table 2.4: Sensitivity Analysis - Modification on Probability Density Functions

Model	Case	α	Q	Π (billion dollars)
TS-1	$f_\alpha(x)$	0.6	1,507	43.35
		0.7	1,515	43.69
		0.8	1,512	43.68
	$f^1_\alpha(x)$	0.6	1,488	45.65
		0.7	1,497	45.86
		0.8	1,495	45.72
TS-2	$f_\alpha(x), g_\alpha(y)$	0.6	1,532	44.01
		0.7	1,549	44.56
		0.8	1,556	44.76
	$f^1_\alpha(x), g_\alpha(y)$	0.6	1,511	46.28
		0.7	1,528	46.67
		0.8	1,530	46.71
	$f_\alpha(x), g^1_\alpha(y)$	0.6	1,553	48.48
		0.7	1,574	49.57
		0.8	1,581	50.35
	$f^1_\alpha(x), g^1_\alpha(y)$	0.6	1,533	51.36
		0.7	1,553	52.58
		0.8	1,559	53.41

It can be seen from the results of the TS-1 model that the improvement of the expected quality level lead to a reduction of the optimal order quantity q and an increased optimal profit Π due to the reduction of the nonconformity production. As an example it is shown that $Q(\alpha = 0.7)$= 1,515 for $f_\alpha(x)$ is greater than $Q(\alpha = 0.7)$= 1,497 for $f^1_\alpha(x)$, but $\Pi(\alpha = 0.7)$= 43.69 for $f_\alpha(x)$ is less than $\Pi(\alpha = 0.7)$= 45.86 for $f^1_\alpha(x)$. The behavior of the optimal order quantity and profit from the TS-2 model is more complex due to $g_\alpha(y)$. Using the same probability density function for quality level, the larger expected market share in supplier's country increases both the optimal order quantity q and the optimal profit Π. For example, when $Q(\alpha = 0.7)$= 1,549 and $\Pi(\alpha = 0.7)$= 44.56 for $f_\alpha(x)$ and $g_\alpha(y)$ are less than $Q(\alpha = 0.7)$= 1,574 and $\Pi(\alpha = 0.7)$= 49.57 for $f_\alpha(x)$ and $g^1_\alpha(y)$. But when the expected quality level is improved we can see a behavior similar to TS-1.

Concavity of Optimal $Q_i(\alpha)$ ***and*** $\Pi^i_{\mathcal{OEM}}(\alpha)$

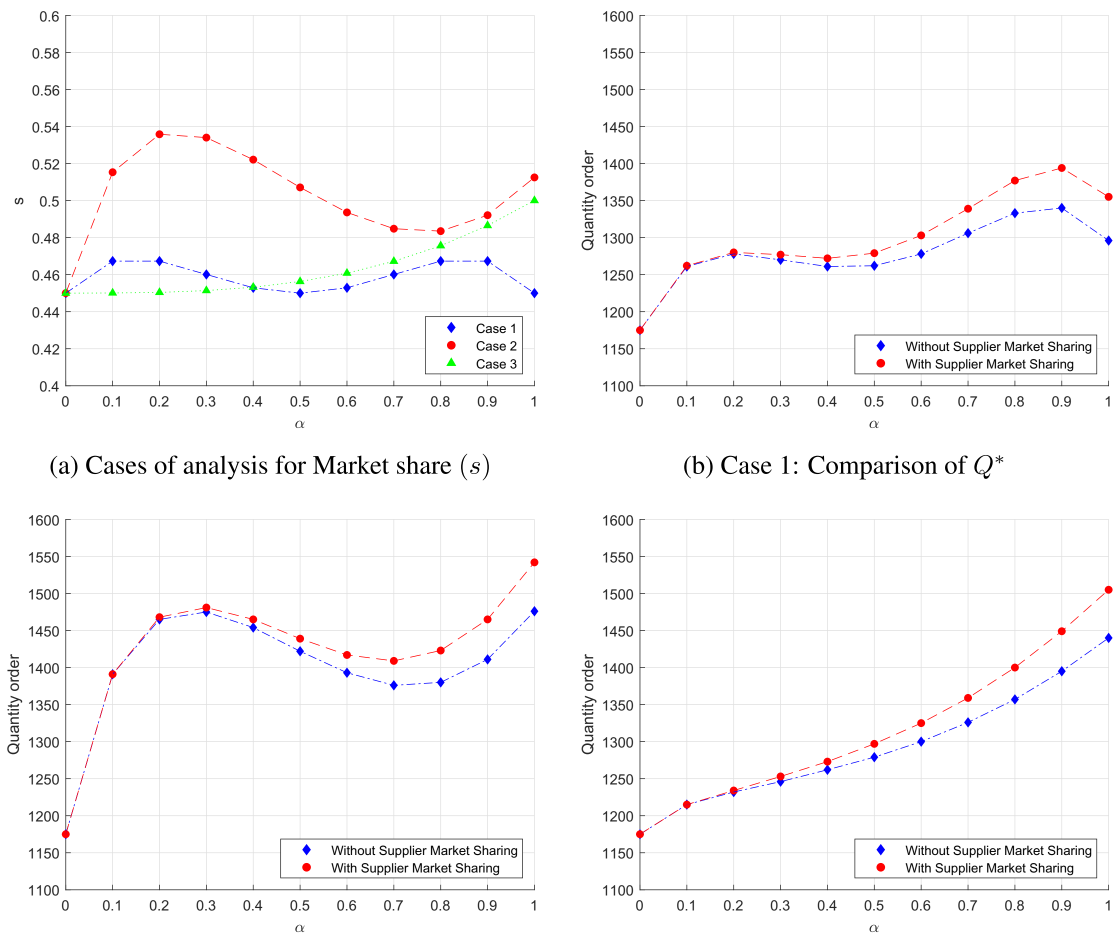
The graphs in Figures 2.1a and 2.1b show that the optimal Q_1, Q_2, $\Pi^1_{\mathcal{OEM}}$ and $\Pi^2_{\mathcal{OEM}}$ are concave functions of α. As discussed earlier, such phenomena depends on the relationship of different functions used in the proposed models. Assume now, for example, the following 3 cases in which the OEM's market share is described by the functions:

$$\begin{cases} \text{Case 1:} & s(\alpha) = s - 1.2(\alpha - 0.5)^4 + 0.3(\alpha - 0.5)^2 \\ \text{Case 2:} & s(\alpha) = s - \frac{\alpha^2}{3}(1 - \alpha) + \frac{\alpha}{(\alpha+1)^4} \\ \text{Case 3:} & s(\alpha) = s - \frac{\alpha^3}{5} + \frac{\alpha^3}{4} \end{cases}$$

In Figure 2.2a it is shown the behavior of these market share functions with respect to α. The optimal quantities are recalculated with results illustrated in Figures 2.2b, 2.2c and 2.2d. It is noticed in these three cases that $Q(\alpha)$ is no longer a concave function of α. Case 1 shown in Figure 2.2b presents two local maximums for the optimal order quantity ($Q_1(\alpha = 0.2) = 1,278$ and $Q_1(\alpha = 0.9) = 1,340$ for TS-1; and $Q_2(\alpha = 0.2) = 1,280$ and $Q_2(\alpha = 0.9) = 1,394$ for TS-2). Similarly, case 2 shown in Figure 2.2c presents two local maximums for the optimal order quantity ($Q_1(\alpha = 0.3) = 1,475$ and $Q_1(\alpha = 1.0) = 1,476$ for TS-1; and $Q_2(\alpha = 0.3) = 1,481$ and $Q_2(\alpha = 1.0) = 1,542$ for TS-2). On the other hand, the optimal quantity in case 3 is a convex function of α with a maximum optimal order quantity at α=1.0 ($Q_1(\alpha = 1.0) = 1,440$ and $Q_2(\alpha = 1.0) = 1,505$ for TS-1 and TS-2 respectively). Proposition 2 can be used to demonstrate the multiple changes in tendency of $Q(\alpha)$ with respect to α.

Optimal α disparity for Q_i and $\Pi^i_{\mathcal{OEM}}$

The numeric example presented in this section considers that both retail price and wholesale price, denoted as $r(\alpha)$ and $w(\alpha)$ respectively, decrease in a similar proportion when α increases. Now it is considered an unusual situation where $w(\alpha)$ decreases faster than $r(\alpha)$ decreases. This situation may occur when, for example, the access to the advanced technology allows the supplier to reduce rework or scrap leading to a reduction in the wholesale price. At the same time, however, OEM-A does not or will not pass this cost reduction to its retail price. The following parameters are redefined in this situation by setting $d = 6$, $m = 12$ and $p = 2$. Under these particular conditions an interesting phenomenon is observed from the results in Table 2.5. As shown in this table, the largest optimal order quantity Q_i and the highest optimal profit value $\Pi^i_{\mathcal{OEM}}$ are obtained with different levels of technology transfer, denoted by α_i^Q and α_i^Π respectively, for i= 1,2.



(a) Cases of analysis for Market share (s)

(b) Case 1: Comparison of Q^*

(c) Case 2: Comparison of Q^*

(d) Case 3: Comparison of Q^*

Figure 2.2: Sensitivity Analysis - Modification on Market Share behavior

Table 2.5: Sensitivity Analysis - Disparity for Q_i and $\Pi^i_{\mathcal{OEM}}$

α	$Q_1(\alpha)$	$Q_2(\alpha)$	$\Pi^1_{\mathcal{OEM}}(\alpha)$ (billion dollars)	$\Pi^2_{\mathcal{OEM}}(\alpha)$ (billion dollars)
0.0	1,175	1,175	32.95	32.95
0.1	1,277	1,278	35.3	35.32
0.2	1,348	1,351	37.14	37.22
0.3	1,406	1,412	38.74	38.91
0.4	1,450	1,461	40.11	40.41
0.5	1,483	1,500	41.28	41.73
0.6	1,504	1,528	42.24	42.88
0.7	**1,513**	1,546	42.98	43.82
0.8	1,510	**1,553**	43.49	44.55
0.9	1,494	1,548	**43.75**	45.05
1.0	1,467	1,529	43.74	**45.31**

As can be seen from Table 2.5, we have $\alpha_1^Q = 0.7 < \alpha_2^Q = 0.8$, $\alpha_1^\Pi = 0.9 < \alpha_2^\Pi = 1.0$, $Q_1(\alpha_1^Q) = 1,513 < Q_2(\alpha_2^Q) = 1,553$, and $\Pi^1_{\mathcal{OEM}}(\alpha_1^\Pi) = 43.75 < \Pi^2_{\mathcal{OEM}}(\alpha_2^\Pi) = 45.31$. These results do not nullify Proposition 3 nor Proposition 5. Rather, they demonstrate that under certain conditions, e.g., an unusual cost structure in the supply chain, it is possible that the highest optimal Q and $\Pi_{\mathcal{OEM}}$ can be obtained at different levels of technology transfer such as $\alpha_1^Q = 0.7 \neq \alpha_1^\Pi = 0.8$ and $\alpha_2^Q = 0.9 \neq \alpha_2^\Pi = 1.0$.

2.6 Conclusion

Challenges from today's globalized economy demand that multi-national OEMs implement new strategies for entering new market and maintaining their presence in different countries. This chapter discusses the possibility and related issues of using technology transfer as a tool to obtain market share from the supplier's country. We consider uncertain product quality level and market share portions and proposed three related models for: (i) supply chains with neither technology transfer nor supplier's market sharing, (ii) supply chains with technology transfer but without supplier's market sharing, and (iii) supply chains with technology transfer and supplier's market sharing. Each of these models was analyzed with observations discussed. Results demonstrate that for each of the considered scenarios, there exists the optimal profit level which is a concave function on the optimal order quantity. The required condition for finding the optimal order quantity is developed.

It is also shown the benefit for an OEM to include supplier's market sharing into the negotiation in setting up the supply chain. For the considered supply chain systems, we prove that for any level of technology transfer, the optimal order quantity and therefore the optimal profit are always higher when the supplier is willing to share some of its market with the OEM than the case that market share is not part of the negotiation. We also notice certain behaviors of the proposed models with respect to technology transfer. This chapter presents the necessary conditions for reaching the optimal technology transfer level even when supplier's market sharing is not included in the supply chain structure. The OEM may attempt to avoid such situation as the supplier may not be willing to open its market. On the other hand, it is also shown the presence of a favorable scenario for the OEM in which the optimal level of technology transfer is higher when the access to the supplier's market is realized than otherwise. To reach this result, access to the supplier's market should be increased faster than product quality improvement through technology transfer. Under this condition, the OEM is willing to engage in higher level of technology transfer as it will lead to higher profit.

The research work presented in this chapter can be extended in several ways. First, it can include and analyze the supplier's benefits in deciding the optimal OEM order quantity. A supply chain system in aerospace industry, for example, normally consists of several different tiers of suppliers. Therefore it is also of interest to study how technology transfer may affects multiple-echelon supply chains. Finally, the models proposed in the present research are based on the assumption of deterministic demand. It is of interest and practical importance to include demand uncertainties in extending the models for practical applications.

Chapter 3

Technology Investment in a One-manufacturer Two-retailer Supply Chain

Access to new technologies is a key factor of competitive advantage for many supply chains. Chapter 3 explores the impact of technology investment on supply chain coordination. To be specific, we analytically investigate the optimal pricing and technology investment decisions in a system consisting of one original equipment manufacturer and two competing retailers. On one hand, the manufacturer is required to invest in new technologies in order to improve its performance. On the other hand, the retailers act as Stackelberg followers, competing in the same market with different products. We find the conditions on which the cost-revenue sharing (CR) contract and the two-part tariff (TPT) contract are capable of coordinating the one-manufacturer two-retailer supply chain. Moreover, through a numerical example we show that under specific conditions both the CR and TPT contracts are capable of reaching a win-win-win state for all member of the supply chain system. The work in Chapter 3 has been submitted and is currently under review on the International Journal of Production Economics.

3.1 Introduction

As reported by Forbes (2018), the manufacturing sector is fundamentally changing. It has been noticed that a growing number of companies are switching their competitive advantage focus from a cost-reduction strategy to more high-tech manufacturing strategies. Hence, regions like the European Union or countries like China have already announced their efforts to support their industry sector on becoming global high-tech manufacturing leaders (Subcommittee on advanced manufacturing, 2018). The Boston Consulting Group (2015) reveals that 72% of the large-size companies are planning to acquire state-of-the are technology in the next five years. Table 3.1 shows a summary of some of the current new technologies that are of interest in the industry sector worldwide.

Table 3.1: New technologies investment worldwide (source: Deloitte (2018))

Technology	Sector	Investment 2016 (US$ billion)	Expected investment 2021 (US$ billion)
Additive manufacturing	Aerospace, automotive	13	36
Advanced materials	Aerospace, automotive	195	283
Advanced robotics and cognitive automation	Manufacturing, health care	92	225
Digital design, simulation, and integration	Computer-Aided design	25	45
Energy storage	Electronics, transportation	37	54

Companies can sought different alternatives when investing on new technologies, i.e. through its acquisition from a third party company, through its internal R&D, among others. Forbes (2018) reported that 86% of the top 100 companies investing into R&D worldwide belong to the manufacturing sector. Examples are General Electric and its efforts to build an engine piece using new technologies on additive manufacturing that decreases its weight by 25% and increases its durability by 5 times, and Ford investment on digital design, simulation, and integration technologies for developing aluminum castings used for engines, that had helped the company to save more than US$120 million and reduced the development time by 15%-25% (The Boston Consulting Group, 2015). Compared to internal R&D, acquisition of third party new high-tech equipment or intellectual property requires smaller size investment, and at the same time could bring considerable benefits to the company. As example, when Airbus suffered a shortage of relatively inexpensive parts bought from a supplier, potential production and revenue losses to the company were caused. To tackle this issue, Airbus decided to invest on a 3D printer to manufacture the pieces in-house, saving the company at least 50 days of supply lead times (Strategy&, 2017).

Although the potential benefits of new technologies acquisition on processes and product enhancement, investment in new technologies is a challenging decision due to their complexity for implementation and the cost involved. Therefore, it become critical for the industry sector to determine the effect of new technologies on the performance of the acquiring company and on its supply chain. Despite the existing of a vast number of empirical studies and reports reviewing the benefits and drawbacks of new technologies investment on supply chain performance, analytical research on this matter is quite scarce. In this chapter, our objective is to model and analyze the effect of new technologies investment on the $\mathcal{SC}$ members performance. Specifically, we aim to answer the following questions:

- Can a one-manufacturer two-retailer $\mathcal{SC}$ system be coordinated in presence of technology investment?
- What is the impact of the coordination contracts on the pricing and technology acquisition decisions of the system?
- If the CR and TPT contracts are used to coordinate the $\mathcal{SC}$, can these contracts be designed to offer a win-win scenario for all agents of the negotiation?

From our findings, the contributions of this chapter can be summarized as follow: (i) we demonstrate that a $\mathcal{SC}$ under technology investment can achieve coordination, and we prove the specific conditions under which the CR contract and the TPT contract are capable of coordinating the system, (ii) we show that coordination of the supply chain can lead to a reduction on the pricing decisions, i.e. wholesale price and retail price, and at the same time can lead to an increment on the level of technology acquisition decision, and (iii) we observe that both the CR and TPT contracts can reach a win-win state for all agents in the supply chain.

3.2 Literature review

Our research is closely related to two streams of literature: the literature on knowledge management that studies the impact of technology in the $\mathcal{SC}$, and the literature on $\mathcal{SC}$ coordination through coordination contracts. We detail below the relevant literature and how our study relates to but greatly differs from these streams.

3.2.1 Impact of technology investment in the supply chain

Global competition makes the investment in new technologies crucial for the success of any firm (Kumar et al., 2015). Due to the increasingly technological complexity and shortened life-cycle of products, organizations are compelled to continually invest in new technologies to maintain their positioning in the market (Bhaskaran & Krishnan, 2009). Technology is seen as a key element for competitive advantage (Reisman, 2005) that can lead companies to access wider markets, sales increment, cost reduction, brand enhancement, to name but a few (da Silva et al., 2019; Kumar et al., 2015). And its benefits are not limited only to the owner of the technology but they can be translated into the performance improvement of the $\mathcal{SC}$ as a whole (Kang & Jiang, 2011). On the other hand, management of new technologies can result challenging because of their complexity and high cost (Bhaskaran & Krishnan, 2009; Günsel, 2015), specially for high-tech industries (Battistella et al., 2016). Firms can access new technologies either through their internal development in their R&D departments (Tatikonda & Stock, 2003), or thanks to their acquisition from external sources (Brunswicker & Vanhaverbeke, 2015). Examples of new technologies in the $\mathcal{SC}$ can be quite diverse. It can refer to any one or the combination of tangible aspects like materials, tools, equipment, machinery; or intangible elements like skills, applied knowledge, methods, intellectual property, among others (da Silva et al., 2019; Liu, Fang, Shi, & Guo, 2016; Reisman, 2005). An example of analytical research regarding the impact of new technologies on $\mathcal{SC}$ performance can be found in the work of Chakraborty et al. (2019). The authors examine the effect of new technologies on product quality improvement and they demonstrate how collaborative contracts can be of benefit for all $\mathcal{SC}$ members. Similarly, Bai et al. (2017) study how the investment in new sustainable green technologies can contribute to the carbon emission reduction in a $\mathcal{SC}$. Furthermore, they use contract coordination to determine the necessary conditions to maximize the $\mathcal{SC}$ profit. Bhaskaran and Krishnan (2009) conceptualize and model the development process of new products between two firms with different R&D capabilities and study how revenue, technological innovation and investment sharing can benefit the overall performance of the $\mathcal{SC}$ system. In their research the authors establish the conditions at which any of the proposed sharing mechanisms would be of interest for the firms. Wang and Shin (2015) review a two-echelon $\mathcal{SC}$ system with a supplier and manufacturer undertaking innovation initiatives. The authors formulated three contract scenarios for the negotiation: wholesale price contract, quality-dependent wholesale price contract, and revenue-sharing contract. They demonstrate that the revenue-sharing contract coordinates the $\mathcal{SC}$, whereas the other two contracts may reach coordination depending on specif conditions. Furthermore, the authors extend the model to analyze the impact on $\mathcal{SC}$ performance when considering the existence of two competing suppliers, and of two complementary suppliers in the system.

Although the existence of an ample number of empirical studies that describe the relation between $\mathcal{SC}$ performance and new technologies investment, analytical research on this matter is quite scarce. In this chapter, our aim is to model and analyze the impact of new technologies investment on the $\mathcal{SC}$ members performance and to determine how it can lead to the coordination of the $\mathcal{SC}$ system. Furthermore, our aim is to prove that on specific conditions, sharing the cost of the technology investment among the $\mathcal{SC}$ parties could result into a win-win-win state for all agents of the negotiation.

3.2.2 Supply chain coordination using cost-revenue sharing or two-part tariff contracts

The field of $\mathcal{SC}$ management has widely examined the $\mathcal{SC}$ coordination. The reader is referred to Chan and Chan (2010) for a detailed review on this topic. $\mathcal{SC}$ contracts is one of the main mechanisms studied in the literature for achieving coordination. Among these contracts, the cost-revenue sharing contract and the two-part tariff contract are well-known and extensively adopted in many organizations. Kunter (2012) investigates a contract of royal payments between a manufacturer and a retailer. The author demonstrates that $\mathcal{SC}$ coordination can be achievable if both parties engage into marketing cost and revenue sharing efforts. Furthermore, he observes that the elimination of double marginalization is not a requirement for coordination. Bai et al. (2017) examine a sustainable $\mathcal{SC}$ formed by one manufacturer and one retailer with deteriorating items and under carbon cap-and-trade regulation. The authors propose two coordination mechanisms in their research, the revenue and promotional cost-sharing contract and the two-part tariff contract. They demonstrate that both contracts are capable to reach coordination and they determine the win-win conditions for the $\mathcal{SC}$ members. Moreover, the authors prove that the two-part tariff contract is more robust compared to the revenue and promotional cost-sharing contract. H. Yang and Chen (2018) investigate a manufacturer-retailer system undertaking carbon emission abatement efforts subject to carbon taxation. The authors propose the cost, the revenue, and the cost-revenue sharing contracts to analyze their impact on the $\mathcal{SC}$ negotiation. They find that under specific conditions the three contracts can offer benefits to both parties while increasing the abatement level in the $\mathcal{SC}$. Zheng et al. (2015) explore the behavior of a supplier-retailer $\mathcal{SC}$ affected by demand disruption and marketing effort. The study reveals the conditions at which the revenue and marketing cost sharing contract is capable to coordinate the $\mathcal{SC}$ in both the normal and the disrupted demand scenarios. Moreover, the authors investigate the impact of the bargain power on the negotiation. Xie et al. (2018) examine a closed-loop $\mathcal{SC}$ consisting on one manufacturer and one retailer. In their model they consider that the manufacturer sells online, while the retailer conducts offline sales and recycles used products through the reverse-channel. The authors demonstrate that the revenue-sharing contract can mitigate the online and offline channel conflict between the parties, whereas that the cost-sharing contract can motivate the remanufacturing efforts of the retailer. T. Li, Zhang, Zhao, and Liu (2019) investigate a two-echelon $\mathcal{SC}$ undertaking carbon emission reduction efforts. The authors propose three coordination mechanisms to motivate participation of the manufacturer on green investment initiatives, namely the cost-sharing, the revenue-sharing and the cost-revenue sharing contracts. In addition, the basic contracts are further extended to consider the bargaining power of the $\mathcal{SC}$ agents. Their findings suggest that the basic models are capable to coordinate the $\mathcal{SC}$, while bargaining scenarios do not. Inaba (2018) analyzes a revenue and cost sharing contract as a mechanism to enhance the remanufacturer-retailer $\mathcal{SC}$. In this study the author investigates the scenario when the retailer is the Stackelberg leader of the negotiation, and the one when the leader is the remanufacturer. Results from the numerical example show that in both cases the proposed contract can achieve a higher expected profit for the two parties.

The two-part tariff contract is another contract extensively adopted in industry. X. Li, Chen, and Ai (2019) investigate a supply chain consisting of two competing manufacturers and two competing retailers where demand information asymmetry takes place. The authors propose a two-part tariff contract with information asymmetry and demonstrate the conditions at which this contract can offer a win-win scenario for both manufacturers and retailers. X. Yan (2015) examines a one-manufacturer one-retailer $\mathcal{SC}$ subject to quality improvement efforts. The author proposes three coordination mechanisms in his research, the two-part tariff contract, the revenue-sharing contract and the effort cost sharing contract. He proves that these three contracts can improve the performance of the $\mathcal{SC}$, but that only the combination of the revenue-sharing contract and the effort cost sharing contract can reach the coordination of the system. Hong and Guo (2019) investigate a two-echelon $\mathcal{SC}$ where environmental responsibilities are considered. The authors model this system using three contracts: the price-only contract, the green-marketing cost-sharing contract, and the two-part tariff contract. They find that the two-part tariff contract offers higher environmental benefits compared to the other two contracts and enables coordination of the $\mathcal{SC}$. Biswas, Avittathur, and Chatterjee (2016) explore the behavior of a one-supplier two-buyers $\mathcal{SC}$ considering complete and partial decentralization under information asymmetry. Their study reveals that both the two-part tariff and the quantity discount contract are capable of coordinating the system regardless the $\mathcal{SC}$ structure. Shen, Xu, and Choi (2019) examine a one-manufacturer one-retailer make-to-order system where two products are offered to the market. The authors show that the two-part tariff contract and the revenue sharing contract can reach to $\mathcal{SC}$ coordination. Furthermore, they extend their study by analyzing two cases: both products are substitutable in the market, and the retailer is a risk averse agent. The authors prove that under these conditions both contracts can still coordinate the system. Feng, Govindan, and Li (2017) investigate a two-echelon reverse $\mathcal{SC}$ consisting of a recyclable dealer and a recycler. The authors propose the study of a dual-recycling channel, formed by a traditional and an online recycling channel. They observe that a contract with transfer and online recycling prices is able to coordinate the systems but it is disadvantageous for the dealer. The authors prove that the two-part tariff contract and the profit sharing contract can coordinate the $\mathcal{SC}$ and that at the same time offer a win-win scenario for both parties.

The limited current literature investigating technology investment presents simple models, considering deterministic conditions or simple $\mathcal{SC}$ structures. In this work, we further approach to a real $\mathcal{SC}$ scenario on which the existence of uncertainty plays a role in the negotiation and at the same time a more complex $\mathcal{SC}$ structure, considering one-manufacturer two-retailer, is studied. Moreover, in this chapter, distinct from the above mentioned literature, we study the cost and revenue sharing contract and the two-part-tariff contract considering important factors such as the positive effect of technology investment in a technology-aware market and the associated costs.

Table 3.2 presents the literature positioning of our research.

Table 3.2: Literature positioning of this research

	$\mathcal{SC}$ decisions			$\mathcal{SC}$ characteristics		Findings	
Paper	Technology investment	Retail pricing	Wholesale pricing	1 manufacturer - 2 retailers	Stochastic demand	Coordination condition	Win-win situation
Bai et al. (2017)	✓	✓	✓			✓	✓
Battistella et al. (2016)	✓						
Bhaskaran and Krishnan (2009)	✓						
Biswas et al. (2016)		✓	✓	✓		✓	
Brunswicker and Vanhaverbeke (2015)	✓						
Chakraborty et al. (2019)	✓	✓	✓			✓	
da Silva et al. (2019)	✓						
Feng et al. (2017)						✓	✓
Günsel (2015)	✓						
Hong and Guo (2019)	✓	✓	✓			✓	
Inaba (2018)					✓		✓
Kang and Jiang (2011)	✓						
Kumar et al. (2015)	✓						
Kunter (2012)			✓			✓	
T. Li et al. (2019)	✓	✓	✓			✓	✓
X. Li et al. (2019)					✓		✓
Liu et al. (2016)	✓						
Reisman (2005)	✓						
Shen et al. (2019)		✓	✓		✓	✓	
Tatikonda and Stock (2003)	✓						
Wang and Shin (2015)	✓	✓	✓			✓	✓
Xie et al. (2018)					✓		✓
X. Yan (2015)		✓				✓	
H. Yang and Chen (2018)	✓		✓				✓
Zheng et al. (2015)			✓			✓	
Our paper	✓	✓	✓	✓	✓	✓	✓

3.3 Base models

We consider in this chapter a supply chain ($\mathcal{SC}$) consisting of one original equipment manufacturer ($\mathcal{OEM}$) who sells similar products to two competing retailers ($\mathcal{R}_i$, where i=1,2). The schematic diagram of the $\mathcal{SC}$ operation is illustrated by Figure 3.1.

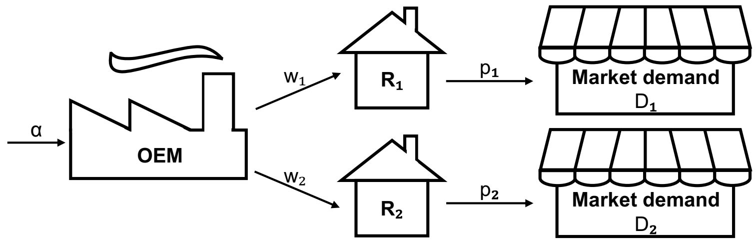


Figure 3.1: Schematic diagram of the $\mathcal{SC}$ operation

It is assumed that the $\mathcal{OEM}$ decides to acquire certain level of technology $0 < \alpha < 1$ to improve its performance. This technology could be required by the $\mathcal{OEM}$ for meeting manufacturing regulations (Bai et al., 2017), enhance quality level (Bhaskaran & Krishnan, 2009; Chakraborty et al., 2019), to name but a few. The new technology acquisition cost is denoted by η and it is considered to be a one-off investment (H. Yang & Chen, 2018). For analytical simplicity, we assume that the investment on technology does not affect the cost structure of the system. Similar assumptions can be found in the work of Chakraborty et al. (2019) and H. Yang and Chen (2018). After receiving the customer's order, $\mathcal{R}_i$ sends it to the $\mathcal{OEM}$ who follows a make-to-order (MTO) manufacturing policy. The unit production cost and unit wholesale price for the final products are c_i and w_i respectively. The unit retail selling price is p_i. In addition, it is established that $p_i > w_i > c_i$. These inequalities assure the non-negative profit for the parties. It is further considered that the market demand $D_i(p_i, p_j, \alpha, \xi_i)$ is stochastic, price dependent (Chakraborty et al., 2019; Ghosh & Shah, 2015), and technology dependent (Bhaskaran & Krishnan, 2009). It is formulated as:

$$D_i(p_i, p_j, \alpha, \xi_i) = d_i - \theta p_i + \gamma p_j + \beta\alpha + \xi_i, \tag{9}$$

where $i \neq j$, $d_i > 0$ is the base demand, $\theta > 0$, $\gamma > 0$ and $\beta > 0$ are the demand sensitivity coefficient to p_i, p_j and to α respectively, and ξ_i is the demand uncertainty with $\mathbb{E}[\xi_i] = 0$ and $\text{Var}[\xi_i] = \sigma_i^2$. Coincident to the work of T.-M. Choi, Ma, Shen, and Sun (2018), we assume $\theta > \gamma$ to model that for R_i the effect of modifying its own retail price p_i has a higher impact on its demand D_i compared to a change in the retail price of the competitor p_j. Similar to the work of H. Yang and Chen (2018), we consider that all information is symmetric between the members, and that the market can accurately perceive the technology enhancement in the final products. In this work we are interested on analyzing the investment on state-of-the-art technology which requires high level investments. To assure this condition in our model, we assume that $\eta > \frac{\beta^2}{\theta-\gamma}$. Finally, for the negotiation, the $\mathcal{OEM}$ acts as the leader while $\mathcal{R}_i$ are the followers.

The sequence of decisions in this Stackelberg game is as follows: (1) the $\mathcal{OEM}$ decides the unit wholesale price w_i and the level of technology α to acquire; (2) knowing w_i and α, $\mathcal{R}_i$ react by deciding the unit retail price p_i. Figure 3.2 depicts the model timeline.

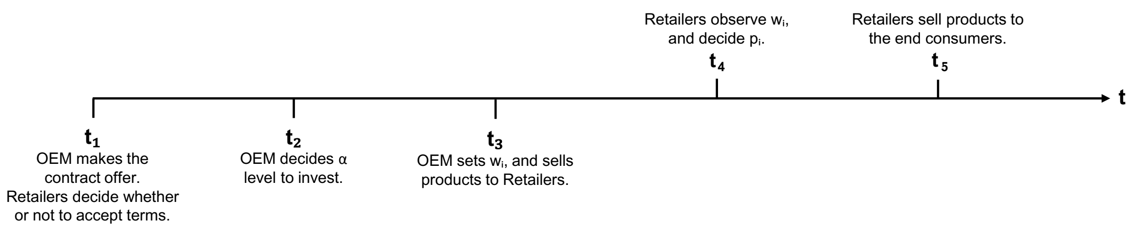


Figure 3.2: The model timeline

Table 3.3 summarizes the notation used in this chapter.

With the base supply chain model established, we now proceed to formulate the profit functions for each participant of the $\mathcal{SC}$. First, Equations 10 and 11 present the profit and expected profit functions for $\mathcal{R}_i$:

$$\Pi^{WS}_{\mathcal{R}_i}(p_i) = (p_i - w_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha + \xi_i), \ where \ i \neq j. \tag{10}$$

$$\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{R}_i}(p_i)] = (p_i - w_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha). \tag{11}$$

Similarly, Equations 12 and 13 show the profit and expected profit functions for the $\mathcal{OEM}$, respectively:

$$\Pi^{WS}_{\mathcal{OEM}}(w_1, w_2, \alpha) = \sum_{i=1}^{2} [(w_i - c_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha + \xi_i)] - \frac{1}{2}\eta\alpha^2. \tag{12}$$

Table 3.3: Notation used in the models

Notation	Meaning
c_i	Unit production cost of product i
w_i	Unit wholesale price of product i
p_i	Unit retail price of product i
α	Percentage of technology acquired ($0 \leq \alpha \leq 1$)
η	Cost coefficient of technology acquired
D_i	Market demand for $\mathcal{R}_i$
d_i	Base demand for $\mathcal{R}_i$
θ	Retail price-dependence coefficient of demand
γ	Competitor's retail price-dependence coefficient of demand
β	Technology-dependence coefficient of demand
ξ_i	Uncertainty component of demand for $\mathcal{R}_i$
$\mathbb{E}[\xi_i]$	Expected value of demand uncertainty for $\mathcal{R}_i$
$\mathrm{Var}[\xi_i]$	Variance of demand uncertainty for $\mathcal{R}_i$
ϕ_i	Technology-cost and revenue sharing percentage in the CR contract
t_i	Fixed cost charged to $\mathcal{R}_i$ in the TPT contract
$\Pi_{\mathcal{OEM}}$	Manufacturer's profit
$\Pi_{\mathcal{R}_i}$	Retailer i's profit
$\Pi_{\mathcal{SC}}$	Supply chain's profit
WS	Wholesale price contract
CR	Cost-revenue sharing contract
TPT	Two-part tariff contract

$$\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(w_1, w_2, \alpha)] = \sum_{i=1}^{2} [(w_i - c_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha)] - \frac{1}{2}\eta\alpha^2. \tag{13}$$

Finally, Equation 14 presents the expected profit function for the $\mathcal{SC}$:

$$\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^{WS}(p_1, p_2, w_1, w_2, \alpha)] = \mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(w_1, w_2, \alpha)] + \mathbb{E}_\xi[\Pi_{\mathcal{R}_1}^{WS}(p_1)] + \mathbb{E}_\xi[\Pi_{\mathcal{R}_2}^{WS}(p_2)] \tag{14}$$

In addition, all proofs are shown in Appendix A.

3.4 Equilibrium analysis

3.4.1 Optimal decisions for the decentralized supply chain

In this section we derive the optimal pricing and technology-acquisition decisions of the WS contract by exploring the equilibrium of the negotiation game. Because $\mathcal{R}_i$ $(i = 1, 2)$ are the followers, we first find the optimal values for the retail price.

Proposition 6. *For $\mathcal{R}_i$, (i=1,2), with a given wholesale price w_i and level of technology acquired α, a unique Nash equilibrium exists for the retail selling price decision, and its optimal retail price p_i^{WS*} can be expressed as:*

$$p_i^{WS*}|_{w_1,w_2,\alpha} = \frac{2\theta\left(w_i\theta + d_i\right) + \gamma\left(w_j\theta + d_j\right) + \beta\alpha\left(2\theta + \gamma\right)}{4\theta^2 - \gamma^2}. \tag{15}$$

By replacing Equations 15 on Equation 13, we obtain the $\mathcal{OEM}$'s expected optimization objective function at the equilibrium retail selling prices p_i^{WS*} for given wholesale prices w_1, w_2 and level of technology α. The $\mathcal{OEM}$'s expected optimization objective function can be expressed as $\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(w_1, w_2, \alpha)] = \mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(p_1^{WS*}|_{w_1,w_2,\alpha}, p_2^{WS*}|_{w_1,w_2,\alpha})]$. Optimization of the latter expression will yield to the optimal wholesale price $w_i^{WS*} = arg\ \underset{w_i}{max}\left(\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(w_1, w_2, \alpha)]\right)$, and to the optimal technology level $\alpha^{WS*} = arg\ \underset{\alpha}{max}\left(\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(w_1, w_2, \alpha)]\right)$.

Proposition 7. *The $\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(w_1, w_2, \alpha)]$ is a strictly concave function of w_i and α; and the optimal wholesale price w_i^{WS*} and level of technology α^{WS*} can be expressed as:*

$$w_i^{WS*} = \frac{c_i}{2} + \frac{2\eta\left(2\theta - \gamma\right)\left(d_i\theta + d_j\gamma\right) - \theta\beta^2\left(d_i - d_j + \left(\theta + \gamma\right)\left(c_i + c_j\right)\right)}{4\left(\theta + \gamma\right)\left[\left(2\theta - \gamma\right)\left(\theta - \gamma\right)\eta - \theta\beta^2\right]}. \tag{16}$$

$$\alpha^{WS*} = \frac{\theta\beta\left[d_1 + d_2 - \left(\theta - \gamma\right)\left(c_1 + c_2\right)\right]}{2\left[\left(2\theta - \gamma\right)\left(\theta - \gamma\right)\eta - \theta\beta^2\right]}. \tag{17}$$

Proposition 7 demonstrates the concavity of $\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(w_1, w_2, \alpha)]$ and therefore the existence of an unique optimal wholesale price w_i^{WS*} and optimal level of technology α^{WS*}.

Proposition 8 is derived by replacing Equations 16 and 17 in Equation 15.

Proposition 8. *The* $\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{R}_i}(p_i)]$ *is a strictly concave function of* p_i*; and the optimal retail price* p_i^{WS*} *can be expressed as:*

$$p_i^{WS*} = \frac{2\theta\left(w_i^{WS*}\theta + d_i\right) + \gamma\left(w_j^{WS*}\theta + d_j\right) + \beta\alpha^{WS*}\left(2\theta + \gamma\right)}{4\theta^2 - \gamma^2}. \tag{18}$$

3.4.2 Optimal decisions for the centralized supply chain

As a benchmark, we now assume that both $\mathcal{R}_i$ (i=1,2) and the $\mathcal{OEM}$ belong to the same centrally coordinated system. Under this assumption, the profit and expected value of profit for the $\mathcal{SC}$ can be expressed as:

$$\Pi_{\mathcal{SC}}(p_1, p_2, \alpha) = \sum_{i=1}^{2}\left[(p_i - c_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha + \xi_i)\right] - \frac{1}{2}\eta\alpha^2. \tag{19}$$

$$\mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p_1, p_2, \alpha)] = \sum_{i=1}^{2}\left[(p_i - c_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha)\right] - \frac{1}{2}\eta\alpha^2. \tag{20}$$

We proceed now to derive the optimal pricing and technology-acquisition decisions for the $\mathcal{SC}$ in the centralized scenario.

Proposition 9. *The* $\mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p_1, p_2, \alpha)]$ *is a strictly concave function of* α *and* p_i*; and the optimal technology level* α^* *and retail price* p_i^* *can be expressed as:*

$$\alpha^* = \frac{\beta}{2}\left[\frac{d_1 + d_2 - (\theta - \gamma)(c_1 + c_2)}{(\theta - \gamma)\eta - \beta^2}\right]. \tag{21}$$

$$p_i^* = \frac{c_i}{2} + \frac{\left(2\theta\eta - \beta^2\right)d_i + \left(2\gamma\eta + \beta^2\right)d_j - (\theta + \gamma)\beta^2(c_i + c_j)}{4(\theta + \gamma)\left[(\theta - \gamma)\eta - \beta^2\right]}. \tag{22}$$

Proposition 9 implies that in the centralized $\mathcal{SC}$, the optimal technology level α^* and retail price p_i^* in the Stackelberg equilibrium uniquely exist.

3.4.3 Comparison of the decentralized and centralized supply chain models

A review of both the decentralized and centralized $\mathcal{SC}$ models lead us to the following interesting observation:

Proposition 10. *The decentralized model can not reach coordination of the supply chain system.*

Proposition 10 presents a clear incentive for all members to collaborate in the expectation to reach the $\mathcal{SC}$ coordination. Next section shows 2 contracts designed to coordinate the $\mathcal{SC}$, namely, the Technology-cost and Revenue sharing (CR) contract and the Two-part tariff (TPT) contract.

3.5 Coordination contracts

In this section we proceed to analyze the Technology-cost and Revenue sharing (CR) contract, and the Two-part tariff contract (TPT) to determine if they can achieve the supply chain coordination.

3.5.1 Analyzing the Technology-cost and Revenue sharing contract

For the CR contract it is now assumed that $\mathcal{R}_i$ is willing to share a fraction of the technology cost paid by the $\mathcal{OEM}$, i.e. $\frac{\eta(1-\phi_i)}{2}$, and a fraction of its revenue, i.e. $p_i(1-\phi_i)$, while on the other hand the $\mathcal{OEM}$ agrees to reduce its wholesale price w_i. Equations 23 and 24 present the profit and expected value of the profit for R_i, respectively:

$$\Pi_{\mathcal{R}_i}^{CR}(p_i) = (p_i\phi_i - w_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha + \xi_i) - \frac{(1-\phi_i)}{2}\eta\alpha^2. \tag{23}$$

$$\mathbb{E}_\xi[\Pi_{\mathcal{R}_i}^{CR}(p_i)] = (p_i\phi_i - w_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha) - \frac{(1-\phi_i)}{2}\eta\alpha^2. \tag{24}$$

Similarly, Equations 25 and 26 show the profit and expected profit functions for the $\mathcal{OEM}$, respectively:

$$\Pi_{\mathcal{OEM}}^{CR}(w_1, w_2, \alpha) = \sum_{i=1}^{2}\left[(p_i(1-\phi_i) + w_i - c_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha + \xi_i) - \frac{(2\phi_i - 1)}{4}\eta\alpha^2\right]. \tag{25}$$

$$\mathbb{E}_\xi[\Pi^{CR}_{\mathcal{OEM}}(w_1, w_2, \alpha)] = \sum_{i=1}^{2} \left[(p_i(1-\phi_i) + w_i - c_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha) - \frac{(2\phi_i - 1)}{4}\eta\alpha^2 \right]. \tag{26}$$

In order to derive the optimal pricing and technology-acquisition decisions of the CR contract, we first proceed to find the optimal values for the retail price.

Proposition 11. *For $\mathcal{R}_i$, (i=1,2), with given wholesale prices w_1, w_2 and level of technology α, its optimal retail price p_i^{CR*} can be expressed as:*

$$p_i^{CR*}|_{w_1,w_2,\alpha} = \frac{(2\theta d_i + \gamma d_j + \beta\alpha\,(2\theta + \gamma))\,\phi_1\phi_2 + \theta\,(2\theta w_i\phi_j + \gamma w_j \phi_i)}{(4\theta^2 - \gamma^2)\,\phi_1\phi_2}. \tag{27}$$

In order to test if the CR contract of the decentralized model can reach coordination, we set $p_i^{CR*}|_{w_1,w_2,\alpha} = p_i^*$. From these results we conclude that:

Proposition 12. *The CR contract leads to coordination of the supply chain system under technology investment when $p_i^{CR*} = p_i^*$ and $\alpha^{CR*} = \alpha^*$. Moreover, we find that:*

(a) For $\mathcal{R}_i$, (i=1,2), its optimal wholesale price w_i^{CR*} can be expressed as:

$$w_i^{CR*} = \phi_i \left[c_i - \frac{\gamma c_j}{4\theta} + \gamma \left(\frac{\left(2\gamma\eta + \beta^2\right) d_i + \left(2\theta\eta - \beta^2\right) d_j - (\theta + \gamma)\left[(\theta - \gamma)\,\eta c_j + \beta^2 c_i\right]}{4\theta\,(\theta + \gamma)\,[(\theta - \gamma)\,\eta - \beta^2]} \right) \right]. \tag{28}$$

(b) The CR contract is able to coordinate the supply chain as long as Equation 29 holds.

$$\gamma\left[\left(2\gamma\eta + \beta^2\right) d_i + \left(2\theta\eta - \beta^2\right) d_j\right] > (\theta + \gamma)\left[\gamma\left(2\,(\theta - \gamma)\,\eta - \beta^2\right) c_j - \left(4\theta\,(\theta - \gamma)\,\eta - \beta^2\,(4\theta + \gamma)\right) c_i\right]. \tag{29}$$

Proposition 12(a) shows that the optimal decision variables for both the $\mathcal{OEM}$ and $\mathcal{R}_i$ in the CR contract can be aligned with those of the centralized system, allowing perfect coordination of the supply chain. Furthermore, Proposition 12(b) reveals the necessary condition at which the CR contract offers a feasible and realistic value of w_i^{CR*}, i.e. $w_i^{CR*} > 0$, to the $\mathcal{OEM}$. Fulfillment of the latter condition is crucial for the $\mathcal{OEM}$ to engage in the negotiation because it ensures that the contract coordinating the supply chain does work close to a real-negotiation situation.

3.5.2 Analyzing the Two-part tariff contract

For the TPT contract, we now consider that the $\mathcal{OEM}$ will charge a lower wholesale price w_i and a fixed cost t_i to $\mathcal{R}_i$. In this contract, the profit and expected profit functions for $\mathcal{R}_i$ are:

$$\Pi_{\mathcal{R}_i}^{TPT}(p_i) = (p_i - w_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha + \xi_i) - t_i. \tag{30}$$

$$\mathbb{E}_\xi[\Pi_{\mathcal{R}_i}^{TPT}(p_i)] = (p_i - w_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha) - t_i. \tag{31}$$

Similarly, Equations 32 and 33 show the profit and expected profit functions for the $\mathcal{OEM}$, respectively:

$$\Pi_{\mathcal{OEM}}^{TPT}(w_1, w_2, \alpha) = \sum_{i=1}^{2} [(w_i - c_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha + \xi_i) + t_i] - \frac{1}{2}\eta\alpha^2. \tag{32}$$

$$\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{TPT}(w_1, w_2, \alpha)] = \sum_{i=1}^{2} [(w_i - c_i)(d_i - \theta p_i + \gamma p_j + \beta\alpha) + t_i] - \frac{1}{2}\eta\alpha^2. \tag{33}$$

In order to derive the optimal pricing and technology-acquisition decisions of the TPT contract, we proceed to find the optimal values for retail price.

Proposition 13. *For $\mathcal{R}_i$, (i=1,2), with given wholesale prices w_1, w_2 and level of technology α, its optimal retail price p_i^{TPT*} can be expressed as:*

$$p_i^{TPT*}|_{w_1,w_2,\alpha} = \frac{2\theta d_i + \gamma d_j + \theta\left(2\theta w_i + \gamma w_j\right) + \left(2\theta + \gamma\right)\beta\alpha}{4\theta^2 - \gamma^2}. \tag{34}$$

In order to test if the TPT contract of the decentralized model can reach coordination, we set $p_i^{TPT*}|_{w_1,w_2,\alpha} = p_i^*$. From these results we conclude that:

Proposition 14. *The TPT contract leads to coordination of the supply chain system under technology investment when $p_i^{TPT*} = p_i^*$ and $\alpha^{TPT*} = \alpha^*$. Moreover, we find that:*

(a) *For $\mathcal{R}_i$, (i=1,2), its optimal wholesale price w_i^{TPT*} can be expressed as:*

$$w_i^{TPT*} = \frac{2\theta c_i - \gamma c_j}{2\theta} + \frac{2\eta\gamma\left(\gamma d_i + \theta d_j\right) + \beta^2\gamma\left[d_i - d_j - \left(\theta+\gamma\right)\left(c_i + c_j\right)\right]}{4\theta\left(\theta+\gamma\right)\left[\left(\theta-\gamma\right)\eta - \beta^2\right]}. \tag{35}$$

(b) *The TPT contract is able to coordinate the supply chain as long as Equation 36 holds.*

$$2\theta c_i - \gamma c_j > \frac{\left(\theta+\gamma\right)\gamma\beta^2\left(c_i + c_j\right) - 2\eta\gamma\left(\gamma d_i + \theta d_j\right) - \gamma\beta^2\left(d_i - d_j\right)}{2\left(\theta+\gamma\right)\left[\left(\theta-\gamma\right)\eta - \beta^2\right]}. \tag{36}$$

Similar to the findings in the CR contract, Proposition 14(a) indicates that the optimal decision variables for the $\mathcal{OEM}$ and $\mathcal{R}_i$ in the TPT contract can be consistent with the ones in the centralized system. Implying that the TPT contract can reach perfect coordination of the supply chain. Moreover, Proposition 14(b) guarantees that the value of w_i^{TPT*} is higher than zero, such that the TPT contract coordinating the supply chain does work close to reality. Latter condition is vital for the $\mathcal{OEM}$ at the time of deciding whether to engage into the contract negotiation or not.

3.6 Numerical analysis

In this section, we present a numerical example with sensitivity analysis in order to illustrate the above theoretical findings and to gain some managerial insights.

3.6.1 Numerical example

For the example shown below, the corresponding parameter values are c_1=60, c_2=40, d_1=400, d_2=200, θ=5, γ=3, β=20, η=3000. With this given data we calculate the optimal value for the decision variables and the expected profit for the $\mathcal{SC}$ members. Computational results are shown in Table 3.4.

We obtain the following observations:

(1) The profit in the centralized system and the corresponding level of technology acquisition are 10739.00 and 0.71, respectively. The profit in the decentralized system (WS contract) and the corresponding level of technology acquisition are 9765.50 and 0.50, respectively. Hence,

Table 3.4: The optimal solution for the example

Model	p_1	p_2	α	w_1	w_2	$\Pi_{\mathcal{R}_1}$	$\Pi_{\mathcal{R}_2}$	$\Pi_{\mathcal{OEM}}$	$\Pi_{\mathcal{SC}}$
Centralized system	114.82	92.32	0.71	–	–	–	–	–	10739.00
Decentralized system	129.52	105.48	0.50	113.75	91.25	1243.30	1012.60	7509.60	9765.50
CR contract									
ϕ_1=0.5 ϕ_2=0.6	114.82	92.32	0.71	45.70	43.74	989.59	826.29	8923.40	10739.00
ϕ_1=0.6 ϕ_2=0.7	114.82	92.32	0.71	54.84	51.03	1340.60	1091.60	8307.20	10739.00
ϕ_1=0.7 ϕ_2=0.8	114.82	92.32	0.71	63.98	58.31	1691.60	1356.80	7690.90	10739.00
ϕ_1=0.8 ϕ_2=0.9	114.82	92.32	0.71	73.11	65.60	2042.50	1622.10	7074.70	10739.00
TPT contract									
t_1=2000 t_2=1000	114.82	92.32	0.71	91.39	72.89	744.49	887.35	9107.40	10739.00
t_1=1500 t_2=800	114.82	92.32	0.71	91.39	72.89	1244.50	1087.30	8407.40	10739.00
t_1=1000 t_2=600	114.82	92.32	0.71	91.39	72.89	1744.50	1287.30	7707.40	10739.00
t_1=500 t_2=400	114.82	92.32	0.71	91.39	72.89	2244.50	1487.30	7007.40	10739.00

when the $\mathcal{OEM}$ and both $\mathcal{R}_1$ and $\mathcal{R}_2$ decide to cooperate, the profit of the system could increase by 9.97%, and at the same time the level of technology acquisition could raise by 42.86%. This occurrence can be explained due to the double marginalization effect appearing in the decentralized system. Because the $\mathcal{OEM}$ decides to work independently, it tries to maximize only its own profit by increasing the wholesale prices charged to $\mathcal{R}_1$ and $\mathcal{R}_2$. As a result, both retailers react by increasing also their retail prices. At the same time, because the $\mathcal{OEM}$ bares alone the cost of the new technology, its investment level is moderate. As a consequence of this chain of actions, the market reacts adversely to the increment on retail prices and moderate technological enhancement of the product by reducing the demand on both products that translates in lower profit for the $\mathcal{SC}$. On the other hand, in the centralized system the three agents decide to work together as an unique entity. Consequently, a reduction on both retail prices is achievable and also an increment on the investment on the new technology. Both decisions are beneficial to the end customer, who in return augment the demand on both products and the total profit of the $\mathcal{SC}$ system.

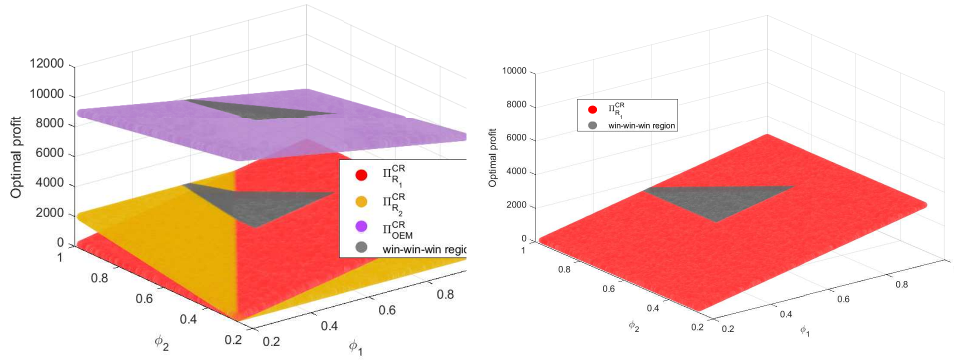
(2) The CR contract offers an incentive for the $\mathcal{SC}$ parties to cooperate. In the example it is shown that when both retailers decide to share a fraction of their revenue and to bare a fraction of the technology cost with the $\mathcal{OEM}$, this allows the $\mathcal{OEM}$ to reduce the wholesale prices charged to both $\mathcal{R}_1$ and $\mathcal{R}_2$, who respond by lowering also their retail prices. Thanks to this cooperation the system is able to increment the level of technology acquisition allowing the $\mathcal{SC}$ system to reach coordination and the same total profit as in the centralized system. The example also shows us that the bargain power of each party during the negotiation is of utmost importance when deciding the fraction of cost-revenue shared by $\mathcal{R}_1$ and $\mathcal{OEM}$, and by $\mathcal{R}_2$ and $\mathcal{OEM}$, denoted by ϕ_1 and ϕ_2 respectively. If the level of ϕ_i is too low, the resulting negotiation is beneficial for the $\mathcal{OEM}$ but not for $\mathcal{R}_1$ neither $\mathcal{R}_2$. When ϕ_1 and ϕ_2 equal to 0.5 and 0.6 respectively, the $\mathcal{OEM}$ increases its profit by 18.8% compared to the WS contact, but $\mathcal{R}_1$ and $\mathcal{R}_2$ reduce their profit by 20.4% and 18.4% respectively. On the other hand, a high level of ϕ_i will deteriorate the $\mathcal{OEM}$ profit but improve it for $\mathcal{R}_i$. For example, when ϕ_1 and ϕ_2 equal to 0.8 and 0.9 respectively, the $\mathcal{OEM}$ reduces its profit by 5.8%, but

$\mathcal{R}_1$ and $\mathcal{R}_2$ augment their profit by 7.8% each. It is interesting to note that the right decision on ϕ_i during the negotiation can result in a win-win-win state for all parties of the system. This is evident in the example when ϕ_1 and ϕ_2 equal to 0.6 and 0.7 respectively. In this case, the $\mathcal{OEM}$ increments its profit by 10.6%, and at the same time both $\mathcal{R}_1$ and $\mathcal{R}_2$ increase their own profit by 7.8%.

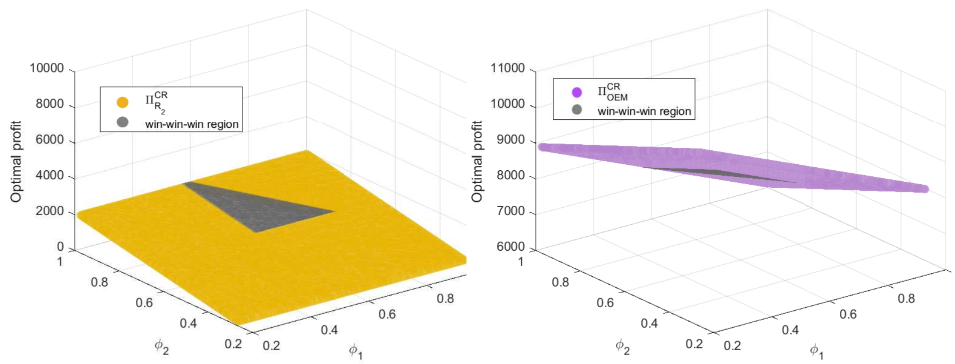
(3) In the case of the TPT contract, there exists a different coordination incentive. Here, each of the parties agree to allow the $\mathcal{OEM}$ to charge a fixed cost in the negotiation, denoted by t_i, and in return the $\mathcal{OEM}$ decides to decrease the wholesale prices charged to both retailers. It is interesting to note in the example that no matter the value of t_1 and t_2 assigned, the wholesale prices remain unchanged while preserving the coordination of the system. Similar to the CR contract, for the TPT contract it is also critical for the $\mathcal{SC}$ agents the decision made on t_1 and t_2. From the example we notice that when the values of t_1 and t_2 is too high, 2000 and 1000 respectively, the $\mathcal{OEM}$ benefits by improving its profit by 21.3%, while the profit of $\mathcal{R}_1$ and $\mathcal{R}_2$ is reduced by 40.1% and 12.4% respectively. On the contrary, when the values of t_1 and t_2 are set too low, 500 and 400 respectively, the profit of the $\mathcal{OEM}$ decrements by 6.7%, but for $\mathcal{R}_1$ and $\mathcal{R}_2$ it increases by 80.5% and 46.9% respectively. From the example we notice that the TPT contract is also able to attain a win-win-win state for the three parties of the negotiation. When the values of t_1 and t_2 are 1000 and 600 respectively, the profit of the $\mathcal{OEM}$ increases by 2.6%, and at the same time the profits for $\mathcal{R}_1$ and $\mathcal{R}_2$ increase by 40.3% and 27.1% respectively.

Previous observations explain that both proposed contracts are able to reach a win-win-win state for all $\mathcal{SC}$ parties under certain conditions. In this numerical example to be specific, Figure 3.3 illustrates this occurrence. Sub-figure 3.3a presents the optimal profit for the $\mathcal{SC}$ agents for given values of ϕ_1 and ϕ_2. Sub-figures 3.3b, 3.3c and 3.3d show the optimal profit for $\mathcal{R}_1$, $\mathcal{R}_2$ and $\mathcal{OEM}$ respectively.

In the latter figures we can appreciate the plane formed by the values of ϕ_1 and ϕ_2 on which the three $\mathcal{SC}$ agents obtain higher optimal profits compared to the decentralized system. Figure 3.4 shows that this plane has a trapeze shape delimited by the vertices (ϕ_1= 0.84 ;ϕ_2= 0.67), (ϕ_1=



(a) Optimal profit for SC in CR contract (b) Optimal profit for $\mathcal{R}_1$ in CR contract



(c) Optimal profit for $\mathcal{R}_2$ in CR contract (d) Optimal profit for $\mathcal{OEM}$ in CR contract

Figure 3.3: Optimal profit in CR contract

0.57;ϕ_2= 0.67), (ϕ_1= 0.60;ϕ_2= 1.00) and (ϕ_1= 0.57;ϕ_2= 1.00). Hence, a CR contract designed considering values of ϕ_1 and ϕ_2 inside this trapeze plane will benefit each of the members.

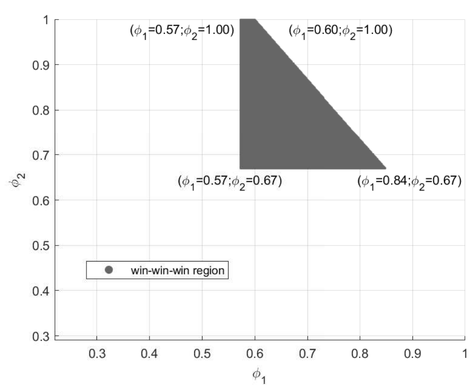
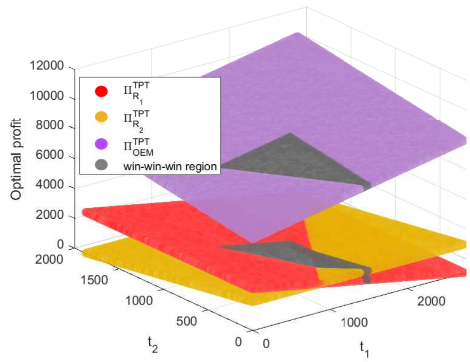
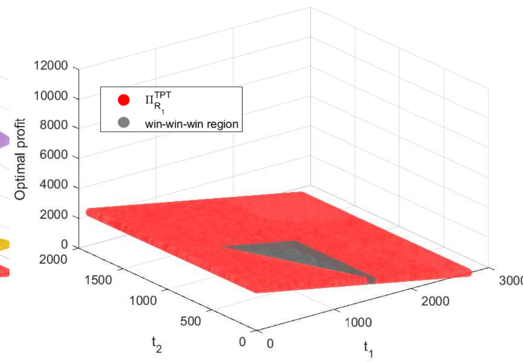


Figure 3.4: Win-win-win region in CR contract

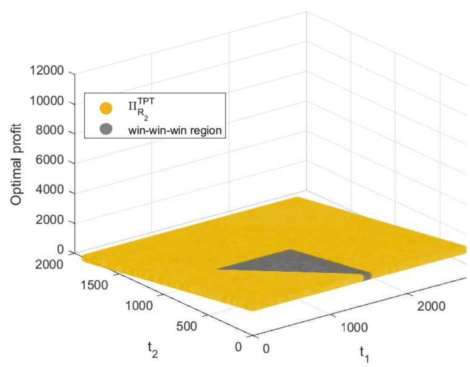
Figure 3.5 illustrates the existence of the win-win-win state in the TPT contract. Sub-figure 3.5a shows the optimal profit for the $\mathcal{SC}$ members for given values of t_1 and t_2. Sub-figures 3.5b, 3.5c and 3.5d present the optimal profit for $\mathcal{R}_1$, $\mathcal{R}_2$ and $\mathcal{OEM}$ respectively.



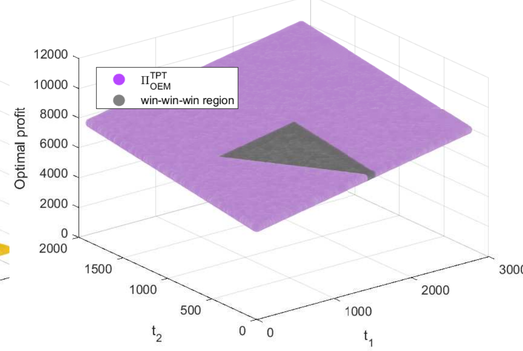
(a) Optimal profit for SC in TPT contract



(b) Optimal profit for $\mathcal{R}_1$ in TPT contract



(c) Optimal profit for $\mathcal{R}_2$ in TPT contract



(d) Optimal profit for $\mathcal{OEM}$ in TPT contract

Figure 3.5: Optimal profit in TPT contract

In the latter figures it can be noticed the plane formed by the values of t_1 and t_2 on which all the $\mathcal{SC}$ parties benefit from the negotiation compared to the decentralized system. Figure 3.6 shows that this plane has a trapeze shape delimited by the vertices (t_1= 532;t_2= 874), (t_1= 1501;t_2= 874), (t_1= 1399;t_2= 0) and (t_1= 1501;t_2= 0). Thus, a TPT contract designed using values of t_1 and t_2 from inside this trapeze plane will result on higher profit for each of the $\mathcal{SC}$ parties.

We further investigate the effect of the parameters θ, γ, β and η using this numerical example. We let $R_\Pi = \frac{\Pi_{\mathcal{SC}}}{\Pi^{WS}_{\mathcal{SC}}}$ represent the benefit in profit when the $\mathcal{SC}$ agents cooperate, and we let

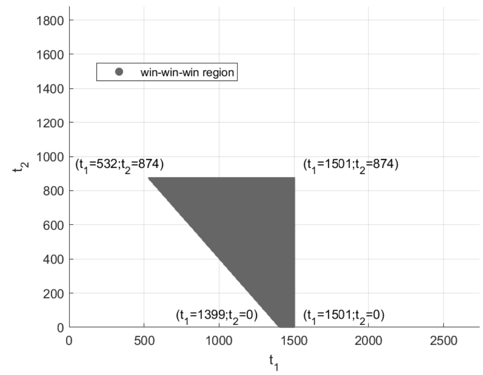


Figure 3.6: Win-win-win region in TPT contract

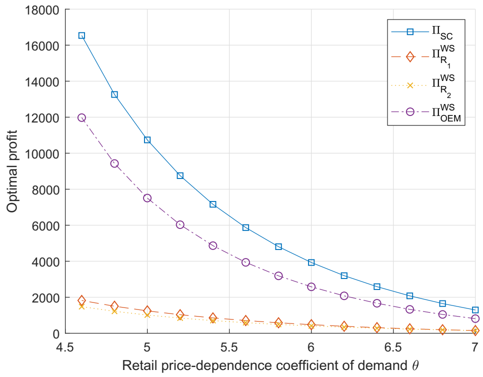
$R_\alpha = \frac{\alpha^*}{\alpha^{WS*}}$ represent the increment on technology acquisition when the system attains coordination. Figure 3.7 shows the results obtained for values of θ from 4.6 to 7. We make the following observations:

(1) From Sub-figure 3.7a it is noticed that variations on θ have a significant impact on reducing the profit in both the centralized and decentralized systems. This is specially evident for the $\mathcal{OEM}$ because in this numerical example it holds the largest portion of profit among the $\mathcal{SC}$ parties.

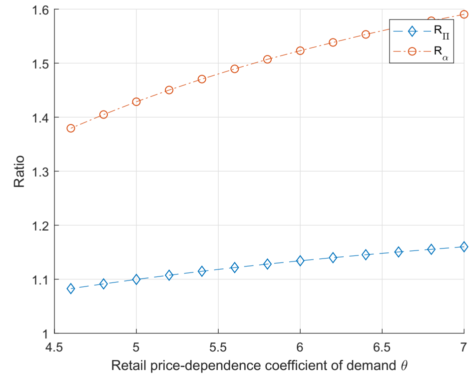
(2) As θ increases, both the profit of the system and the level of technology acquisition decrease. On the contrary, it is interesting to see in Sub-figure 3.7b that an increment of θ leads to higher values of R_Π and R_α. We conclude that this takes place because as θ increases, the $\mathcal{OEM}$ in the decentralized system is dissuaded faster to invest in the new technology compared to the centralized scenario.

We also analyze the impact of the competitor's retail price-dependence coefficient of demand γ on the profit, R_Π and R_α. Figure 3.8 illustrates the results for values of γ between 1.92 and 3.36. We explain the findings:

(1) Sub-figure 3.8a evidence that an increment on γ has a positive impact on the optimal profit of the $\mathcal{SC}$ agents. This is evident because as consumers get more sensitive to the price of the competitor's final product, the demand on its own product will raise.



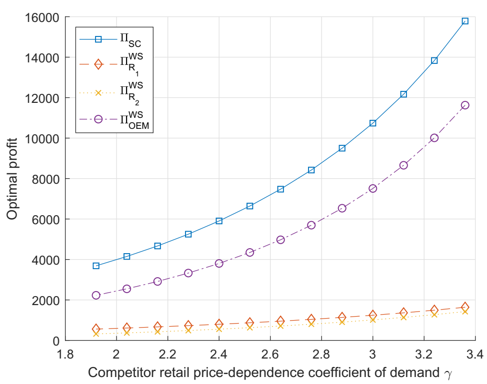
(a) Effect of θ on profit



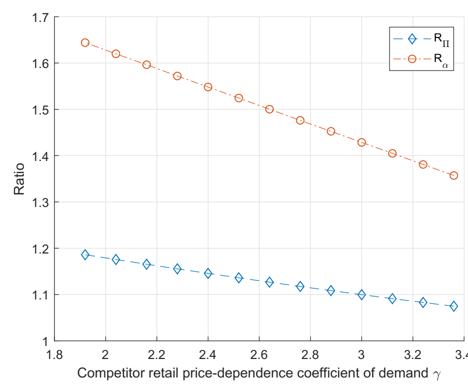
(b) Effect of θ on R_Π and R_α

Figure 3.7: Effect of θ on profit, R_Π and R_α

(2) In Sub-figure 3.8b we notice that as γ increases, both the profit and level of technology acquisition of the decentralized system get closer to those of the centralized system. We conclude that this situation takes place because the market demand is more sensitive to γ when the members of the $\mathcal{SC}$ work independently compared to the scenario of an unique entity.



(a) Effect of γ on profit



(b) Effect of γ on R_Π and R_α

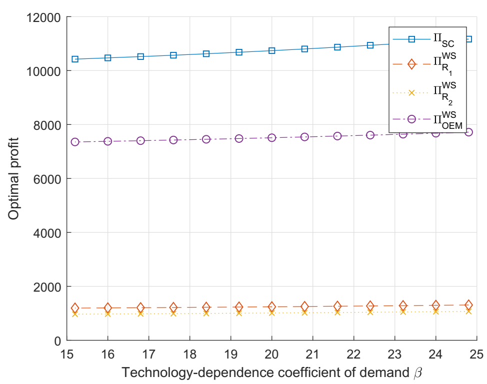
Figure 3.8: Effect of γ on profit, R_Π and R_α

Figure 3.9 shows the scenario of how the technology-dependence coefficient of demand β affects the negotiation. The results shown consider values of β ranging from 15.20 to 24.80. We make the following observations:

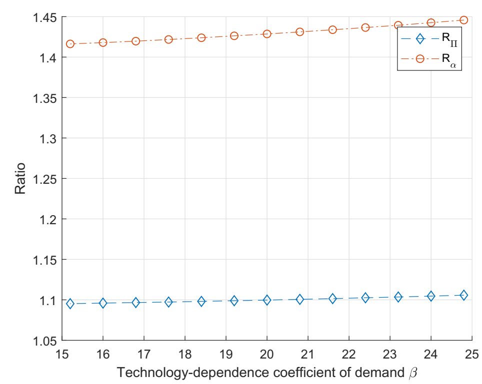
(1) From Sub-figure 3.9a we can appreciate that β has a positive impact on the optimal profit of

the system. This is evident as the proposed $\mathcal{SC}$ model considers that the end consumers are technology-aware. Hence, increasing their sensitivity to new technologies will lead to higher benefits when the $\mathcal{SC}$ members decide to invest on them.

(2) Sub-figure 3.9b shows how an increment on β translates into higher values of R_Π and R_α. We conclude that because the centralized system has more availability of resources to invest in new technologies, when the sensitivity on new technologies increases, then the centralized system is able to invest on a higher level of technology that results on higher profits compared to the decentralized scenario.



(a) Effect of β on profit



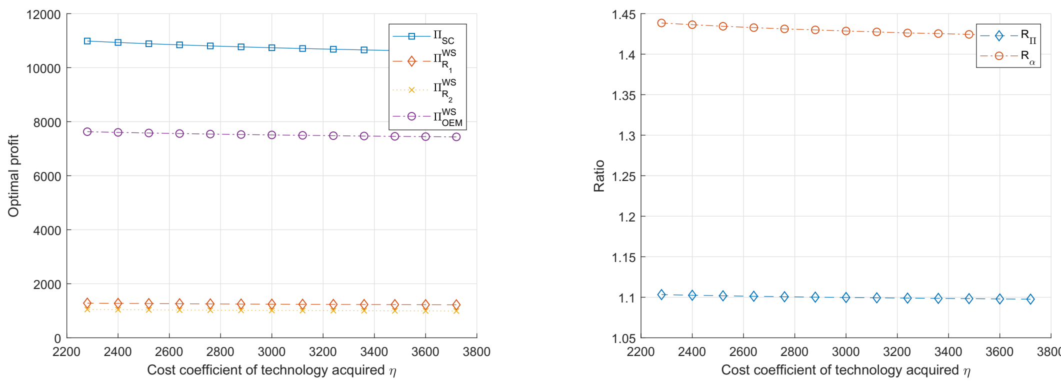
(b) Effect of β on R_Π and R_α

Figure 3.9: Effect of β on profit, R_Π and R_α

Lastly, Figure 3.10 presents the effect of the cost coefficient of technology acquired η on the $\mathcal{SC}$ negotiation. The figure considers values of η between 2280 and 3720. We explain the findings:

(1) As expected, Sub-figure 3.10a illustrates that for a given value of β, increasing the cost on new technologies will have an averse effect on the market demand and on the optimal profit of the system.

(2) Sub-figure 3.10b exhibits the negative impact of η on R_Π and R_α. We conclude that this situation occurs because the loss rate of profit and technology level is more pronounced in the centralized system.



(a) Effect of η on profit

(b) Effect of η on R_{Π} and R_{α}

Figure 3.10: Effect of η on profit, R_{Π} and R_{α}

3.6.2 Sensitivity analysis

We use the same numerical example to investigate the effects of the parameters θ, γ, β and η on the $\mathcal{SC}$ system coordination strategies. The study is performed by modifying each of the parameters by +8 %, +4 %, -4 % and -8%, changing one parameter at a time while keeping the rest unchanged. In this sensitivity analysis we consider for the CR contract the value of the decision variables to be ϕ_1=0.6 and ϕ_2=0.7; and for the TPT contract the value of the decision variables are set to t_1=1500 and t_2=800. Tables 3.5 and 3.6 present the results for the CR and TPT contracts, respectively. From Table 3.5, we explain the following findings:

(1) In the CR contract, the retail price-dependence coefficient of demand θ has a negative impact on the retail prices, wholesales prices, level of technology acquisition and on the profit of each of the members of the system. As the market increases its sensitivity against the retail price of the final product, retailers are urged to reduce their retail prices. Due to the cooperation with the $\mathcal{OEM}$, this reduction is also undertaken on the wholesale prices it charges to both retailers. Because in our example θ has higher impact on the market demand compared to β, this increment on θ also leads the parties to reduce their investment on new technologies. Consequently, the optimal profit of all members of the $\mathcal{SC}$ is cut down.

(2) In the CR contract, opposite to θ, the competitor's retail price-dependence coefficient of demand γ has a positive impact on the retail prices, wholesales prices, level of technology

acquisition and on the profit of the $\mathcal{SC}$ parties. Because the value of $\gamma < \theta$, we can appreciate that the marginal increment on the values of the decision variables and optimal profits is less pronounced compared to the marginal reduction of the value of the decision variables and optimal profits when modifying the value of parameter θ. We conclude that an increment in γ is favorably perceived by the end consumers increasing the market demand of the products. This favorable perception encourages the retailers to augment their retail prices, allowing the $\mathcal{OEM}$ to charge higher wholesale prices to both retailers. Furthermore, due to the improved perception of the customers on the final products, the $\mathcal{SC}$ agents decide to further invest in new technologies. At last, this chain of decisions translates into improved optimal profits for the $\mathcal{OEM}$ and both retailers.

(3) In the CR contract, it is interesting to notice that when the technology-dependence coefficient of demand β increases, the retail prices, wholesale prices, level of technology acquisition and optimal profit of the $\mathcal{OEM}$ increase, whereas the optimal profit of both retailers decrease. Investment on new technologies have two opposite effects on the negotiation. On the one hand, it favors the expansion of the market demand benefiting the revenue of the agents. But on the other hand, it increases the cost incurred by them. Depending on how the contract is designed, an increment on α could result on the detriment of the optimal profit for some of the members of the negotiation. In this example in particular, we notice that while the $\mathcal{OEM}$'s optimal profit increases along with β, for both $\mathcal{R}_1$ and $\mathcal{R}_2$ an increment on β diminishes their respective optimal profits.

(4) In the CR contract, we notice that as the cost coefficient of technology acquired η increases, the retail prices, wholesale prices, level of technology acquisition and optimal profit of the $\mathcal{OEM}$ decrease, while the optimal profit of both retailers increase. Similar to β, parameter η is directly related to α. Therefore, even-tough and increment on η translates in a reduction on α, it is possible for some agents of the system to increase their optimal profit.

From Table 3.6 we observe:

(1) In the TPT contract, when the retail price-dependence coefficient of demand θ increases, the retail prices, wholesale prices, level of technology acquisition and profit of each of the

Table 3.5: Sensitivity analysis for CR contract

Parameter	Value(%)	p_1	p_2	α	w_1	w_2	$\Pi_{\mathcal{R}_1}$	$\Pi_{\mathcal{R}_2}$	$\Pi_{\mathcal{OEM}}$	$\Pi_{\mathcal{SC}}$
θ	5.4(+8.0%)	100.66	78.75	0.53	48.92	43.81	1017.40	861.69	5283.30	7162.30
	5.2(+4.0%)	107.07	84.87	0.61	51.53	47.01	1174.00	973.54	6606.00	8753.60
	4.8(-4.0%)	124.41	101.59	0.84	59.10	56.18	1511.10	1211.70	10538.00	13261.00
	4.6(-8.0%)	136.58	113.42	1.00	64.73	62.96	1672.70	1325.00	13540.00	16538.00
γ	3.24(+8.0%)	126.23	104.10	0.87	60.92	58.04	1377.00	1230.00	11227.00	13834.00
	3.12(+4.0%)	120.13	97.81	0.79	57.64	54.26	1364.60	1163.10	9641.80	12169.00
	2.88(-4.0%)	110.17	87.48	0.65	52.41	48.23	1308.20	1017.80	7174.60	9500.70
	2.76(-8.0%)	106.06	83.18	0.59	50.30	45.80	1270.10	943.43	6207.40	8420.90
β	21.6(+8.0%)	115.47	92.97	0.78	55.07	51.30	1317.40	1082.20	8468.60	10868.00
	20.8(+4.0%)	115.14	92.64	0.75	54.95	51.16	1329.40	1087.00	8385.70	10802.00
	19.2(-4.0%)	114.52	92.02	0.68	54.73	50.90	1351.00	1095.70	8232.90	10680.00
	18.4(-8.0%)	114.24	91.74	0.65	54.63	50.78	1360.70	1099.60	8162.80	10623.00
η	3240(+8.0%)	114.54	92.04	0.66	54.73	50.91	1350.40	1095.50	8237.00	10683.00
	3120(+4.0%)	114.67	92.17	0.68	54.78	50.96	1345.70	1093.60	8270.60	10710.00
	2880(-4.0%)	114.98	92.48	0.75	54.89	51.09	1334.90	1089.30	8347.10	10771.00
	2760(-8.0%)	115.16	92.66	0.78	54.96	51.17	1328.70	1086.70	8390.90	10806.00

members of the system decrease. As expected, we observe that the value of the decision variables p_1, p_2 and α remain the same for both coordination mechanisms. It is interesting to notice that the profit of the retailers in the TPT contract has a higher sensitivity to θ than that in the CR contract. For example, when θ changes from 4.6 to 5.4, the profits of $\mathcal{R}_1$ and $\mathcal{R}_2$ in the TPT contract decrease by 79.20% and 64.79%, respectively, while the profits of $\mathcal{R}_1$ and $\mathcal{R}_2$ in the CR contract decrease by 39.18% and 34.97%, respectively. With respect to the $\mathcal{OEM}$'s profit, now the CR contract shows to be more sensitive to changes on θ, although this difference is less pronounced. For the same values of θ the profit of the $\mathcal{OEM}$ in the TPT and CR contracts decrease by 51.45% and 60.98%, respectively.

(2) In the TPT contract, when the competitor's retail price-dependence coefficient of demand γ increases, the retail prices, wholesale prices, level of technology acquisition and profit of each of the members of the system increase. Similar to θ, we notice that the optimal profits of both retailers in the TPT contract are more sensitive to changes in γ, while the $\mathcal{OEM}$' profit in the CR contract is more sensitive to changes in this parameter. For example, when γ increases from 2.88 to 3.24, the profits of $\mathcal{R}_1$ and $\mathcal{R}_2$ in the TPT contract increase by 40.36% and 55.70%, respectively, while the profits of $\mathcal{R}_1$ and $\mathcal{R}_2$ in the CR contract increase by 5.26% and 20.85%, respectively. With respect to the $\mathcal{OEM}$'s profit, the profit of the $\mathcal{OEM}$ in the TPT and CR contracts increase by 45.13% and 56.48%, respectively.

(3) In the TPT contract, the technology-dependence coefficient of demand β has a positive impact on the retail prices, wholesale prices, level of technology acquisition and profit of each of the $\mathcal{SC}$ parties. It is interesting to notice that while an increase of β in the TPT contract benefits the optimal profit of both retailers, in the CR contract, however, their profits are reduced.

(4) In the TPT contract, the cost coefficient of technology acquired η has a negative impact on the retail prices, wholesale prices, level of technology acquisition and profit of each of the $\mathcal{SC}$ parties. On this numerical example we observe that an increase of η in the TPT contract decreases the profit of both retailers, whereas in the CR contract their profits augment.

Table 3.6: Sensitivity analysis for TPT contract

Parameter	Value(%)	p_1	p_2	α	w_1	w_2	$\Pi_{\mathcal{R}_1}$	$\Pi_{\mathcal{R}_2}$	$\Pi_{\mathcal{OEM}}$	$\Pi_{\mathcal{SC}}$
θ	5.4(+8.0%)	100.66	78.75	0.53	81.53	62.59	475.87	611.16	6075.30	7162.30
	5.2(+4.0%)	107.07	84.87	0.61	85.89	67.15	832.39	832.26	7089.00	8753.60
	4.8(-4.0%)	124.41	101.59	0.84	98.49	80.26	1724.00	1384.50	10152.00	13261.00
	4.6(-8.0%)	136.58	113.42	1.00	107.88	89.94	2287.80	1735.70	12514.00	16538.00
γ	3.24(+8.0%)	126.23	104.10	0.87	101.53	82.92	1549.90	1442.50	10841.00	13834.00
	3.12(+4.0%)	120.13	97.81	0.79	96.07	77.52	1392.60	1258.90	9517.90	12169.00
	2.88(-4.0%)	110.17	87.48	0.65	87.35	68.90	1104.20	926.46	7470.00	9500.70
	2.76(-8.0%)	106.06	83.18	0.59	83.83	65.43	970.84	775.29	6674.80	8420.90
β	21.6(+8.0%)	115.47	92.97	0.78	91.78	73.28	1305.20	1137.80	8425.20	10868.00
	20.8(+4.0%)	115.14	92.64	0.75	91.58	73.08	1274.00	1111.80	8416.30	10802.00
	19.2(-4.0%)	114.52	92.02	0.68	91.21	72.71	1216.60	1064.20	8398.80	10680.00
	18.4(-8.0%)	114.24	91.74	0.65	91.04	72.54	1190.30	1042.40	8390.30	10623.00
η	3240(+8.0%)	114.54	92.04	0.66	91.22	72.72	1218.10	1065.50	8399.30	10683.00
	3120(+4.0%)	114.67	92.17	0.68	91.30	72.80	1230.80	1076.00	8403.20	10710.00
	2880(-4.0%)	114.98	92.48	0.75	91.49	72.99	1259.50	1099.50	8412.00	10771.00
	2760(-8.0%)	115.16	92.66	0.78	91.59	73.09	1276.00	1113.50	8416.80	10806.00

3.7 Conclusions and future research

This chapter studies the technology investment strategy in a two echelon supply chain consisting of one manufacturer and two competing retailers. By comparing a non-collaborative scenario with wholesale price contract and collaborative scenarios with Cost-revenue sharing (CR) and Two-part tariff (TPT) contracts, we analyze whether a collaborative technology enhancement initiative is beneficial to all supply chain parties. We demonstrate that under specific conditions both, the CR and TPT contracts, are capable of coordinating the supply chain system. Furthermore, with the use of a numerical example we illustrate that both the CR and TPT contracts can offer a win-win-win state for all $\mathcal{SC}$ parties.

This chapter can be further extended in a number of directions. Firstly, in this chapter we study coordination in a one-manufacturer two-retailer system. For practical applications, it would be interesting to extend our conclusions for the scenario of a single-manufacturer multi-retailer. Secondly, in this work we consider that the $\mathcal{OEM}$ makes the decision on the level of technology α to acquire. It would be important to investigate the behavior of a system formed by two-supplier one-manufacturer where each supplier decides on the level of technology α_1 and α_2 they acquire, respectively. Lastly, this chapter focuses on examining the investment on new technologies as a coordination tool in which the technology is obtained from an external entity out of the supply chain system, or through the R&D of a single party in the system. Another direction of our research would review how the transfer of technologies among members of the same $\mathcal{SC}$ could be of benefit for coordinating the system.

Chapter 4

Technology Investment in a Multi-supplier Single-manufacturer Supply Chain

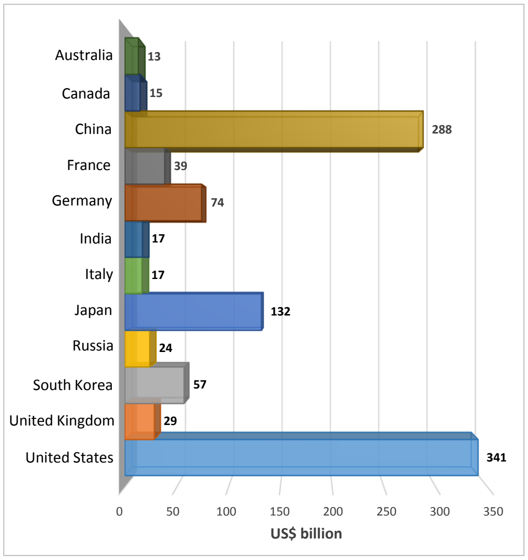
In Chapter 4 we review the effect of technology investment on coordinating a supply chain formed by multiple complementary suppliers and a single original equipment manufacturer. We assume that the suppliers are required to invest in new technologies in order to participate in the supply chain negotiations. While the manufacturer acts as the Stackelberg leader, who offers a wholesale price (WS) contract to the suppliers. Through our research we prove that if the supply chain members decide to cooperate and coordinate the system, they could increase the overall expected profit by at least 1/3 compared to the non-cooperative scenario. We then find that although the cost-sharing (CS) contract is unable to coordinate the system, the cost-revenue sharing (CR) contract is capable of coordinating the multi-supplier and single-manufacturer supply chain. Moreover, we establish the conditions at which the CR contract offers a win-win profit scenario to all parties of the negotiation and review how bargaining analysis can lead to the optimal negotiation ability of each member. Results shown in Chapter 4 have been submitted for review on the journal Production and Operations Management.

4.1 Introduction

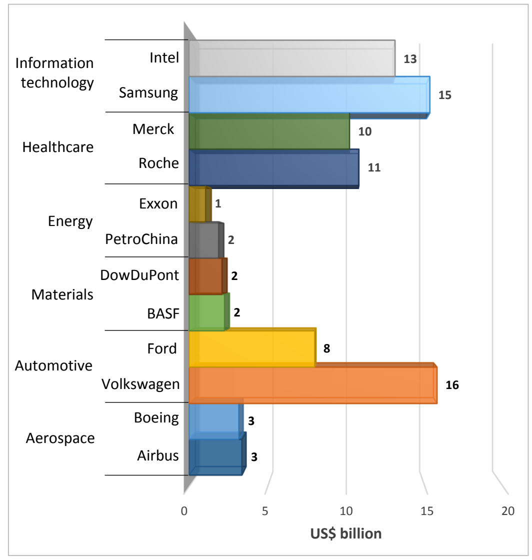
A report from Forbes (2018) make it evident that increasingly industries are turning their competitive advantage focus from a cost-reduction strategy to a more robust high-tech manufacturing. Cutting-edge technologies enable companies to develop advanced processes and products which offer higher levels of productivity and quality, and that are better perceived by the end customer. McKinsey Global Institute (2017) reveals that the manufacturing sector in U.S. currently represents 35% of the productivity growth, 60% of exports, 70% of R&D in the private sector , 9% of employment and 12% of GDP. This report suggests that by 2025, with the contribution of state-of-the-art technology, U.S. manufacturing industry could augment their value up to US$530 billion which represents a 20% increase, in addition to add 2.4 million jobs to the economy. U.S.-based manufacturing companies have taken note on this potential benefits. A survey from The Boston Consulting Group (2015) reveals that 72% of the large-size companies interviewed have plans to invest in new advanced technologies in the next five years.

There exist different mechanisms for companies to get access to avant garde technology. Among them we can mention the merge and acquisition of tech-companies, internal R&D efforts, to name but a few. According to Thomson Reuters (2016), from the 46,055 merger transactions taken place worldwide on 2016, 13% (US$487.63 billion) were acquisitions of high-tech companies. Value only surpassed by merges in the energy and power sector. We can mention cases like Qualcomm's US$39 billion purchase of NXP Semiconductors (The New York Times, 2017), Ulta acquisition of QM Scientific and GlamST (Digiday UK, 2019), and Intel's US$13.8 billion purchase of Mobileye (J.P. Morgan, 2018). Regarding the efforts on internal R&D, Forbes (2018) reported that 86% of the top 100 companies investing into R&D worldwide belong to the manufacturing sector. Among them it is worth to mention Ford investment on digital design, simulation, and integration technologies for developing aluminum castings used for engines, that had helped the company to save more than US$120 million and reduced the development time by 15%-25% (The Boston Consulting Group, 2015). To present the importance of investment on R & D, Figure 4.1a illustrates the private-sector investment per country, and Figure 4.1b shows the investment per industry sector on 2018.

In this globalized economy, the fierce competence in the market, added to the increasingly



(a) Private-sector expenditure in R&D per country (source: Unesco (2018))



(b) Expenditure in R&D per company (source: Strategy& (2018))

Figure 4.1: Expenditure in R&D (2018)

exigences from customers demanding products with more added value and lower prices, force organizations to be always at the vanguard to maintain their positioning in the market. One critical ingredient for maintaining the competitive advantage is the acquisition and implementation of new technologies for achieving process and product enhancement. This is specially the case for high-tech industries in sectors like aerospace, pharmaceutic and telecommunication, to name but a few. But investment in new technologies is a challenging decision due to its complexity for implementation and the cost involved. Configuration of the $\mathcal{SC}$ plays also a crucial role in this decision-making process as high-tech products are commonly assembled using components from a number of suppliers, each of them in need of different levels of technological upgrade. Table 4.1 shows an example of how complex are two-echelon $\mathcal{SC}$ in the aerospace sector. Therefore, it is of utmost importance to understand the effect of new technologies on the performance of the acquiring company and on its supply chain.

Although the existence of an ample number of empirical studies in the current literature describing the relation between supply chain ($\mathcal{SC}$) performance and new technologies investment, analytical research on this matter is quite scarce. In this chapter, our aim is to model and analyze

Table 4.1: Number of suppliers for different high-tech products (source: Oliver Wyman (2015))

Company	Type	Product model	Number of suppliers
Airbus	$\mathcal{OEM}$	A380	200^a
		A350	90^a
Embraer	$\mathcal{OEM}$	EMB 145	350
		EMB 170/190	38
Rolls-Royce	Tier 1	Trent 500	250
		Trent 900	140
		Trent 1000	75

[a] Number of Tier 1 suppliers.

the impact of new technologies investment on the $\mathcal{SC}$ members performance and to demonstrate how it can lead to the coordination of the system. Specifically, we aim to answer the following questions:

- Can $\mathcal{SC}$ coordination be achieved in a multi-supplier single-manufacturer system in presence of technology investment?
- What is the impact of the coordination contracts on the pricing and technology acquisition decisions of the system?
- If the CS and CR contracts reach $\mathcal{SC}$ coordination, can these contracts be designed to offer a win-win scenario for all parties of the negotiation?
- What is the influence of bargaining power on the negotiation?

The contributions and results of this chapter can be summarized as follow: (i) we prove that a supply chain consisting of multiple suppliers and a single manufacturer can reach coordination in presence of technology investment decisions. In addition, we show the specific conditions under which the CR contract is capable of coordinating the system, (ii) we present the particular conditions under which coordination of the supply chain brings a reduction on the retail price, while increasing at the same time the level of technology acquisition, (iii) we identify the CR contract parameter values that allow the contract design to reach a win-win state for all agents in the supply chain, (iv) and we demonstrate the increasing benefit of coordinating a supply chain system in presence of technology investment when augmenting the number of participants in the negotiation.

4.2 Literature review

The literature review is divided in two main directions: (1) a review of the impact of technology in the $\mathcal{SC}$, and (2) the literature on $\mathcal{SC}$ coordination through coordination contracts.

4.2.1 Technology and its role in the supply chain

Traditionally, supply chain ($\mathcal{SC}$) management has centered its attention in studying how materials, monetary funds and information influence the competitive advantage of the $\mathcal{SC}$ agents (Cerchione & Esposito, 2016); but a fourth dimension, knowledge, has become an increasingly important factor to be considered (Jiabin et al., 2010; Kang & Jiang, 2011). The field of knowledge management makes a clear distinction between information and knowledge (Erickson & Rothberg, 2014). Information is seen as descriptions that support the understanding of a specific subject and that is explicit and easily transferred (Rowley, 2007). There exist a vast literature on analytical studies that tackle the impact of different types of information on $\mathcal{SC}$ performance and how its accessibility can be of benefit for the $\mathcal{SC}$ members. Examples can be found for demand forecast (Ha et al., 2011; Leng & Parlar, 2009; T. Li & Zhang, 2015; Rached et al., 2015), production plans (Huang et al., 2003), inventory level (Rached et al., 2015; H. Zhang et al., 2010), order quantities (Xue et al., 2011), shipment information (Scott, 2015; C. Zhang et al., 2006), lead time (F. Chen & Yu, 2005; Rached et al., 2015), quality level (H.-c. P. Choi et al., 2008; Wu et al., 2011; Xue et al., 2011), product return information (J. Chen, 2011; R. Yan & Cao, 2017), and cost information (Güler et al., 2018).

Knowledge stands a step further from information as the accumulation of learning, expertise and know-how useful for the problem solving process but that at the same time poses more difficulties when being managed and shared (Rowley, 2007). Battistella et al. (2016) highlighted that the $\mathcal{SC}$ knowledge consists of four basic components, one of them been the technological component. This latter is the subject of our research. Technology is seen as a key element for competitive advantage (Reisman, 2005) that can lead companies to access wider markets, sales increment, cost reduction, brand enhancement, to name but a few (da Silva et al., 2019; Kumar et al., 2015). And its benefits are not limited only to the owner of the technology but they can be translated into the performance improvement of the $\mathcal{SC}$ as a whole (Kang & Jiang, 2011).

An example on this field is the work of Wang and Shin (2015). The authors model a one-supplier one-manufacturer system that considers innovation initiatives. They propose three contract for the negotiation: wholesale price contract, quality-dependent wholesale price contract, and revenue-sharing contract. The authors demonstrate that although the three contracts are capable to coordinate the system, both the wholesale price contract and quality-dependent wholesale price contract should fulfill certain conditions to do so. Another interesting example is found in the work of Chakraborty et al. (2019). They review the impact of new technologies on product quality improvement and prove that collaborative contracts can be of benefit for all $\mathcal{SC}$ members. Lastly, Bhaskaran and Krishnan (2009) develop a model to represent the process of new products between two firms with different R&D capabilities and study how revenue, technological innovation and investment sharing can benefit the overall performance of the $\mathcal{SC}$ system.

Regarding the impact of new technology investment on $\mathcal{SC}$ performance, we notice that the analytical research on this area is quite scarce. Hence, our main objective for this chapter is to model and analyze the impact of new technologies investment on the $\mathcal{SC}$ members performance and to determine how it can lead to the coordination of the $\mathcal{SC}$ system. Furthermore, our aim is to prove that on specific conditions, sharing the cost of the technology investment among the $\mathcal{SC}$ parties could result into a win-win state for all agents of the negotiation.

4.2.2 Supply chain contract coordination

Supply chain contract coordination is one of the main mechanisms studied in the literature for achieving coordination. Among these contracts, the cost sharing contract and the cost and revenue sharing contract are well-known and extensively adopted in many organizations. F. Yang, Shan, and Jin (2017) examine the performance of a two-echelon supply chain consisting of one manufacturer and one retailer under stochastic demand. For the negotiation the authors propose and compare two contracts, the full and the partial capacity cost sharing contracts. From their findings, they demonstrate that when using the first contract the retailer would tend to share a higher cost but fewer capacity quantity with the manufacturer. They also identify the threshold of capacity level at which each agent of the $\mathcal{SC}$ would prefer a given contract. Chakraborty et al. (2019) study a $\mathcal{SC}$ formed by one retailer and two competing suppliers and analyze how collaborative quality improvement can be of benefit for all the parties. The authors propose different coordination mechanisms to incentive the retailer and suppliers to share the cost on quality investment. Their results show that with the cost-sharing contract the $\mathcal{SC}$ can attain higher quality improvement levels and higher profits compared to the wholesale price contract. Chao, Iravani, and Savaskan (2009) formulate a two-echelon $\mathcal{SC}$ model with quality improvement efforts. The authors introduce two product recall cost-sharing contracts, based in selective and in complete root cause analysis, as mechanisms to coordinate the negotiation between the manufacturer and the supplier. They find that although both contracts can coordinate the supply chain, they offer different levels of profit to the manufacturer. Furthermore, the authors review how information asymmetry in quality can affect the negotiation. Ghosh and Shah (2015) explore the benefit of cost sharing contracts over a supplier-manufacturer $\mathcal{SC}$ negotiation committed towards green initiatives. Utilizing a game theoretic approach, the authors identify how the proposed contract can influence the product greening levels and profits of the $\mathcal{SC}$ participants. They further prove that implementation of the cost sharing contract results in higher profits for both parties and for the $\mathcal{SC}$ as a whole. X. Yan, Zhao, and Tang (2015) formulate a penalty cost sharing contract model for a supplier-buyer system and analyze how it can enhance quality improvement efforts and profits in the $\mathcal{SC}$. The authors consider two different strategies for the negotiation, the first in which the buyer sets the quality requirement to the supplier (QR), and a second one in which the buyer allows the supplier to decide the promised quality level (QP). The study reveals that if the quality verification cost is sufficiently small, then the buyer tends to prefer the QP design. Otherwise, it will opt for the QR model. Additionally, the authors extend their research to consider how more complex scenarios (asymmetric information and competitor suppliers) affect the negotiation.

The cost and revenue sharing contract is another contract extensively adopted in industry. T. Li et al. (2019) review a model considering carbon emission reduction efforts. The authors propose three coordination mechanisms to motivate participation of the manufacturer on green investment initiatives. Furthermore, the authors extend the original models to consider the bargaining power of the $\mathcal{SC}$ agents. From their results they notice that the basic models are capable of coordinating the $\mathcal{SC}$, while bargaining scenarios are not. Zheng et al. (2015) model the behavior of a system impacted by demand disruption and marketing effort. The study demonstrates the conditions at which the revenue and marketing cost sharing contract is capable to coordinates the $\mathcal{SC}$ in both the normal and the disrupted demand scenarios. H. Yang and Chen (2018) analyze a manufacturer-retailer system affected by carbon emission abatement efforts subject to carbon taxation. The authors propose the cost, the revenue, and the cost-revenue sharing contracts to analyze their impact on the $\mathcal{SC}$ negotiation. They find that under specific conditions the three contracts can offer benefits to both parties while increasing the abatement level in the $\mathcal{SC}$. Kunter (2012) review a contract of royal payments between a manufacturer and a retailer. The study shows that supply chain coordination can be achievable if both parties engage into marketing cost and revenue sharing efforts. Inaba (2018) studies a revenue and cost sharing contract as a mechanism to enhance the remanufacturer-retailer $\mathcal{SC}$. The author investigates the scenario when the retailer is the Stackelberg leader of the negotiation, and the one when the leader is the remanufacurer. Xie et al. (2018) explore a $\mathcal{SC}$ consisting on one manufacturer and one retailer. The authors consider that the manufacturer sells products online, while the retailer conducts offline sales and recycles used products through the reverse-channel. The authors demonstrate that the revenue-sharing contract can mitigate the online and offline channel conflict between the parties, whereas that the cost-sharing contract can motivate the remanufacturing efforts of the retailer. Bai et al. (2017) examine a sustainable $\mathcal{SC}$ formed by one manufacturer and one retailer with deteriorating items and under carbon cap-and-trade regulation. The authors propose two coordination mechanisms in their research, the revenue and promotional cost-sharing contract and the two-part tariff contract. They demonstrate that both contracts are capable to reach coordination and they determine the win-win conditions for the $\mathcal{SC}$ members. Moreover, the authors prove that the two-part tariff contract is more robust compared to the revenue and promotional cost-sharing contract.

Different to previous research, in this chapter, we further approach to a real $\mathcal{SC}$ scenario by considering a supply chain consisting of multiple suppliers and one manufacturer. In addition, in this chapter, we review how the cost-sharing contract and the cost-revenue sharing contract are affected by critical factors such as the positive effect of technology investment in a technology-aware market and the associated costs.

Table 4.2 presents the literature positioning of our research.

Table 4.2: Literature positioning of this research

Paper	$\mathcal{SC}$ decisions			$\mathcal{SC}$ characteristics		Findings		
	Technology investment	Retail pricing	Wholesale pricing	multi-supplier single-manufacturer	Stochastic demand	Coordination condition	Win-win situation	Bargaining effect
Bai et al. (2017)	✓	✓	✓			✓	✓	
Battistella et al. (2016)	✓							
Bhaskaran and Krishnan (2009)	✓							✓
Brunswicker and Vanhaverbeke (2015)	✓							
Chakraborty et al. (2019)	✓	✓	✓			✓		✓
Chao et al. (2009)						✓		
da Silva et al. (2019)	✓							
Ghosh and Shah (2015)		✓	✓			✓	✓	✓
Günsel (2015)	✓							
Inaba (2018)					✓		✓	
Kang and Jiang (2011)	✓							
Kumar et al. (2015)	✓							
Kunter (2012)			✓			✓		✓
T. Li et al. (2019)	✓	✓	✓			✓	✓	✓
Liu et al. (2016)	✓							
Reisman (2005)	✓							
Tatikonda and Stock (2003)	✓							
Wang and Shin (2015)	✓	✓	✓			✓	✓	
Xie et al. (2018)					✓		✓	
X. Yan et al. (2015)			✓					
F. Yang et al. (2017)					✓			✓
H. Yang and Chen (2018)	✓		✓				✓	
Zheng et al. (2015)			✓			✓		✓
Our paper	✓	✓	✓	✓	✓	✓	✓	✓

4.3 Base models

4.3.1 Supply chain model

We consider in this chapter a supply chain ($\mathcal{SC}$) consisting of multiple complementary suppliers ($\mathcal{S}_i$, where i=1,2,...,m) who sell a component (i) to one original equipment manufacturer (OEM) that uses them to assembly the final product to be sold in the market. The schematic diagram of the $\mathcal{SC}$ operation is illustrated by Figure 4.2.

We consider that the upstream component suppliers need to invest in certain level of technology $0 < \alpha_i < 1$ in order to participate in the $\mathcal{SC}$ negotiation. This technology could be required by the suppliers for meeting manufacturing regulations (Bai et al., 2017), enhance quality level (Bhaskaran & Krishnan, 2009; Chakraborty et al., 2019), to name but a few. The new technology cost is denoted by η_i and it is considered to be a one-off investment (H. Yang & Chen, 2018). Similar

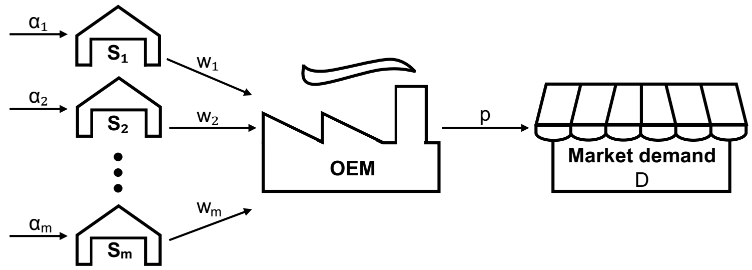


Figure 4.2: Schematic diagram of the $\mathcal{SC}$ operation

to the work of Ghosh and Shah (2015), we consider an increasing and convex cost structure for the technology improvement in order to reflect the increasingly level of investment as higher level technologies are acquired. We further establish that the investment on technology does not affect the cost structure of the system, as assumed in the work of Chakraborty et al. (2019) and H. Yang and Chen (2018). After receiving the customer's order, the $\mathcal{OEM}$ sends it to the $\mathcal{S}_i$ that follow a make-to-order (MTO) manufacturing policy. The MTO policy is particularly adopted by upstream suppliers participating in high-tech customized $\mathcal{SC}$s such as in the aerospace sector (Buergin et al., 2018). The unit production cost and unit wholesale price for component (i) are c_i and w_i respectively. The unit retail price of the final product is p. The relation between the pricing values is $p > \sum_{i=1}^{m} w_i$ and $w_i > c_i$. These inequalities assure the non-negative profit for the parties. It is further considered that the market demand $D(p, \alpha_i, \xi)$ is stochastic, price dependent (Chakraborty et al., 2019; Ghosh & Shah, 2015), and technology dependent (Bhaskaran & Krishnan, 2009). It is formulated as:

$$D(p, \alpha_i, \xi) = d - \theta p + \sum_{i=1}^{m} \beta_i \alpha_i + \xi, \tag{37}$$

where $d > 0$ is the base demand, $\theta > 0$ and $\beta_i > 0$ are the demand sensitivity coefficient to p and to α_i respectively, and ξ is the demand uncertainty with $\mathbb{E}[\xi] = 0$ and $\text{Var}[\xi] = \sigma^2$. Similar to the work of H. Yang and Chen (2018), we consider that all information is symmetric between the members, and that the market can accurately perceive the technology enhancement in the final product. Finally, for the negotiation the $\mathcal{OEM}$ acts as the leader while $\mathcal{S}_i$ are the followers.

The sequence of decisions in this Stackelberg game is as follows: (1) the $\mathcal{OEM}$ decides about the unit retail price p; (2) knowing p, $\mathcal{S}_i$ react by simultaneously deciding the unit wholesale price w_i and the level of technology α_i to acquire. Figure 4.3 depicts the model timeline.

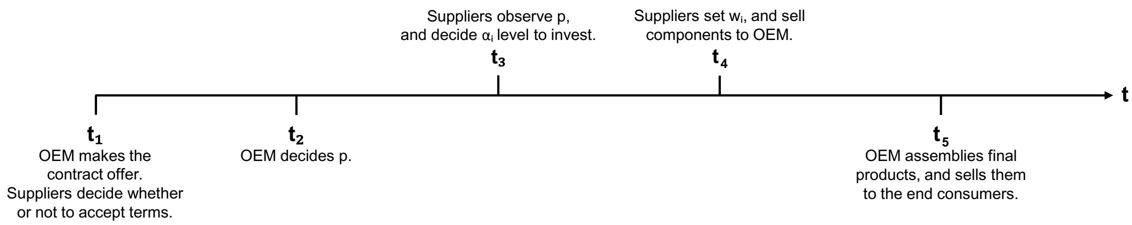


Figure 4.3: The model timeline

Table 4.3 summarizes the notation used in this chapter.

Table 4.3: Notation used in the models

Notation	Meaning
m	Number of suppliers participating in the $\mathcal{SC}$
c_i	Unit production cost of component i from $\mathcal{S}_i$
w_i	Unit wholesale price of component i from $\mathcal{S}_i$
p	Unit retail price of final product
α_i	Percentage of technology acquired by $\mathcal{S}_i$ ($0 \leq \alpha_i \leq 1$)
η_i	Cost coefficient of technology acquired by $\mathcal{S}_i$
D	Market demand
d	Base demand
θ	Retail price-dependence coefficient of demand
β_i	Technology-dependence coefficient of demand from $\mathcal{S}_i$
ξ	Uncertainty component of demand
$\mathbb{E}[\xi]$	Expected value of demand uncertainty
Var$[\xi]$	Variance of demand uncertainty
ϕ_i	Technology-cost sharing percentage in CS contract
	Technology-cost and revenue sharing percentage in CR contract
$\Pi_{\mathcal{OEM}}$	Manufacturer's profit
$\Pi_{\mathcal{S}_i}$	Supplier i's profit
$\Pi_{\mathcal{SC}}$	Supply chain's profit
WS	Wholesale price contract
CS	Cost sharing contract
CR	Cost-revenue sharing contract

4.3.2 Profit objective functions

For simplicity we use $F(m)$ to denote all expressions considering the case of m-supplier. First, Eqs. (38) and (39) present the profit and expected profit functions for the $\mathcal{OEM}$:

$$\Pi_{\mathcal{OEM}}^{WS}(p)\,(m) = \left(p - \sum_{j\in J_m} w_j\right)\left(d - \theta p + \sum_{j\in J_m} \beta_j\alpha_j + \xi\right). \tag{38}$$

$$\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(p)]\,(m) = \left(p - \sum_{j\in J_m} w_j\right)\left(d - \theta p + \sum_{j\in J_m} \beta_j\alpha_j\right). \tag{39}$$

where $W_m = \{w1, w2, ..., w_m\}$, $A_m = \{\alpha_1, \alpha_2, ..., \alpha_m\}$ and J_m is the index set for W_m and A_m. Similarly, Eqs. (40) and (41) show the profit and expected profit functions for $\mathcal{S}_i$, (i=1,2,3,...,m), respectively:

$$\Pi_{\mathcal{S}_i}^{WS}(w_i,\alpha_i)\,(m) = (w_i - c_i)\left(d - \theta p + \sum_{j\in J_m} \beta_j\alpha_j + \xi\right) - \frac{1}{2}\eta_i\alpha_i^2. \tag{40}$$

$$\mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{WS}(w_i,\alpha_i)]\,(m) = (w_i - c_i)\left(d - \theta p + \sum_{j\in J_m} \beta_j\alpha_j\right) - \frac{1}{2}\eta_i\alpha_i^2. \tag{41}$$

Eq. (42) illustrates the expected profit function for the $\mathcal{SC}$:

$$\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^{WS}(p, \forall w \in W_m, \forall\alpha \in A_m)]\,(m) = \mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(p)]\,(m) + \sum_{j\in J_m} \mathbb{E}_\xi[\Pi_{\mathcal{S}_j}^{WS}(w_j,\alpha_j)]\,(m) \tag{42}$$

In addition, all proofs are shown in Appendix B.

4.4 Equilibrium analysis

4.4.1 Decentralized supply chain considering the Wholesale price contract

We review now the optimal pricing and technology-acquisition decisions of the WS contract by exploring the equilibrium of the negotiation game. For simplicity we denote $\Omega_m = 2\theta - \sum_{j\in J_m} \frac{\beta_j^2}{\eta_j}$

and $\Psi_m = d - \theta \sum_{j \in J_m} c_j$. Because $\mathcal{S}_i$ $(i = 1, 2, 3, ..., m)$ are the followers, we first find the optimal values for wholesale price and level of technology.

Proposition 15. *For $\mathcal{S}_i$, (i=1,2,3,...,m), with a given retail price p, a unique Nash equilibrium exists for the wholesale price and level of technology decisions, and its optimal wholesale price w_i^{WS*} and optimal level of technology acquired α_i^{WS*} can be expressed as:*

$$w_i^{WS*}|_p\,(m) = c_i + \frac{d - p\theta}{\Omega_m - \theta}. \tag{43}$$

$$\alpha_i^{WS*}|_p\,(m) = \frac{\beta_i\,(d - p\theta)}{\eta_i\,(\Omega_m - \theta)}. \tag{44}$$

Substituting Eqs. (43) and (44) on Eq. (39), we obtain the $\mathcal{OEM}$'s expected optimization objective function at the equilibrium wholesale prices w_i^{WS*} and level of technology α_i^{WS*} for a given retail price p. It can be expressed as $\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(p)](m) = \mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(w_i^{WS*}|_p, \alpha_i^{WS*}|_p)](m)$. Optimization of the latter expression leads to the optimal retail price $p^{WS*} = arg\,\underset{p}{max}\left(\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(p)](m)\right)$.

Proposition 16. *The $\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(p)](m)$ is a strictly concave function of p; and the optimal retail price p^{WS*} can be expressed as:*

$$p^{WS*}\,(m) = \frac{2md\theta - (\Psi_m - 2d)\,(\Omega_m - \theta)}{2\theta\,[\Omega_m + (m-1)\,\theta]}. \tag{45}$$

Proposition 16 proofs the concavity of $\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(p)](m)$ and the existence of an unique optimal retail price p^{WS*}. By replacing Eq. (45) in Eqs. (43) and (44) it is derived Proposition 17.

Proposition 17. *The $\mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{WS}(w_i, \alpha_i)](m)$ is a strictly concave function of w_i and α_i; and the optimal wholesale price w_i^{WS*} and technology level α_i^{WS*} can be expressed as:*

$$w_i^{WS*}\,(m) = c_i + \frac{\Psi_m}{2\,[\Omega_m + (m-1)\,\theta]}. \tag{46}$$

$$\alpha_i^{WS*}\,(m) = \frac{\beta_i \Psi_m}{2\eta_i\,[\Omega_m + (m-1)\,\theta]}. \tag{47}$$

Proposition 17 evidences that in the decentralized $\mathcal{SC}$, the optimal wholesale price w_i^{WS*} and technology level α_i^{WS*} in the Stackelberg equilibrium uniquely exist and are given by Eqs. (46) and (47), respectively.

4.4.2 Behavior of the centralized system

We now consider that $\mathcal{S}_i$ (i=1,2,...,m) and the $\mathcal{OEM}$ belong to the same system. Under this assumption, the profit and expected value of profit for the $\mathcal{SC}$ can be expressed as:

$$\Pi_{\mathcal{SC}}(p, \forall\alpha \in A_m)\,(m) = \left(p - \sum_{j\in J_m} c_j\right)\left(d - \theta p + \sum_{j\in J_m} \beta_j\alpha_j + \xi\right) - \frac{1}{2}\sum_{j\in J_m} \eta_j\alpha_j^2. \tag{48}$$

$$\mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p, \forall\alpha \in A_m)]\,(m) = \left(p - \sum_{j\in J_m} c_j\right)\left(d - \theta p + \sum_{j\in J_m} \beta_j\alpha_j\right) - \frac{1}{2}\sum_{j\in J_m} \eta_j\alpha_j^2. \tag{49}$$

Next it is shown the optimal pricing and technology-acquisition decisions for the $\mathcal{SC}$ in the centralized system.

Proposition 18. *The $\mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p, \forall\alpha \in A_m)](m)$ is a strictly concave function of p and α_i; and the optimal retail price p^* and technology level α_i^* can be expressed as:*

$$p^*\,(m) = \frac{d + (\Omega_m - \theta)\sum_{j\in J_m} c_j}{\Omega_m}. \tag{50}$$

$$\alpha_i^*\,(m) = \frac{\beta_i\Psi_m}{\eta_i\Omega_m}. \tag{51}$$

Proposition 18 demonstrates that in the centralized $\mathcal{SC}$, the optimal retail price p^* and technology level α_i^* in the Stackelberg equilibrium uniquely exist.

4.4.3 Comparison of the decentralized and centralized supply chain models

Comparing the decision variables from the decentralized system $p^{WS*}(m)$, $\alpha_i^{WS*}(m)$ and its optimal demand function $D^{WS*}(m)$ with their counterparts from the centralized system, $p^*(m)$, $\alpha_i^*(m)$ and $D^*(m)$, we found that:

Proposition 19. *The relation between $p^{WS*}(m)$ and $p^*(m)$, $\alpha_i^{WS*}(m)$ and $\alpha_i^*(m)$, $D^{WS*}(m)$ and $D^*(m)$ is:*

(a)

$$\Omega_m > \theta \Longrightarrow p^*(m) < p^{WS*}(m). \tag{52}$$

(b)

$$\alpha_i^*(m) > \alpha_i^{WS*}(m). \tag{53}$$

(c)

$$\mathbb{E}[D^*](m) > \mathbb{E}\left[D^{WS*}\right](m). \tag{54}$$

Proposition 19(a) reveals a quite interesting peculiarity. Commonly, it would be expected a reduction of the retail price when the system reaches coordination, but in this model in particular there exist a specific condition that requires to be fulfilled in order to attain this outcome. Interestingly, Propositions 19(b) and 19(c) show that a coordinated $\mathcal{SC}$ always favors the investment on new technologies and also entails further opening of the market demand. Moreover, a review of both the decentralized and centralized $\mathcal{SC}$ models lead us to the following interesting observations:

Proposition 20. *If the supply chain members decide to cooperate and reach coordination, they can increase the expected optimal profit of the supply chain at least $1/3$ compared to the decentralized scenario.*

Proposition 20 justify the reason why the $\mathcal{SC}$ should seek the system coordination. Next section shows 2 contracts designed to coordinate the $\mathcal{SC}$. These contracts are tested to verify: (1) their ability to coordinate and reach the maximum expected profit for the system, and (2) the existence of win-win conditions that will lead to an increment of the profit for all members of the $\mathcal{SC}$.

In the sections below we proceed to analyze the Technology-cost sharing (CS) contract, and the Technology-cost and Revenue sharing (CR) contract to determine if they can achieve the supply chain coordination and the win-win conditions.

4.5 Technology-cost sharing (CS) contract

4.5.1 CS contract model

The model described in this subsection further assumes that the $\mathcal{OEM}$ decides to share a fraction of the technology cost paid by $\mathcal{S}_i$, i.e. $\frac{\eta_i(1-\phi_i)}{2}$. Eqs. (55) and (56) present the profit and expected value of the profit for the $\mathcal{OEM}$, respectively:

$$\Pi^{CS}_{\mathcal{OEM}}(p)\,(m) = \left(p - \sum_{j \in J_m} w_j\right)\left(d - \theta p + \sum_{j \in J_m} \beta_j \alpha_j + \xi\right) - \frac{1}{2}\sum_{j \in J_m} \eta_j (1-\phi_j)\alpha_j^2. \tag{55}$$

$$\mathbb{E}_\xi[\Pi^{CS}_{\mathcal{OEM}}(p)]\,(m) = \left(p - \sum_{j \in J_m} w_j\right)\left(d - \theta p + \sum_{j \in J_m} \beta_j \alpha_j\right) - \frac{1}{2}\sum_{j \in J_m} \eta_j (1-\phi_j)\alpha_j^2. \tag{56}$$

Eqs. (57) and (58) present the profit and expected profit functions for $\mathcal{S}_i$, $(i = 1, 2, ..., m)$, respectively:

$$\Pi^{CS}_{\mathcal{S}_i}(w_i, \alpha_i)\,(m) = (w_i - c_i)\left(d - \theta p + \sum_{j \in J_m} \beta_j \alpha_j + \xi\right) - \frac{1}{2}\eta_i \phi_i \alpha_i^2. \tag{57}$$

$$\mathbb{E}_\xi[\Pi^{CS}_{\mathcal{S}_i}(w_i, \alpha_i)]\,(m) = (w_i - c_i)\left(d - \theta p + \sum_{j \in J_m} \beta_j \alpha_j\right) - \frac{1}{2}\eta_i \phi_i \alpha_i^2. \tag{58}$$

4.5.2 CS contract coordination analysis

We now find the optimal values for wholesale price and level of technology in the CS contract.

Proposition 21. *For $\mathcal{S}_i$, (i=1,2,...,m), with a given retail price p, its optimal wholesale price w_i^{CS*}, and optimal level of technology acquired α_i^{CS*} can be expressed as:*

$$w_i^{CS*}|_p\,(m) = c_i + \frac{d - p\theta}{\theta - \displaystyle\sum_{j\in J_m} \frac{\beta_j^2}{\eta_j\phi_j}}. \tag{59}$$

$$\alpha_i^{CS*}|_p\,(m) = \frac{\beta_i\,(d - p\theta)}{\eta_i\phi_i\left(\theta - \displaystyle\sum_{j\in J_m} \frac{\beta_j^2}{\eta_j\phi_j}\right)}. \tag{60}$$

Previous results allow us to analyze the conditions at which the CS contract can coordinate the $\mathcal{SC}$.

For analyzing if the Technology-cost sharing contract of the decentralized model can reach coordination, we equal $\alpha_i^{CS*}|_p = \alpha_i^*$ and then from these results we determine if $p^{CS*} = p^*$.

Proposition 22. *The Technology-cost sharing contract is unable of coordinating the supply chain.*

The CS contract can achieve $p^{CS*} = p^*$ only when $\phi_i = 1$, value at which it develops into the WS contract. Hence, the CS contract does not provide the necessary incentives to the participants of the negotiation to reach system coordination. Now, we propose a new contract which is able to reach coordination and the win-win state for all members of the $\mathcal{SC}$.

4.6 Technology-cost and Revenue sharing (CR) contract

4.6.1 CR contract model

For the CR contract it is now assumed that the $\mathcal{OEM}$ is willing to share a fraction of the technology cost paid by $\mathcal{S}_i$, i.e. $\frac{\eta_i(1-\phi_i)}{2}$, while on the other hand $\mathcal{S}_i$ agree to share a fraction of its revenue with the $\mathcal{OEM}$, i.e. $w_i(1-\phi_i)$. For simplicity we utilize the parameter ϕ_i to express both the fraction of cost and revenue shared among the parties. Although its simplicity, this assumption is quite realistic since organizations usually prefer to engage into less complex contracts due to their practical implementation. This is specially the case for multi-product supply chains (Shen et al., 2019). Eqs. (61) and (62) present the profit and expected value of the profit for the $\mathcal{OEM}$, respectively:

$$\Pi^{CR}_{\mathcal{OEM}}(p)(m) = \left(p - \sum_{j\in J_m} w_j\phi_j\right)\left(d - \theta p + \sum_{j\in J_m}\beta_j\alpha_j + \xi\right) - \frac{1}{2}\sum_{j\in J_m}\eta_j(1-\phi_j)\alpha_j^2. \tag{61}$$

$$\mathbb{E}_\xi[\Pi^{CR}_{\mathcal{OEM}}(p)](m) = \left(p - \sum_{j\in J_m} w_j\phi_j\right)\left(d - \theta p + \sum_{j\in J_m}\beta_j\alpha_j\right) - \frac{1}{2}\sum_{j\in J_m}\eta_j(1-\phi_j)\alpha_j^2. \tag{62}$$

Similarly, Eqs. (63) and (64) show the profit and expected profit functions for $\mathcal{S}_i$, $(i = 1, 2, ..., m)$, respectively:

$$\Pi^{CR}_{\mathcal{S}_i}(w_i, \alpha_i)(m) = (w_i\phi_i - c_i)\left(d - \theta p + \sum_{j\in J_m}\beta_j\alpha_j + \xi\right) - \frac{1}{2}\eta_i\phi_i\alpha_i^2. \tag{63}$$

$$\mathbb{E}_\xi[\Pi^{CR}_{\mathcal{S}_i}(w_i, \alpha_i)](m) = (w_i\phi_i - c_i)\left(d - \theta p + \sum_{j\in J_m}\beta_j\alpha_j\right) - \frac{1}{2}\eta_i\phi_i\alpha_i^2. \tag{64}$$

4.6.2 CR contract coordination analysis

In order to derive the optimal pricing and technology-acquisition decisions of the CR contract, we proceed to find the optimal values for wholesale price and level of technology.

Proposition 23. *For $\mathcal{S}_i$, $(i = 1, 2, ..., m)$, with a given retail price p, its optimal wholesale price w_i^{CR*}, and optimal level of technology acquired α_i^{CR*} can be expressed as:*

$$w_i^{CR*}|_p\,(m) = \frac{c_i}{\phi_i} + \frac{d - p\theta}{\Omega_m - \theta}. \tag{65}$$

$$\alpha_i^{CR*}|_p\,(m) = \frac{\beta_i\,(d - p\theta)}{\eta_i\,(\Omega_m - \theta)}. \tag{66}$$

In order to test if the CR contract of the decentralized model can reach coordination, we set $\alpha_i^{CR*}|_p = \alpha_i^*$ and then from these results determine if $p^{CR*} = p^*$.

Proposition 24. *We reach to the following observations:*

(a) The CR contract coordinates the supply chain.

(b) $p^{CR*} = p^*$ and $\alpha_i^{CR*} = \alpha_i^*$.

Proposition 24 shows that the CR contract can successfully coordinate the $\mathcal{SC}$. Furthermore, it is proved that $p^{CR*} = p^*$ and $\alpha_i^{CR*} = \alpha_i^*$, meaning that the CR contract can attain perfect coordination of the supply chain. Now, it is analyzed the behavior of the wholesale price and the win-win conditions of this contract.

Proposition 25. *For $\mathcal{S}_i$, (i=1,2,...,m), its optimal wholesale price w_i^{CR*} can be expressed as:*

$$w_i^{CR*}(m) = \frac{c_i}{\phi_i} + \frac{\Psi_m}{\Omega_m}. \tag{67}$$

Comparing the wholesale price from the CR contract $w_i^{CR*}(m)$ with its counterpart from the decentralized system $w_i^{WS*}(m)$ and with the retail price from the centralized system $p^*(m)$, we found that:

Proposition 26. *The relation between $w_i^{CR*}(m)$, $w_i^{WS*}(m)$ and $p^*(m)$ is:*

(a)

$$w_i^{CR*}(m) > w_i^{WS*}(m). \tag{68}$$

(b)

$$c_i < \phi_i \sum_{j \in J_m} c_j \Longrightarrow w_i^{CR*}(m) < p^*(m). \tag{69}$$

Proposition 26(a) exposes an interesting behavior of the CR contract. Contrary to the expected outcome, the wholesale price in the CR contract is always higher than its counterpart in the decentralized system. Although at first this happening could seem an unusual phenomenon, its explanation is quite simple. In the CR contract, on the one hand, the supplier pays a fraction ϕ of the technology cost and receives a fraction ϕ of the revenue generated by selling its component to the $\mathcal{OEM}$.

On the other hand, the $\mathcal{OEM}$ pays the remaining fraction $1-\phi$ of the technology cost and gets in return the remaining fraction $1-\phi$ of the revenue generated by the supplier when selling its component. Hence, in the CR contract the unit revenue for the suppliers is $w_i^{CR*}\phi_i(m) < w_i^{CR*}(m)$. Proposition 26(b) presents a quite interesting phenomenon in which under given conditions a supplier could charge a higher wholesale price to the $\mathcal{OEM}$ compared to the retail price of the market. But again, this occurrence can be easily explained because both the supplier and the $\mathcal{OEM}$ share a fraction ϕ and $1-\phi$ of the wholesale price, respectively. Comparing the optimal expected profit functions of the OEM and $\mathcal{S}_i$ for both the WS and CR contract lead us to the next interesting findings.

4.6.3 Win-win condition

Proposition 27. *We reach to the following observations:*

(a) There exist a feasible solution for ϕ_i that offers a win-win condition for the $\mathcal{OEM}$ and the $\mathcal{S}_i$ in the CR contract.

(b) The value of ϕ_i for reaching the win-win condition state of the $\mathcal{SC}$ is delimited by the bounds:

$$\phi_i(m) \geq LB_{\phi_i(m)} = \frac{\Omega_m^2}{4\left[\Omega_m + (m-1)\theta\right]^2}. \tag{70}$$

$$\phi_i(m) \leq UB_{\phi_i(m)} = 1 - \frac{\sum_{j\in J_m; j\neq i}\left[2\theta\phi_j + (1-\phi_j)\frac{\beta_j^2}{\eta_j}\right]}{2\theta - \frac{\beta_i^2}{\eta_i}} - \frac{\Omega_m^2}{2\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)\left[\Omega_m + (m-1)\theta\right]}. \tag{71}$$

Proposition 27 presents the value of ϕ_i at which the $\mathcal{OEM}$ and $\mathcal{S}_i$ increase their profits when compared to the decentralized system. This condition is of utmost importance for the successful implementation of the CR contract. Although a contract could prove to coordinate the $\mathcal{SC}$, if it can not be designed to reach a win-win state for all participants, then these members could lack incentive to engage into the negotiation. In addition, it is interesting to see in Proposition 27(b) that there exist a unique LB_{ϕ_i}.

4.6.4 Bargaining analysis

An extension of the proposed CR contract considers now the bargaining process of the decision variable ϕ_i between the parties of the negotiation. Similar to the work of Ghosh and Shah (2015), we assume that the SC members follow the Nash bargaining process. The optimal ϕ_i obtained from the bargaining model is presented in Eq. 72

$$\phi_i^{CR*}(m) = arg \max_{\phi_i} \mathbb{E}_\xi[\Pi_{B_i}^{CR}(p^{CR*}, w_i^{CR*}, \alpha_i^{CR*})](m), \tag{72}$$

where $\Pi_{B_i}^{CR}(p^{CR*}, w_i^{CR*}, \alpha_i^{CR*})](m) = [[\Pi_{\mathcal{OEM}}^{CR}(p^{CR*})](m)][[\Pi_{\mathcal{S}_i}^{CR}(w_i^{CR*}, \alpha_i^{CR*})](m)]$. By substituting Eqs. 50, 51 and 67 in Eq. 72 and by solving latter expression, it is derived Proposition 28.

Proposition 28. *The $\mathbb{E}_\xi[\Pi_{B_i}^{CR}(p^{CR*}, w_i^{CR*}, \alpha_i^{CR*})](m)$ is a strictly concave function of ϕ_i; and the optimal $\phi_i^{CR*}(m)$ can be expressed as:*

$$\phi_i^{CR*}(m) = \frac{\Omega_m}{(m+1)\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)}. \tag{73}$$

Proposition 28 is of special interest for the parties as it reflects the optimal negotiation ability of each member of the negotiation. Furthermore, we notice that there exist a distinct value of $\phi_i^{CR*}(m)$ depending on the $\mathcal{S}_i$ negotiating with the $\mathcal{OEM}$. This is expected as although the SC members are cooperating, each of the suppliers is an independent decision maker. Furthermore, we derive the relation between the optimal value of ϕ_i in the CR contract under bargain with respect to the technology-dependence coefficient of demand β_i and the cost coefficient of technology acquired η_i. Findings are summarized in Proposition 29.

Proposition 29. *The cost-revenue sharing decision variable $[1 - \phi_i^{CR*}(m)]$ is increasing in the technology-dependence coefficient of demand β_j ($j = 1, 2, .., m$) and decreasing in the cost coefficient of technology acquired η_j ($j = 1, 2, .., m$).*

Proposition 29 means that under high cost of technology investment the $\mathcal{OEM}$ and $\mathcal{S}_i$ would share a lower portion of the technology cost and revenue, respectively. This is to expect because with higher level investments the members have less incentives to cooperate in order to protect their profitability. However, when the technology sensitivity of the market is high, the parties share a higher portion. Opposite to the previous finding, now we notice that the SC parties decide to further cooperate in the acquisition of new technologies as it benefits their profitability. Therefore, the cost-revenue sharing decision of the $\mathcal{OEM}$ and $\mathcal{S}_i$ is influenced by the technology acquisition cost and the market sensitivity to the new technologies.

4.7 Numerical analysis

Now we introduce a numerical example to gain some managerial insights from the proofs shown in previous sections.

4.7.1 Numerical example

In this example the parameter values are d=10000, θ=180. In addition, the parameter values of c, β, η, ϕ for the $\mathcal{SC}$ systems considering m= 1, 2, 4, 10, 30, 50 suppliers are summarized in Table D.1. With this given data we calculate the optimal values for the market demand, the decision variables and the expected profit for the $\mathcal{SC}$ members. Computational results for the cases of m= 1, 2, 4, 10, 30, 50 suppliers are shown in Table D.2. A summary of the computational results is presented in Table 4.4.

From the results we conclude:

(1) Considering the 1-supplier 1-manufacturer $\mathcal{SC}$ ($m = 1$), the profit in the centralized system and the corresponding level of technology acquisition are 31.75 and 0.2857, respectively. The level of technology acquisition is a percentage value where 0 signifies the no investment on technology, and values near to 1 mean investment on state-of-the-art technology, which normally implies higher costs and product enhancement. Decisions on how to interpret the percentage value of technology investment is part of the negotiation process of the $\mathcal{SC}$ parties. The profit in the WS contract and the corresponding level of technology acquisition are 23.81

Table 4.4: The optimal solution for the example

m	Model	D	Decision variables					Profit			
			p	μ_w	σ_w	μ_α	σ_α	$\Pi_{\mathcal{OEM}}$	$\mu_{\Pi_{\mathcal{S}_m}}$	$\sigma_{\Pi_{\mathcal{S}_m}}$	$\Pi_{\mathcal{SC}}$
1	Centralized system	114.29	55.63	—	—	0.2857	0.0000	—	—	—	31.75
	Decentralized system	57.14	55.60	55.32	0.00	0.1429	0.0000	15.87	7.94	0.00	23.81
	CR contract										
	μ_{ϕ_A}=0.1500 σ_{ϕ_A}=0.0000	114.29	55.63	367.30	0.00	0.2857	0.0000	26.98	4.76	0.00	31.75
	μ_{ϕ_B}=0.2500 σ_{ϕ_B}=0.0000	114.29	55.63	220.63	0.00	0.2857	0.0000	23.81	7.94	0.00	31.75
	μ_{ϕ_C}=0.3500 σ_{ϕ_C}=0.0000	114.29	55.63	157.78	0.00	0.2857	0.0000	20.63	11.11	0.00	31.75
	μ_{ϕ_D}=0.4500 σ_{ϕ_D}=0.0000	114.29	55.63	122.86	0.00	0.2857	0.0000	17.46	14.29	0.00	31.75
2	Centralized system	3979.74	33.61	—	—	0.5896	0.2085	—	—	—	87664.82
	Decentralized system	1324.94	48.25	13.11	6.01	0.1963	0.0694	29185.44	9734.50	12.77	48654.44
	CR contract										
	μ_{ϕ_A}=0.100 σ_{ϕ_A}=0.0707	3979.74	33.61	70.44	25.93	0.5896	0.2085	70107.42	8778.70	6198.84	87664.82
	μ_{ϕ_B}=0.175 σ_{ϕ_B}=0.1061	3979.74	33.61	49.61	17.68	0.5896	0.2085	56937.33	15363.75	9295.38	87664.82
	μ_{ϕ_C}=0.250 σ_{ϕ_C}=0.1414	3979.74	33.61	41.40	13.13	0.5896	0.2085	43767.23	21948.80	12391.92	87664.82
	μ_{ϕ_D}=0.325 σ_{ϕ_D}=0.1768	3979.74	33.61	36.97	10.41	0.5896	0.2085	30597.14	28533.84	15488.46	87664.82
4	Centralized system	3761.73	34.90	—	—	0.6448	0.1760	—	—	—	78160.41
	Decentralized system	749.73	51.44	7.67	2.09	0.1285	0.0351	15577.77	3118.26	3.54	28050.82
	CR contract										
	μ_{ϕ_A}=0.0650 σ_{ϕ_A}=0.0580	3761.73	34.90	106.54	53.82	0.6448	0.1760	57764.35	5099.01	4549.87	78160.41
	μ_{ϕ_B}=0.0875 σ_{ϕ_B}=0.0613	3761.73	34.90	64.58	8.21	0.6448	0.1760	50699.63	6865.19	4806.04	78160.41
	μ_{ϕ_C}=0.1075 σ_{ϕ_C}=0.0680	3761.73	34.90	54.68	5.82	0.6448	0.1760	44420.83	8434.89	5331.01	78160.41
	μ_{ϕ_D}=0.1325 σ_{ϕ_D}=0.0789	3761.73	34.90	47.77	4.09	0.6448	0.1760	36574.83	10396.39	6182.91	78160.41
10	Centralized system	3492.38	36.26	—	—	0.1603	0.0369	—	—	—	67569.82
	Decentralized system	316.76	53.81	3.45	0.87	0.0145	0.0033	6128.63	557.28	0.08	11701.38
	CR contract										
	μ_{ϕ_A}=0.0192 σ_{ϕ_A}=0.0150	3492.38	36.26	172.05	174.84	0.1603	0.0369	54556.73	1301.31	1014.30	67569.82
	μ_{ϕ_B}=0.0384 σ_{ϕ_B}=0.0299	3492.38	36.26	95.72	87.42	0.1603	0.0369	41543.63	2602.62	2028.59	67569.82
	μ_{ϕ_C}=0.0576 σ_{ϕ_C}=0.0449	3492.38	36.26	70.28	58.28	0.1603	0.0369	28530.54	3903.93	3042.89	67569.82
	μ_{ϕ_D}=0.0768 σ_{ϕ_D}=0.0599	3492.38	36.26	57.56	43.71	0.1603	0.0369	15517.45	5205.24	4057.18	67569.82
30	Centralized system	3129.32	38.47	—	—	0.1645	0.0605	—	—	—	53942.49
	Decentralized system	100.15	55.01	1.26	0.31	0.0053	0.0019	1726.28	55.70	0.01	3397.31
	CR contract										
	μ_{ϕ_A}=0.0071 σ_{ϕ_A}=0.0045	3129.32	38.47	532.84	1406.9	0.1645	0.0605	42422.85	383.99	243.24	53942.49
	μ_{ϕ_B}=0.0141 σ_{ϕ_B}=0.0089	3129.32	38.47	275.11	703.45	0.1645	0.0605	30903.21	767.98	486.49	53942.49
	μ_{ϕ_C}=0.0212 σ_{ϕ_C}=0.0134	3129.32	38.47	189.20	468.97	0.1645	0.0605	19383.57	1151.96	729.73	53942.49
	μ_{ϕ_D}=0.0282 σ_{ϕ_D}=0.0179	3129.32	38.47	206.39	314.05	0.1645	0.0605	28575.67	845.56	683.28	53942.49
50	Centralized system	2242.03	43.48	—	—	0.1343	0.0684	—	—	—	27504.73
	Decentralized system	43.32	55.32	0.86	0.38	0.0026	0.0013	531.49	10.42	0.00	1052.70
	CR contract										
	μ_{ϕ_A}=0.0043 σ_{ϕ_A}=0.0031	2242.03	43.48	436.29	884.95	0.1343	0.0684	21488.54	120.32	87.73	27504.73
	μ_{ϕ_B}=0.0086 σ_{ϕ_B}=0.0063	2242.03	43.48	224.37	442.48	0.1343	0.0684	15472.35	240.65	175.46	27504.73
	μ_{ϕ_C}=0.0129 σ_{ϕ_C}=0.0094	2242.03	43.48	153.73	294.98	0.1343	0.0684	9456.15	360.97	263.19	27504.73
	μ_{ϕ_D}=0.0172 σ_{ϕ_D}=0.0126	2242.03	43.48	118.41	221.24	0.1343	0.0684	3439.96	481.30	350.92	27504.73

and 0.1429, respectively. This means that when the $\mathcal{OEM}$ and $\mathcal{S}_1$ decide to coordinate the system, the profit of the $\mathcal{SC}$ raises by 33.35%, and at the same time the level of technology acquisition raises by 99.93%. This occurrence can be explained due to the decision of the OEM of sharing with $\mathcal{S}_1$ a fraction of its technology acquisition cost. Thanks to this agreement, the $\mathcal{SC}$ is able to further invest in technology enhancement for the end product, which in return helps to double the market demand due to the technology awareness of the end customers. In addition, it is interesting to see in this example that $p^* = 55.63 > p^{WS*} = 55.60$, due to the non fulfillment of the condition in Proposition 19(a). Regarding the results from

the CR contract, it is evident that depending on the level of ϕ_1 selected, a win-win state could be reached for both agents of the negotiation. For example, by comparing the profits from the $\mathcal{OEM}$ in the decentralized scenario with its counterpart from the CR contract, we can notice that for case C (when $\phi_1 = 0.35$), $\Pi_{\mathcal{OEM}}$ passed from 15.87 to 20.63, representing a 29.99% increase. Similarly, $\Pi_{\mathcal{S}_1}$ augmented from 7.94 to 11.11, which is an improvement of 39.92% .

(2) For the 2-supplier 1-manufacturer $\mathcal{SC}$ ($m = 2$), we notice that the $\mathcal{SC}$'s profit in the centralized and decentralized scenarios are 87664.82 and 48654.44, respectively. This means that when both $\mathcal{S}_1$, $\mathcal{S}_2$ and the $\mathcal{OEM}$ decide to cooperate, the profit of the system increases by 80.18%. Furthermore, the level of technology acquisitions in the centralized system are $\alpha_1^* = 0.4422$ and $\alpha_2^* = 0.7370$, while in the decentralized system are $\alpha_1^{WS*} = 0.1472$ and $\alpha_2^{WS*} = 0.2454$. Comparable to the profit's behavior, in the centralized scenario when the three agents decide to work together as an unique entity, the level of α_1 and α_2 acquired triple. Considering the CR contract results, we observe that cases A and B do not offer a beneficial scenario for all parties. For example, for case A (when $\phi_1 = 0.100$ and $\phi_2 = 0.175$), the profit of the agents are $\Pi_{\mathcal{OEM}}^{CR} = 70107.42$, $\Pi_{\mathcal{S}_1}^{CR} = 13161.94$, $\Pi_{\mathcal{S}_2}^{CR} = 4395.46$. The value of profit of their counterparts in the decentralized system are $\Pi_{\mathcal{OEM}}^{WS} = 29185.44$, $\Pi_{\mathcal{S}_1}^{WS} = 9725.47$, $\Pi_{\mathcal{S}_2}^{WS} = 9743.53$. Therefore, the profit value of the $\mathcal{OEM}$, $\mathcal{S}_1$ and $\mathcal{S}_2$ in the CR contract is modified by 140.21%, 35.33%, and -57.89%, respectively. Because of the profit reduction for $\mathcal{S}_2$, this agent will be reluctant to engage in this negotiation. Hence, the terms of ϕ need to be decided considering Proposition 27(b) in order to assure a $win - win$ scenario for all the $\mathcal{SC}$ participants. Finally, it is interesting to see in case D for the CR contract that $w_2^{CR} = 29.61 < p = 33.61$, due to the fulfillment of the condition in Proposition 26(b).

(3) For the 4-supplier 1-manufacturer $\mathcal{SC}$ ($m = 4$), we notice that the optimal retail price in the centralized scenario is $p = 34.90$, and the wholesale price for the suppliers in the CR contract for case A are $w_1^{CR} = 62.57$, $w_2^{CR} = 180.90$, $w_3^{CR} = 110.90$, $w_4^{CR} = 71.81$. Thus, each of the wholesale prices from the suppliers are higher than the retail price of the $\mathcal{OEM}$. Although at first this happening could seem an unusual phenomenon, its explanation is quite

simple. In the CR contract, on the one hand, the supplier pays a fraction ϕ of the technology cost and receives a fraction ϕ of the revenue generated by selling its component to the $\mathcal{OEM}$. On the other hand, the $\mathcal{OEM}$ pays the remaining fraction $1-\phi$ of the technology cost and gets in return the remaining fraction $1-\phi$ of the revenue generated by the supplier when selling its component. So for the CR contract in case A, the unit revenue for the suppliers can be expressed as $w_1^{CR}\phi_1 = 7.51$, $w_2^{CR}\phi_2 = 1.81$, $w_3^{CR}\phi_3 = 2.22$, $w_4^{CR}\phi_4 = 7.90$. Latter unit revenues for the suppliers are lower than the unit retail price of the $\mathcal{OEM}$. Moreover, we observe that $w_1^{CR}\phi_1 = 7.51 < w_1^{WS} = 9.17$, $w_2^{CR}\phi_2 = 1.81 < w_2^{WS} = 5.77$, $w_3^{CR}\phi_3 = 2.22 < w_3^{WS} = 5.97$, $w_4^{CR}\phi_4 = 7.90 < w_4^{WS} = 9.77$. This occurrence can be explained due to the double marginalization effect appearing in the decentralized system. Because the $\mathcal{OEM}$ and suppliers decide to work independently, each of them try to maximize only its own profit by increasing the wholesale prices charged to $\mathcal{OEM}$ and the retail price charged to the end customer. At the same time, because the suppliers bare alone the cost of the new technologies, their investment level is moderate. As a consequence of this chain of actions, the market reacts adversely to the increment on retail prices and moderate technological enhancement of the product by reducing the demand of the final product that translates in lower profit for the $\mathcal{SC}$. On the other hand, in the centralized system the three agents decide to work together as an unique entity. Consequently, a reduction of the retail price is achievable and also an increment on the investment on the new technologies. Both decisions are beneficial to the end customer, who in return augment the market demand and the total profit of the $\mathcal{SC}$ system.

(4) In the case of the 10-supplier 1-manufacturer $\mathcal{SC}$ ($m = 10$), we note that the $\mathcal{SC}$'s profit in the centralized and decentralized systems are 67569.82 and 11701.38, respectively, which signifies an increment of 477.45%. But despite this high raise on the total profit, depending on the terms of ϕ, not all the parties of the negotiation could benefit form the CR contract agreement. As example, by comparing the decentralized scenario with the CR contract in case B, we observe that the profit of $\mathcal{S}_2$ and $\mathcal{S}_{10}$ decrease by 63.53% and by 14.91%, respectively.

(5) For the 30-supplier 1-manufacturer $\mathcal{SC}$ ($m = 30$), we again observe that the CR contract

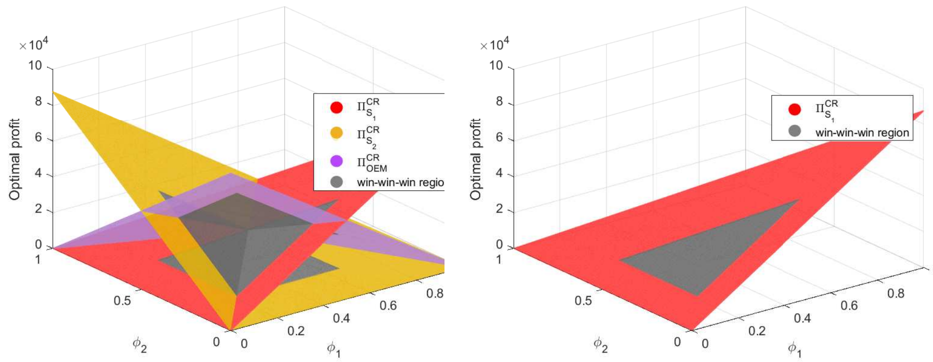
offers an incentive for the $\mathcal{SC}$ parties to cooperate, but depending on the terms of ϕ, not necessarily all the agents of the negotiation will benefit from the agreement. Using Proposition 27(b) we can calculate the lower bound of ϕ at which all the members of the $\mathcal{SC}$ will reach a win-win state on their profits. For this example, the value $\phi \geq LB_{\phi} = 0.001024$. In case C, the values of ϕ lower than 0.001024 are $\phi_7 = 0.0006$ and $\phi_{24} = 0.0003$. Therefore, both $\mathcal{S}_7$ and $\mathcal{S}_{24}$ are affected by a decrement on their profits when compared to the decentralized system (a reduction of 41.41% for $\mathcal{S}_7$, and of 70.71% for $\mathcal{S}_{24}$).

(6) In the case of the 50-supplier 1-manufacturer $\mathcal{SC}$ ($m = 50$), we note that thanks to the cooperation of the $\mathcal{SC}$ members, the system is able to increment the level of technology acquisition for each of the suppliers allowing the $\mathcal{SC}$ system to reach coordination and at the same time increasing the total profit when compared to the decentralized scenario. The example also shows us that the bargain power of each party during the negotiation is of utmost importance when deciding the fraction ϕ of cost-revenue shared by the members. For the scenario of $m = 50$, $\phi \geq LB_{\phi} = 0.000373$. It is observed in case D that all values of ϕ are greater than 0.000373, and therefore all suppliers and $\mathcal{OEM}$ are capable to reach a win-win state for their respective profits.

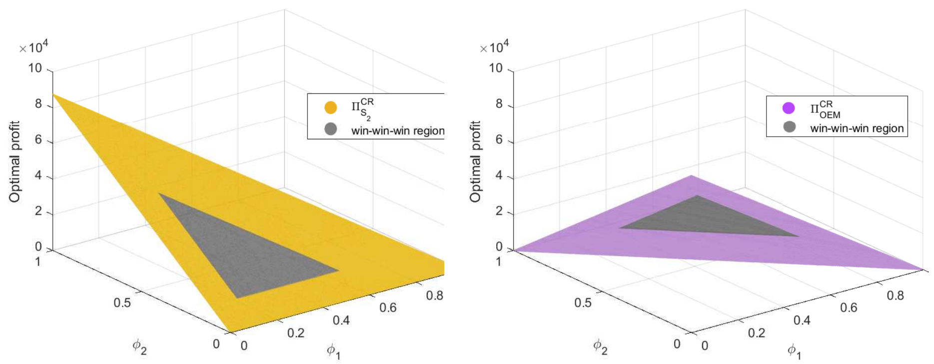
As discussed, the CR contract is able to reach a win-win state for all $\mathcal{SC}$ parties under certain conditions. By using the parameter values from scenario $m = 2$ in Table D.1, Figure 4.4 is constructed to illustrate this occurrence. Sub-figure 4.4a presents the optimal profit for the $\mathcal{SC}$ agents for given values of ϕ_1 and ϕ_2. Sub-figures 4.4b, 4.4c and 4.4d show the optimal profit for $\mathcal{S}_1$, $\mathcal{S}_2$ and $\mathcal{OEM}$ respectively. We can notice the plane formed by the values of ϕ_1 and ϕ_2 on which the three $\mathcal{SC}$ agents obtain higher optimal profits compared to the decentralized system.

Figure 4.5 shows that the win-win-win region has a triangular shape delimited by the vertices (ϕ_1= 0.11 ;ϕ_2= 0.11), (ϕ_1= 0.55;ϕ_2= 0.11) and (ϕ_1= 0.11;ϕ_2= 0.55). Hence, a CR contract designed considering values of ϕ_1 and ϕ_2 inside this triangular plane attains a win-win-win profit state for all parties of the negotiation.

Using scenario $m = 2$ in Table D.1, we analyze the relation of the parameter θ on the profit and on the demand market for both the decentralized and centralized scenarios. Figure 4.6 shows the



(a) Optimal profit for SC in CR contract (b) Optimal profit for $\mathcal{S}_1$ in CR contract



(c) Optimal profit for $\mathcal{S}_2$ in CR contract (d) Optimal profit for $\mathcal{OEM}$ in CR contract

Figure 4.4: Optimal profit in CR contract

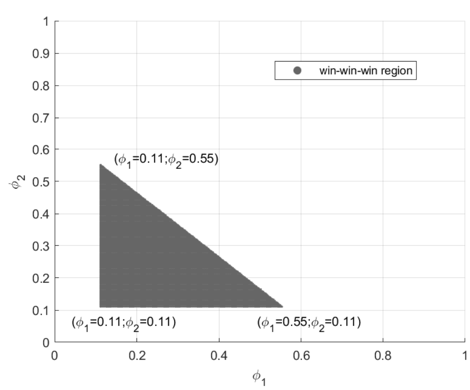


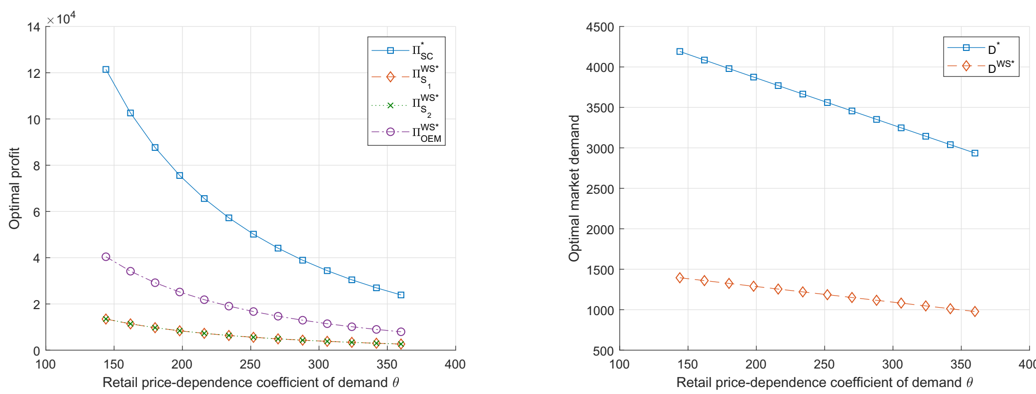
Figure 4.5: Win-win-win region in CR contract

results obtained for values of θ from 144 to 360. We make the following observations:

(1) From Sub-figure 4.6a it is noticed that variations on θ have a significant impact on reducing

the profit in both the centralized and decentralized systems. This is specially evident for the $\mathcal{OEM}$ because in this numerical example it holds the largest portion of profit among the $\mathcal{SC}$ parties.

(2) As θ increases, both the demand market on the decentralized and centralized systems decrease. It is interesting to see in Figure 4.6b the linear decrement trend for both scenarios. In this example in particular, the reduction slope of the market demand on the centralized system is three times higher than the one in the decentralized scenario. We conclude that this takes place because as θ increases, the suppliers and the $\mathcal{OEM}$ in the centralized system are dissuaded faster to invest in the new technologies compared to the decentralized scenario, impacting in a faster rate the reduction of the demand due to the technology awareness of the end customers.



(a) Effect of θ on profit

(b) Effect of θ on market demand

Figure 4.6: Effect of θ on profit and market demand

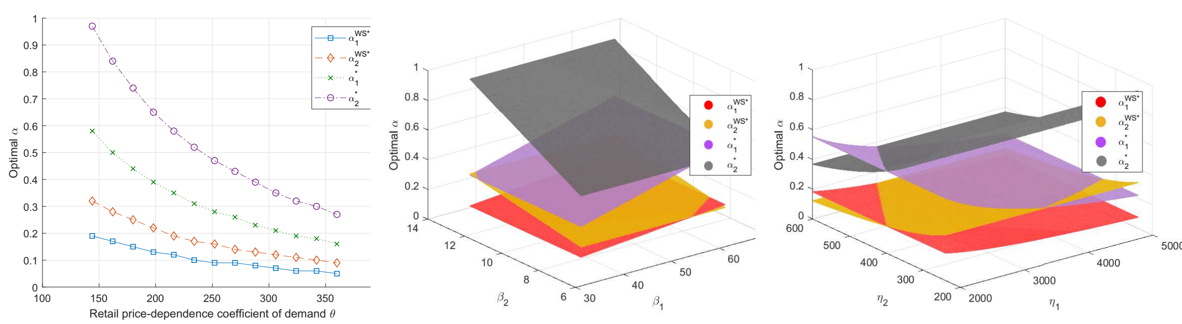
We also analyze the impact of θ, β and η on the level of technology acquisition α using the scenario $m = 2$ in Table D.1. Figure 4.7 illustrates the results for values of $\theta = [144, 360]$, $\beta_1 = [35, 65]$, $\beta_2 = [7, 13]$, $\eta_1 = [2000, 5000]$ and $\eta_2 = [240, 600]$. We explain the findings:

(1) Sub-figure 4.7a evidences that an increment on θ has a negative impact on the optimal level of technology acquisition α. This is evident because as consumers get more sensitive to the retail price, they become less predisposed to acquire the final product. As a result, the $\mathcal{SC}$ members are less stimulated on enhancing their components and end product through new

technologies investment. This phenomenon appears in both the decentralized and centralized scenarios.

(2) In Sub-figure 4.7b we notice that even though β has a positive effect on α, the effect of β_1 is insignificant on α_2, while the effect of β_2 is insignificant on α_1. Furthermore, we observe that there exist a linear incremental trend between β_1 and α_1, and between β_2 and α_2. We conclude that this situation takes place because of the relation between β and α on the market demand, that incentives the parties of the $\mathcal{SC}$ system to further invest on new technologies in the expectation of improving their benefits.

(3) From Sub-figure 4.7c we can appreciate the negative impact of the cost coefficient of technology η on α. Similar to β, we notice that the effect of η_1 is insignificant on α_2, while the effect of η_2 is insignificant on α_1. Unlike β, we can comment that there exist a non-linear incremental trend between η_1 and α_1, and between η_2 and α_2.



(a) Effect of θ on α (b) Effect of β on α (c) Effect of η on α

Figure 4.7: Effect of θ, β and η on α

We further investigate the effect of the number of suppliers participating in the $\mathcal{SC}$ m using the results from Table 4.4. We let $R_\Pi = \frac{\Pi_{\mathcal{SC}}}{\Pi_{\mathcal{SC}}^{WS}}$ represent the benefit in profit when the $\mathcal{SC}$ agents cooperate, and we let $R_\alpha = \frac{\mu_{\alpha*}}{\mu_{\alpha^{WS*}}}$ represent the increment on the average level of technology acquisition when the system attains coordination. Figure 4.8 shows the results obtained for values of $m = 1, 2, 4, 10, 30, 50$. We make the following observations:

(1) It is interesting to see that an increment of m leads to higher values of R_Π. We conclude that this takes place because when the number of suppliers increases in the decentralized system,

the summation of the bullwhip effect created by each of them has a higher negative impact on the profit of the system when compared to a scenario with fewer suppliers. Thanks to the cooperation of the $\mathcal{SC}$ members in the centralized scenario, the bullwhip effect disappears allowing the reduction of the retail price charged to the end customer, and the reduction of the wholesale prices charged to the $\mathcal{OEM}$. Thanks to this occurrence, when having more suppliers participating in the negotiation, this cooperation further incentive the demand growth and ameliorate the subsequent profits of the participants.

(2) Similar to R_{Π}, we observe that m has a positive influence on R_{α}. Having a larger number of suppliers in the centralized system favors the demand boost when compared to the decentralized scenario. Because of this, a higher number of cooperative suppliers encourages also the system to further invest in new technologies for the components used to assembly the final product.

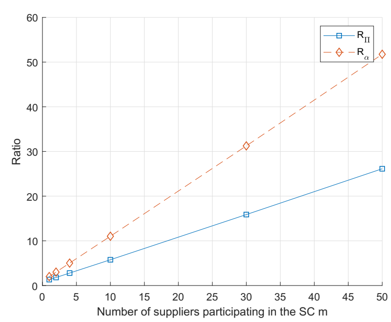


Figure 4.8: Effect of m on R_{Π} and R_{α}

4.7.2 Sensitivity analysis

We use scenario $m = 4$ in Table D.1 to investigate the effects of the parameters θ, β and η on the $\mathcal{SC}$ system coordination strategies. We modify each of the parameters by +10%, +5%, -5% and -10%, changing one parameter at a time while keeping the rest unchanged. We assume for the CR contract the value of the decision variables to be ϕ_1=0.20, ϕ_2=0.05, ϕ_3=0.08 and ϕ_4=0.20. From Table 4.5, we explain the following findings:

(1) The parameter θ has a negative impact on the market demand, retail price, wholesale prices, levels of technology acquisition and on the profit of all participants. As the retail price-dependence coefficient of demand increases, the $\mathcal{OEM}$ decides to lower its retail price. This decision is also followed by the the suppliers who decrease the wholesale prices charged to the $\mathcal{OEM}$. Because in our example θ has higher impact on the market demand compared to β_1, β_2, β_3 and β_4, an increase on θ force the $\mathcal{SC}$ to reduce their investment on new technologies. Consequently, the optimal profit of all members of the $\mathcal{SC}$ decrease.

(2) The parameter β has a positive effect on the demand market, retail price, wholesale prices, levels of technology acquisition and on the profit of the system. Higher values of β_1, β_2, β_3 and β_4 favor the expansion of the market demand due to the technology awareness of the end customers. Because of this occurrence, the parties are more willing to further invest in new technologies for the components used to assembly the final product. As an outcome, the four suppliers and the $\mathcal{OEM}$ see their respective profits augmented thanks to the cooperative agreement.

(3) As the parameter η increases, the market demand, retail price, wholesale prices, levels of technology acquisition and the profit of each of the members of the system decrease. As the new technologies become more expensive, the members of the $\mathcal{SC}$ are discourage to enhance the components used to assembly the final product. This decision has a negative reaction on the end customers, who in return opt to cut down the market demand. As a contingency measure, the $\mathcal{OEM}$ lower the retail price as an attempt to minimize the demand shrink. Because the suppliers and the $\mathcal{OEM}$ agree to cooperate, the reduction on the retail price is also assumed by the suppliers, who decide to lower the wholesale prices charged to the $\mathcal{OEM}$. As a final result, the profit for all members of the system is negatively affected by the increment of η_1, η_2, η_3 and η_4.

Table 4.5: Sensitivity analysis for CR contract

				Decision variables			Profit		
Parameter	%	Value	D	p	w	α	$\Pi_{\mathcal{OEM}}$	$\Pi_{\mathcal{S}_m}$	$\Pi_{\mathcal{SC}}$
θ	+10.0%	198	3633.08	32.35	w_1=43.35 w_2=50.35 w_3=40.85 w_4=46.35	α_1=0.63 α_2=0.38 α_3=0.51 α_4=0.74	31043.28	$\Pi_{\mathcal{S}_1}$=13309.38 $\Pi_{\mathcal{S}_2}$= 3332.27 $\Pi_{\mathcal{S}_3}$= 5329.30 $\Pi_{\mathcal{S}_4}$=13298.65	66312.88
	+5.0%	189	3697.34	33.56	w_1=44.56 w_2=51.56 w_3=42.06 w_4=47.56	α_1=0.67 α_2=0.41 α_3=0.54 α_4=0.79	33667.30	$\Pi_{\mathcal{S}_1}$=14439.57 $\Pi_{\mathcal{S}_2}$= 3615.49 $\Pi_{\mathcal{S}_3}$= 5782.13 $\Pi_{\mathcal{S}_4}$=14427.39	71931.88
	-5.0%	171	3826.27	36.38	w_1=47.38 w_2=54.38 w_3=44.88 w_4=50.38	α_1=0.77 α_2=0.47 α_3=0.62 α_4=0.90	39810.72	$\Pi_{\mathcal{S}_1}$=17088.65 $\Pi_{\mathcal{S}_2}$= 4279.49 $\Pi_{\mathcal{S}_3}$= 6843.71 $\Pi_{\mathcal{S}_4}$=17072.71	85095.29
	-10.0%	162	3890.98	38.02	w_1=49.02 w_2=56.02 w_3=46.52 w_4=52.02	α_1=0.83 α_2=0.50 α_3=0.67 α_4=0.97	43429.77	$\Pi_{\mathcal{S}_1}$=18651.19 $\Pi_{\mathcal{S}_2}$= 4671.24 $\Pi_{\mathcal{S}_3}$= 7469.98 $\Pi_{\mathcal{S}_4}$=18632.82	92855.00
β	+10.0%	β_1=22.0 β_2=5.5 β_3=11.0 β_4=27.5	3766.33	34.92	w_1=45.92 w_2=52.92 w_3=43.42 w_4=48.92	α_1=0.79 α_2=0.48 α_3=0.64 α_4=0.93	36585.52	$\Pi_{\mathcal{S}_1}$=15724.82 $\Pi_{\mathcal{S}_2}$= 3938.96 $\Pi_{\mathcal{S}_3}$= 6298.65 $\Pi_{\mathcal{S}_4}$=15707.95	78255.90
	+5.0%	β_1=21.0 β_2=5.3 β_3=10.5 β_4=26.3	3763.97	34.91	w_1=45.91 w_2=52.91 w_3=43.41 w_4=48.91	α_1=0.76 α_2=0.46 α_3=0.61 α_4=0.89	36580.06	$\Pi_{\mathcal{S}_1}$=15708.41 $\Pi_{\mathcal{S}_2}$= 3934.16 $\Pi_{\mathcal{S}_3}$= 6291.31 $\Pi_{\mathcal{S}_4}$=15693.06	78206.99
	-5.0%	β_1=19.0 β_2=4.8 β_3=9.5 β_4=23.8	3759.60	34.89	w_1=45.89 w_2=52.89 w_3=43.39 w_4=48.89	α_1=0.68 α_2=0.41 α_3=0.55 α_4=0.80	36569.85	$\Pi_{\mathcal{S}_1}$=15677.96 $\Pi_{\mathcal{S}_2}$= 3925.25 $\Pi_{\mathcal{S}_3}$= 6277.67 $\Pi_{\mathcal{S}_4}$=15665.42	78116.16
	-10.0%	β_1=18.0 β_2=4.5 β_3=9.0 β_4=22.5	3757.58	34.88	w_1=45.88 w_2=52.88 w_3=43.38 w_4=48.88	α_1=0.65 α_2=0.39 α_3=0.52 α_4=0.76	36565.12	$\Pi_{\mathcal{S}_1}$=15663.91 $\Pi_{\mathcal{S}_2}$= 3921.14 $\Pi_{\mathcal{S}_3}$= 6271.38 $\Pi_{\mathcal{S}_4}$=15652.67	78074.22
η	+10.0%	η_1=638 η_2=264 η_3=396 η_4=682	3759.74	34.89	w_1=45.89 w_2=52.89 w_3=43.39 w_4=48.89	α_1=0.65 α_2=0.40 α_3=0.53 α_4=0.77	36570.19	$\Pi_{\mathcal{S}_1}$=15678.96 $\Pi_{\mathcal{S}_2}$= 3925.55 $\Pi_{\mathcal{S}_3}$= 6278.12 $\Pi_{\mathcal{S}_4}$=15666.33	78119.15
	+5.0%	η_1=609 η_2=252 η_3=378 η_4=651	3760.69	34.89	w_1=45.89 w_2=52.89 w_3=43.39 w_4=48.89	α_1=0.69 α_2=0.41 α_3=0.55 α_4=0.80	36572.40	$\Pi_{\mathcal{S}_1}$=15685.54 $\Pi_{\mathcal{S}_2}$= 3927.47 $\Pi_{\mathcal{S}_3}$= 6281.07 $\Pi_{\mathcal{S}_4}$=15672.31	78138.79
	-5.0%	η_1=551 η_2=228 η_3=342 η_4=589	3762.88	34.90	w_1=45.90 w_2=52.90 w_3=43.40 w_4=48.90	α_1=0.76 α_2=0.46 α_3=0.61 α_4=0.89	36577.52	$\Pi_{\mathcal{S}_1}$=15700.81 $\Pi_{\mathcal{S}_2}$= 3931.93 $\Pi_{\mathcal{S}_3}$= 6287.90 $\Pi_{\mathcal{S}_4}$=15686.16	78184.32
	-10.0%	η_1=522 η_2=216 η_3=324 η_4=558	3764.16	34.91	w_1=45.91 w_2=52.91 w_3=43.41 w_4=48.91	α_1=0.80 α_2=0.48 α_3=0.65 α_4=0.94	36580.49	$\Pi_{\mathcal{S}_1}$=15709.72 $\Pi_{\mathcal{S}_2}$= 3934.54 $\Pi_{\mathcal{S}_3}$= 6291.89 $\Pi_{\mathcal{S}_4}$=15694.25	78210.90

4.8 Conclusions and future research

This chapter studies the technology investment strategy in a two echelon supply chain consisting of multiple complementary suppliers and one manufacturer. By comparing a decentralized system with wholesale price contract and collaborative scenarios with cost-sharing (CS) and cost-revenue sharing (CR) contracts, we review if a collaborative technology investment initiative is beneficial to all supply chain parties. Specifically, the main findings in this research are:

(1) If the $\mathcal{SC}$ members decide to cooperate and coordinate the system, they could increase the overall expected profit by at least 1/3 compared to the non-cooperative scenario.

(2) Under particular conditions, coordination of the $\mathcal{SC}$ can lead to a reduction on the retail price, and at the same time can lead to an increment on the level of technology acquisition.

(3) Although the CS contract does not offer the necessary incentives to coordinate the $\mathcal{SC}$, the CR contract proves to reach perfect coordination of the system.

(4) There exist a feasible solution for $LB_{\phi_i} \leq \phi_i \leq UB_{\phi_i}$ that offers a win-win condition for the $\mathcal{OEM}$ and $\mathcal{S}_i$ in the CR contract.

(5) Through bargaining analysis it is possible to determine the optimal negotiation ability of each SC member.

(6) The numerical example shows that as the number of suppliers involved in the negotiation increase, benefits on profit and level of technology acquisition further improve when compared to the decentralized scenario.

This chapter can be further extended in a number of directions. Firstly, in this chapter we study coordination in a two echelon supply chain consisting of multiple suppliers and a single manufacturer. For practical applications, it would be interesting to extend our conclusions for the scenario of a multi-echelon supply chain where lower tier level suppliers are also considered. Secondly, in this work we consider that all the participants of the negotiation are risk-neutral. Because the acquisition of new technologies entails high level investments, it would be important to investigate the behavior of a system formed by risk-averse parties. Lastly, this chapter focuses on examining the investment on new technologies as a coordination tool in which the technology is obtained from an external entity out of the supply chain system, or through the R&D of a single party in the system. Another direction of our research would review how the transfer of technologies among members of the same $\mathcal{SC}$ could be of benefit for coordinating the system.

Chapter 5

Conclusions and Future research

5.1 Conclusions

Companies especially in the high-tech sector pursue the acquisition and implementation of new technologies as a mean to achieve process and product enhancement. But new technologies investment is a difficult decision because of the costs related and the complexity for its implementation. Hence, it becomes crucial to understand the impact of new technologies on the performance of the acquiring company and on its supply chain. Therefore, we propose two main directions of research to model and analyze this phenomenon. Firstly, we study the effect of transferring an existing technology in a supply chain from its owner to a different member in the system. Secondly, we investigate the effect of new technology investment when it is independently acquired by one of the members in the supply chain, i.e. obtained from a third-party or through internal R&D.

Following the first research direction, in Chapter 2 we model and discuss the dynamics of using technology transfer as a tool to obtain market share from a supplier's country. We consider uncertain product quality level and market share portions and propose three related models: (i) a supply chain system with neither technology transfer nor supplier's market sharing, (ii) a system that takes into consideration technology transfer but without supplier's market sharing, and (iii) a supply chain affected by technology transfer and supplier's market sharing. In Chapter 3 we study the technology investment strategy in a two echelon supply chain consisting of one manufacturer and two competing retailers. By comparing a non-collaborative scenario with wholesale price contract and collaborative scenarios with Cost-revenue sharing (CR) and Two-part tariff (TPT) contracts, we analyze whether a collaborative technology enhancement initiative is beneficial to all supply chain parties. Lastly, in Chapter 4 of this thesis, we review a model consisting of multiple complementary suppliers and one manufacturer. We perform an analysis to determine if the cost-sharing (CS) and cost-revenue sharing (CR) contracts are capable of coordinating the supply chain. Furthermore, we study whether or not this contracts are able to offer a win-win scenario for all members of the negotiation and review how bargaining analysis can lead to the optimal negotiation ability of each member.

5.2 Future research

The research work presented in this thesis can be extended in several directions. First for Chapter 2, it can include and analyze the supplier's benefits in deciding the optimal manufacturer's order quantity. A supply chain system in aerospace industry, for example, normally consists of several different tiers of suppliers. Therefore it is also of interest to study how technology transfer may affect multi-echelon supply chains. Furthermore, the models proposed in Chapter 2 are based on the assumption of deterministic demand. It is of interest and practical importance to include demand uncertainties in extending the models for practical applications.

In Chapter 3 we study coordination in a one-manufacturer two-retailer system. For practical applications, it would be interesting to extend our conclusions for the scenario of a single-manufacturer multi-retailer supply chain. In addition, this chapter focuses on examining the investment on new technologies as a coordination tool in which the technology is obtained from an external entity out of the supply chain system, or through the R&D of a single party in the system. Another direction of our research would review how the transfer of technologies among members of the same $\mathcal{SC}$ could be of benefit for coordinating the system.

Chapter 4 reviews coordination in a two echelon supply chain consisting of multiple suppliers and a single manufacturer. Additional work can be done to extend our conclusions for the scenario of a multi-echelon supply chain where lower tier level suppliers are also considered. In addition, in Chapter 4 we consider that all the participants of the negotiation are risk-neutral. Because the acquisition of new technologies entails high level investments, it would be important to investigate the behavior of a system formed by risk-averse parties. Lastly, in this work we have considered the acquisition of a general type of technology. It will be interesting to investigate the attributes and particular impacts of specific technologies, i.e. additive manufacturing, advanced robotics, etc., on the supply chain performance.

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Appendix A

Mathematical proofs Chapter 2

Proof of Proposition 6: We first check if the profit function for $\mathcal{R}_i$ is concave in p_i by calculating the first and second order derivatives:

$$\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{R}_i}^{WS}(p_i)]}{\partial p_i} = d_i + \gamma p_j - \theta\left(2p_i - w_i\right) + \beta\alpha,\ where\ i \neq j;$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi_{\mathcal{R}_i}^{WS}(p_i)]}{\partial p_i^2} = -2\theta.$$

We have proved that $\mathbb{E}_\xi[\Pi_{\mathcal{R}_i}^{WS}(p_i)]$ is a strictly concave function of p_i as long as $2\theta > 0$ holds. Now, by setting $\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{R}_i}^{WS}(p_i)]}{\partial p_i} = 0$ we obtain:

$$p_i^{WS*}|_{p_j,w_i,\alpha} = \frac{d_i + w_i\theta + \gamma p_j + \beta\alpha}{2\theta},\ where\ i \neq j. \tag{74}$$

Finally, solving Equation 74 for $i = 1, 2$ leads to Equation 15.

□

Proof of Proposition 7: After finding $p_i^{WS*}|_{w_1,w_2,\alpha}$, we proceed to calculate the optimal wholesale price w_i^{WS*} and level of technology α^{WS*} for the $\mathcal{OEM}$. By solving Equation 13 using Equation 15 it is obtained:

$$\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(w_1,w_2,\alpha)] = \frac{\theta\sum_{i=1}^{2}\left[(w_i-c_i)\left(\gamma^2 w_i - 2\theta\left(\theta w_i - d_i\right) + \gamma\left(\theta w_j + d_j\right) + \beta\alpha\left(2\theta+\gamma\right)\right)\right]}{4\theta^2-\gamma^2} - \frac{1}{2}\eta\alpha^2. \tag{75}$$

Now we proceed to verify the mathematical properties of the profit function for the $\mathcal{OEM}$. We calculate the Hessian matrix to verify if it is concave in w_i and α. The following first and second order derivatives are then obtained:

$$\frac{\partial\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(w_1,w_2,\alpha)]}{\partial w_i} = \frac{\theta\left[2\theta d_i + \gamma d_j - \left(2\theta^2-\gamma^2\right)\left(2w_i-c_i\right) + \theta\gamma\left(2w_j-c_j\right) + \beta\alpha\left(2\theta+\gamma\right)\right]}{4\theta^2-\gamma^2};$$

$$\frac{\partial\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(w_1,w_2,\alpha)]}{\partial\alpha} = \frac{\theta\beta\left(w_1+w_2-c_1-c_2\right)}{2\theta-\gamma} - \eta\alpha; \qquad \frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(w_1,w_2,\alpha)]}{\partial w_i^2} = \frac{-2\theta\left(2\theta^2-\gamma^2\right)}{4\theta^2-\gamma^2};$$

$$\frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(w_1,w_2,\alpha)]}{\partial\alpha\partial w_i} = \frac{\theta\beta}{2\theta-\gamma}; \qquad \frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(w_1,w_2,\alpha)]}{\partial\alpha^2} = -\eta; \qquad \frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(w_1,w_2,\alpha)]}{\partial w_i\partial w_j} = \frac{2\theta^2\gamma}{4\theta^2-\gamma^2}.$$

The Hessian matrix $H_{\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}]}$ can be expressed as:

$$H_{\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}]} = \begin{bmatrix} \frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}]}{\partial w_1^2} & \frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}]}{\partial w_1\partial w_2} & \frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}]}{\partial w_1\partial\alpha} \\ \frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}]}{\partial w_2\partial w_1} & \frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}]}{\partial w_2^2} & \frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}]}{\partial w_2\partial\alpha} \\ \frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}]}{\partial\alpha\partial w_1} & \frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}]}{\partial\alpha\partial w_2} & \frac{\partial^2\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}]}{\partial\alpha^2} \end{bmatrix} = \begin{bmatrix} \frac{-2\theta\left(2\theta^2-\gamma^2\right)}{4\theta^2-\gamma^2} & \frac{2\theta^2\gamma}{4\theta^2-\gamma^2} & \frac{\theta\beta}{2\theta-\gamma} \\ \frac{2\theta^2\gamma}{4\theta^2-\gamma^2} & \frac{-2\theta\left(2\theta^2-\gamma^2\right)}{4\theta^2-\gamma^2} & \frac{\theta\beta}{2\theta-\gamma} \\ \frac{\theta\beta}{2\theta-\gamma} & \frac{\theta\beta}{2\theta-\gamma} & -\eta \end{bmatrix}$$

The determinant $|H_{\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}]}| = \frac{-4\theta^2\left[\left(\theta^2-\gamma^2\right)(2\theta-\gamma)\eta - \theta\beta^2(\theta+\gamma)\right]}{(4\theta^2-\gamma^2)(2\theta-\gamma)}$. Then, we have proved that $\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(w_1,w_2,\alpha)]$ is a strictly concave function of w_i and α as long as $\left(\theta^2-\gamma^2\right)\left(2\theta-\gamma\right)\eta > \theta\beta^2\left(\theta+\gamma\right)$ holds. Now, by setting $\frac{\partial\mathbb{E}[\Pi^{WS}_{\mathcal{OEM}}]}{\partial w_i} = 0$ and $\frac{\partial\mathbb{E}[\Pi^{WS}_{\mathcal{OEM}}]}{\partial\alpha} = 0$ we obtain:

$$w_i^{WS*}|_{w_j,\alpha} = \frac{c_i}{2} + \frac{2\theta d_i + \gamma d_j + \theta\gamma\left(2w_j - c_j\right) + \beta\alpha\left(2\theta + \gamma\right)}{2\left(2\theta^2 - \gamma^2\right)}. \tag{76}$$

$$\alpha^{WS*}|_{w_1,w_2} = \frac{\theta\beta\left(w_1 + w_2 - c_1 - c_2\right)}{\eta\left(2\theta - \gamma\right)}. \tag{77}$$

Finally, solving Equations 76 and 77 yields to Equations 16 and 17.

□

Proof of Proposition 8: Substituting Equations 16 and 17 in Equation 15 leads to Equation 18.

□

Proof of Proposition 9: We first calculate the Hessian matrix to verify if it is concave in p_i and α. From Equation 20 the following first and second order derivatives are obtained:

$$\frac{\partial\mathbb{E}_\xi[\Pi_{\mathcal{SC}}]}{\partial p_i} = d_i - \theta(2p_i - c_i) + \gamma(2p_j - c_j) + \beta\alpha; \quad \frac{\partial^2\mathbb{E}_\xi[\Pi_{\mathcal{SC}}]}{\partial p_i^2} = -2\theta; \quad \frac{\partial^2\mathbb{E}_\xi[\Pi_{\mathcal{SC}}]}{\partial p_i \partial p_j} = 2\gamma;$$

$$\frac{\partial\mathbb{E}_\xi[\Pi_{\mathcal{SC}}]}{\partial\alpha} = \beta\left(p_1 + p_2 - c_1 - c_2\right) - \eta\alpha; \qquad \frac{\partial^2\mathbb{E}_\xi[\Pi_{\mathcal{SC}}]}{\partial\alpha^2} = -\eta; \qquad \frac{\partial^2\mathbb{E}_\xi[\Pi_{\mathcal{SC}}]}{\partial\alpha\partial p_i} = \beta.$$

The Hessian matrix $H_{\mathbb{E}[\Pi_{\mathcal{SC}}]} = \begin{bmatrix} \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial p_1^2} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial p_1\partial p_2} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial p_1\partial\alpha} \\ \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial p_2\partial p_1} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial p_2^2} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial p_2\partial\alpha} \\ \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha\partial p_1} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha\partial p_2} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha^2} \end{bmatrix} = \begin{bmatrix} -2\theta & 2\gamma & \beta \\ 2\gamma & -2\theta & \beta \\ \beta & \beta & -\eta \end{bmatrix}$

The determinant $|H_{\mathbb{E}[\Pi_{\mathcal{SC}}]}| = -4\left(\theta+\gamma\right)\left[\left(\theta-\gamma\right)\eta - \beta^2\right]$. We have proved that $\mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p_1, p_2, \alpha)]$ is a strictly concave function of p_i and α as long as $\left(\theta-\gamma\right)\eta > \beta^2$ holds. Now, by setting $\frac{\partial\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha} = 0$ and $\frac{\partial\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial p_i} = 0$ we obtain:

$$\alpha^*|_{p_1,p_2} = \frac{\beta}{\eta}(p_1 + p_2 - c_1 - c_2). \tag{78}$$

$$p_i^*|_{p_j,\alpha} = \frac{1}{2\theta}\left[d_i + \theta c_i + \gamma\left(2p_j - c_j\right) + \beta\alpha\right],\ where\ i \neq j. \tag{79}$$

By solving Equations 78 and 79 we obtain Equations 21 and 22, respectively.

□

Proof of Proposition 10: The optimal expected profit for the decentralized supply chain is obtained by replacing the values of p_i^{WS*}, w^{WS*} and α^{WS*} in Equation 14:

$$\begin{aligned}\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^{WS*}] =& \frac{\theta\left(d_1^2+d_2^2\right)\left[\eta^2\left(\theta-\gamma\right)\left(28\theta^3-6\gamma^3-28\theta^2\gamma+15\theta\gamma^2\right)-\eta\theta\beta^2\left(20\theta^2+9\gamma^2-20\theta\gamma\right)+4\theta^2\beta^4\right]}{8\left[\eta\left(2\theta-\gamma\right)\left(\theta-\gamma\right)-\theta\beta^2\right]^2\left(2\theta+\gamma\right)^2} \\ &- \frac{2d_1d_2\theta\left[\eta^2\left(\theta-\gamma\right)\left(4\theta^3-2\gamma^3-36\theta^2\gamma+25\theta\gamma^2\right)-\eta\theta\beta^2\left(12\theta^2+7\gamma^2-28\theta\gamma\right)+4\theta^2\beta^4\right]}{8\left[\eta\left(2\theta-\gamma\right)\left(\theta-\gamma\right)-\theta\beta^2\right]^2\left(2\theta+\gamma\right)^2} \\ &- \frac{4\theta\eta\left(2\theta+\gamma\right)^2\left(\theta-\gamma\right)\left[\eta\left(3\theta-2\gamma\right)\left(\theta-\gamma\right)-\theta\beta^2\right]\left[d_1+d_2-c\left(\theta-\gamma\right)\right]c}{8\left[\eta\left(2\theta-\gamma\right)\left(\theta-\gamma\right)-\theta\beta^2\right]^2\left(2\theta+\gamma\right)^2}.\end{aligned} \tag{80}$$

The optimal expected profit for the centralized supply chain is obtained by replacing the values of p_i^* and α^* in Equation 20:

$$\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^*] = \frac{\left(2\theta\eta-\beta^2\right)\left(d_1^2+d_2^2\right)+2\left(2\gamma\eta+\beta^2\right)d_1d_2-4\left(\theta^2-\gamma^2\right)\eta\left[d_1+d_2-\left(\theta-\gamma\right)c\right]c}{8\left(\theta+\gamma\right)\left[\left(\theta-\gamma\right)\eta-\beta^2\right]}. \tag{81}$$

Comparing Equation 80 and Equation 81, we demonstrate that the relationship between the centralized and decentralized system is $\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^{WS*}(p_1^{WS*}, p_2^{WS*}, w^{WS*}, \alpha^{WS*})] < \mathbb{E}_\xi[\Pi_{\mathcal{SC}}^*(p_1^*, p_2^*, \alpha^*)]$.

□

Proof of Proposition 11: We first check if the profit function for $\mathcal{R}_i$ is concave in p_i by calculating the first and second order derivatives:

$$\frac{\partial\mathbb{E}_\xi[\Pi_{\mathcal{R}_i}^{CR}(p_i)]}{\partial p_i} = \left(d_i - 2\theta p_i + \gamma p_j + \beta\alpha\right)\phi_i + \theta w_i; \qquad \frac{\partial^2\mathbb{E}_\xi[\Pi_{\mathcal{R}_i}^{CR}(p_i)]}{\partial p_i^2} = -2\theta\phi_i.$$

We have proved that $\mathbb{E}_\xi[\Pi^{CR}_{\mathcal{R}_i}(p_i)]$ is a strictly concave function of p_i as long as $2\theta > 0$ holds. Now, by setting $\frac{\partial \mathbb{E}_\xi[\Pi^{CR}_{\mathcal{R}_i}(p_i)]}{\partial p_i} = 0$ we obtain:

$$p_i^{CR*}|_{p_j,w_i,\alpha} = \frac{(d_i + \gamma p_j + \beta\alpha)\,\phi_i + \theta w_i}{2\theta\phi_i}. \tag{82}$$

Finally, solving Equation 82 for $i = 1, 2$ leads to Equation 27.

□

Proof of Proposition 12: From $p_i^{CR*}|_{w_1,w_2,\alpha} = p_i^*$ we get:

$$\begin{aligned} w_i^{CR*}|_\alpha = &\phi_i \left[c_i - \frac{\gamma c_j}{2\theta} - \frac{\beta\alpha}{\theta}\right] \\ &+ \phi_i \left[\frac{\left[2\gamma^2\eta + \beta^2(2\theta+3\gamma)\right] d_i + \left[2\theta\gamma\eta + \beta^2(2\theta+\gamma)\right] d_j - \beta^2(2\theta-\gamma)(\theta+\gamma)(c_1+c_2)}{4\theta(\theta+\gamma)\left[(\theta-\gamma)\eta - \beta^2\right]}\right]. \end{aligned} \tag{83}$$

By further substituting Equation 21 in Equation 83 yields to Equation 28. Finally, knowing that for the CR contract to be feasible $w_i^{CR*} > 0$, Equation 29 should hold.

□

Proof of Proposition 13: We first check if the profit function for $\mathcal{R}_i$ is concave in p_i by calculating the first and second order derivatives:

$$\frac{\partial \mathbb{E}_\xi[\Pi^{TPT}_{\mathcal{R}_i}(p_i)]}{\partial p_i} = d_i + \gamma p_j - \theta(2p_i - w_i) + \beta\alpha,\ where\ i \neq j; \quad \frac{\partial^2 \mathbb{E}_\xi[\Pi^{TPT}_{\mathcal{R}_i}(p_i)]}{\partial p_i^2} = -2\theta.$$

We have proved that $\mathbb{E}_\xi[\Pi^{TPT}_{\mathcal{R}_i}(p_i)]$ is a strictly concave function of p_i as long as $2\theta > 0$ holds. Now, by setting $\frac{\partial \mathbb{E}_\xi[\Pi^{TPT}_{\mathcal{R}_i}(p_i)]}{\partial p_i} = 0$ we obtain:

$$p_i^{TPT*}|_{p_j,w_i,\alpha} = \frac{d_i + \gamma p_j + \theta w_i + \beta\alpha}{2\theta},\ where\ i \neq j. \tag{84}$$

Finally, solving Equation 84 for $i = 1, 2$ leads to Equation 34.

□

Proof of Proposition 14: From $p_i^{TPT*}|_{w_1,w_2,\alpha} = p_i^*$ we get:

$$\begin{aligned} w_i^{TPT*}|_{\alpha} = & \frac{\left[2\gamma^2\eta + \beta^2\left(2\theta+3\gamma\right)\right] d_i + \left[2\theta\gamma\eta + \beta^2\left(2\theta+\gamma\right)\right] d_j - \left(2\theta-\gamma\right)\left(\theta+\gamma\right)\beta^2\left(c_i+c_j\right)}{4\theta\left(\theta+\gamma\right)\left[\left(\theta-\gamma\right)\eta-\beta^2\right]} \\ & + \frac{2\theta c_i - \gamma c_j - 2\beta\alpha}{2\theta}. \end{aligned} \tag{85}$$

By further substituting Equation 21 in Equation 85 yields to Equation 35. Finally, knowing that for the TPT contract to be feasible $w_i^{TPT*} > 0$, Equation 36 should hold.

□

Appendix B

Mathematical proofs Chapter 3

In this section it is presented first the proof of results for a three-supplier and one-manufacturer $\mathcal{SC}$ model, whose formulas are denoted as $F(m=3)$. Then these results are generalized considering a multi-supplier and single-manufacturer $\mathcal{SC}$ system, whose expressions are denoted as $F(m)$. Through the use of mathematical induction we verify that all $F(m)$ equations hold. For the mathematical induction proof we analyze: (i) the case of $(m+1)$ suppliers denoted as $F(m+1)$, and (ii) the case of a single supplier denoted as $F(m=1)$. Table B.1 presents the sets and index sets defined for (m) and $(m+1)$ supplier systems. For simplicity we denote $\Omega_{m=3} = 2\theta - \sum_1^3 \frac{\beta_j^2}{\eta_j}$, $\Psi_{m=3} = d - \theta\sum_1^3 c_j$, $\Omega_{m+1} = 2\theta - \sum_{j\in J_{m+1}} \frac{\beta_j^2}{\eta_j}$, $\Psi_{m+1} = d - \theta\sum_{j\in J_{m+1}} c_j$, $\Omega_{m=1} = 2\theta - \frac{\beta_1^2}{\eta_1}$ and $\Psi_{m=1} = d - \theta c_1$

Proof of Proposition 15: We first check the mathematical properties of the profit function for $\mathcal{S}_1$ (similar results can be derived for $\mathcal{S}_2$ and $\mathcal{S}_3$). We calculate the Hessian matrix to verify if it is concave in w_1 and α_1. By replacing $p = \Delta + \sum_{j=1}^3 w_j$ in Eq. (41) it is obtained the following first and second order derivatives:

$$\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{WS}(w_1,\alpha_1)]\,(m=3)}{\partial w_1} = d - \theta\left(2w_1 + \sum_{j=2}^{3} w_j + \Delta - c_1\right) + \sum_{j=1}^{3}\beta_j\alpha_j; \tag{86}$$

$$\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{WS}(w_1,\alpha_1)]}{\partial \alpha_1} = \beta_1(w_1 - c_1) - \eta_1\alpha_1; \tag{87}$$

Table B.1: Set and index set notation

(m)-supplier		$(m+1)$-supplier	
Set	Index set	Set	Index set
$W_m = \{w_1, w_2, ..., w_m\}$ $W_m^{WS*} = \{w_1^{WS*}, w_2^{WS*}, ..., w_m^{WS*}\}$ $A_m = \{\alpha_1, \alpha_2, ..., \alpha_m\}$ $A_m^{WS*} = \{\alpha_1^{WS*}, \alpha_2^{WS*}, ..., \alpha_m^{WS*}\}$ $A_m^{*} = \{\alpha_1^{*}, \alpha_2^{*}, ..., \alpha_m^{*}\}$ $\Phi_m = \{\phi_1, \phi_2, ..., \phi_m\}$	J_m	$W_{m+1} = W_m + \{w_{m+1}\}$ $W_{m+1}^{WS*} = W_m^{WS*} + w_{m+1}^{WS*}$ $A_{m+1} = A_m + \{\alpha_{m+1}\}$ $A_{m+1}^{WS*} = \{\alpha_1^{WS*}, \alpha_2^{WS*}, ..., \alpha_m^{WS*}, \alpha_{m+1}^{WS*}\}$ $A_{m+1}^{*} = \{\alpha_1^{*}, \alpha_2^{*}, ..., \alpha_m^{*}, \alpha_{m+1}^{*}\}$ $\Phi_{m+1} = \Phi_m + \{\phi_{m+1}\}$	J_{m+1}
$\widehat{W}_m = \{w \in W_m \mid w \to w_i(w)\}$ $\widehat{\Phi}_m = \{\phi \in \Phi_m \mid \phi \to \phi_i(\phi)\}$	$\widehat{J}_m$	$\widehat{W}_{m+1} = \{w \in W_{m+1} \mid w \to w_i(w)\}$ $\widehat{\Phi}_{m+1} = \{\phi \in \Phi_{m+1} \mid \phi \to \phi_i(\phi)\}$	$\widehat{J}_{m+1}$
$\widehat{W}_m^c = W_m - \widehat{W}_m$ $\widehat{\Phi}_m^c = \Phi_m - \widehat{\Phi}_m$	$\widehat{J}_m^c$	$\widehat{W}_{m+1}^c = W_{m+1} - \widehat{W}_{m+1}$ $\widehat{\Phi}_{m+1}^c = \Phi_{m+1} - \widehat{\Phi}_{m+1}$	$\widehat{J}_{m+1}^c$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{WS}(w_1, \alpha_1)]}{\partial w_1^2} = -2\theta; \qquad (88)$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{WS}(w_1, \alpha_1)]}{\partial \alpha_1 \partial w_1} = \beta_1; \qquad (89)$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{WS}(w_1, \alpha_1)]}{\partial \alpha_1^2} = -\eta_1; \qquad (90)$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{WS}(w_1, \alpha_1)]}{\partial w_1 \partial \alpha_1} = \beta_1. \qquad (91)$$

The second order derivatives are used to construct the Hessian matrix $H_{\mathbb{E}[\Pi_{\mathcal{S}_1}^{WS}]}$ shown in Eq. (92).

$$H_{\mathbb{E}[\Pi_{\mathcal{S}_1}^{WS}]} = \begin{bmatrix} \frac{\partial^2 \mathbb{E}[\Pi_{\mathcal{S}_1}^{WS}]}{\partial w_1^2} & \frac{\partial^2 \mathbb{E}[\Pi_{\mathcal{S}_1}^{WS}]}{\partial w_1 \partial \alpha_1} \\ \frac{\partial^2 \mathbb{E}[\Pi_{\mathcal{S}_1}^{WS}]}{\partial \alpha_1 \partial w_1} & \frac{\partial^2 \mathbb{E}[\Pi_{\mathcal{S}_1}^{WS}]}{\partial \alpha_1^2} \end{bmatrix} = \begin{bmatrix} -2\theta & \beta_1 \\ \beta_1 & -\eta_1 \end{bmatrix} \qquad (92)$$

The determinant $|H_{\mathbb{E}[\Pi_{\mathcal{S}_1}^{WS}]}| = 2\theta\eta_1 - \beta_1^2$. We have proved that $\mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{WS}(w_1, \alpha_1)]$ is a strictly concave function of w_1 and α_1 as long as $2\theta\eta_1 > \beta_1^2$ holds. Now, by replacing $\Delta = p - \sum_{j=1}^{3} w_j$ in $\frac{\partial \mathbb{E}[\Pi_{\mathcal{S}_1}^{WS}]}{\partial w_1}$ and setting $\frac{\partial \mathbb{E}[\Pi_{\mathcal{S}_1}^{WS}]}{\partial w_1} = 0$ and $\frac{\partial \mathbb{E}[\Pi_{\mathcal{S}_1}^{WS}]}{\partial \alpha_1} = 0$ we obtain:

$$w_1^{WS*}|_{p,\alpha_1,\alpha_2,\alpha_3}\,(m=3) = c_1 + \frac{1}{\theta}\left(d - \theta p + \sum_{j=1}^{3} \beta_j \alpha_j\right). \qquad (93)$$

$$\alpha_i^{WS*}|_{w_i} = \frac{\beta_i}{\eta_i}(w_i - c_i), \text{ where } i = 1, 2, 3. \tag{94}$$

Replacing Eq. (94) in Eq. (93) yields to:

$$w_1^{WS*}|_{p,w_2,w_3}\,(m=3) = c_1 + \frac{d - p\theta + \sum_{j=2}^{3}\left[(w_j - c_j)\,\frac{\beta_j^2}{\eta_j}\right]}{\theta - \frac{\beta_1^2}{\eta_1}}. \tag{95}$$

Using $w_2^{WS*}|_{p,w_1,w_3}\,(m=3)$ to solve Eq. (95) yields to:

$$w_1^{WS*}|_{p,w_3}\,(m=3) = c_1 + \frac{d - p\theta + (w_3 - c_3)\,\frac{\beta_3^2}{\eta_3}}{\theta - \sum_{j=1}^{2}\frac{\beta_j^2}{\eta_j}}. \tag{96}$$

By replacing $w_3^{WS*}|_{p,w_1}\,(m=3)$ into Eq. (96) we obtain:

$$w_1^{WS*}|_p\,(m=3) = c_1 + \frac{d - p\theta}{\Omega_{m=3} - \theta}. \tag{97}$$

Finally, substituting Eq. (97) in Eq. (94) yields to Eq. (98).

$$\alpha_1^{WS*}|_p\,(m=3) = \frac{\beta_1\,(d - p\theta)}{\eta_1\,(\Omega_{m=3} - \theta)}. \tag{98}$$

Eqs. (86), (93), (95) - (96), (97) and (98) are now generalized using Eqs. (171), (174), (177), (43) and (44), respectively, for the scenario of (m) supplier. Eq. (43) is a particular case of Eq. (177) when $|\widehat{W}_m| = 0$. The relation between Eqs. (177) and (43) can be summarized in the following algorithm:

$w_i^{WS*}|_p\,(m)$:

repeat

replace a given $w \in \widehat{W}_m$ in $w_i^{WS*}|_{p,\forall w \in \widehat{W}_m}\,(m)$

update $\widehat{W}_m$

until $|\widehat{W}_m| = 0$

Now we proceed to prove that Equations representing a supply chain system with (m) suppliers and a single manufacturer hold. Using Mathematical induction we review two cases:

(i) Case of $(m+1)$ suppliers: Assuming Eqs. (171), (174), (177), (43) and (44) are true, we analyze if Eqs. (172), (175), (178), (179) and (181) hold. By replacing $p = \Delta + \sum_{j \in J_{m+1}} w_j$ in $\mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{WS}(w_i, \alpha_i)]\,(m+1) = (w_i - c_i)\left(d - \theta p + \sum_{j \in J_{m+1}} \beta_j \alpha_j\right) - \frac{1}{2}\eta_i \alpha_i^2$, and by solving $\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{WS}(w_i,\alpha_i)](m+1)}{\partial w_i}$ leads to Eq. (172). By replacing $\Delta = p - \sum_{j \in J_{m+1}} w_j$ in Eq. (172) and setting $\frac{\partial \mathbb{E}[\Pi_{\mathcal{S}_i}^{WS}](m+1)}{\partial w_i} = 0$ we obtain Eq. (175). Substituting Eq. (94) in Eq. (175) yields to Eq. (178). Eq. (179) is a particular case of Eq. (178) when $|\widehat{W}_{m+1}| = 0$. By replacing Eq. (179) into Eq. (94) we get Eq. (181).

(ii) Case of $(m=1)$ supplier: Assuming Eqs. (171), (174), (43) and (44) are true, we review if Eqs. (173), (176), (180) and (182) hold. Proofs for Eq. (177) is disregarded for the case of $(m=1)$ supplier. Replacing $p = \Delta + w_1$ into $\mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{WS}(w_1, \alpha_1)]\,(m=1) = (w_1 - c_1)\,(d - \theta p + \beta_1 \alpha_1) - \frac{1}{2}\eta_1 \alpha_1^2$, and solving $\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{WS}(w_1,\alpha_1)](m=1)}{\partial w_1}$ leads to Eq. (173). By replacing $\Delta = p - w_1$ in Eq. (173) and setting $\frac{\partial \mathbb{E}[\Pi_{\mathcal{S}_1}^{WS}](m=1)}{\partial w_1} = 0$ we obtain Eq. (176). Substituting Eq. (94) into Eq. (176) leads to Eq. (180). Replacing Eq. (180) in Eq. (94) yields to Eq. (182).

□

Proof of Proposition 16: After finding $w_i^{WS*}|_p$ and $\alpha_i^{WS*}|_p$, we proceed to calculate the optimal retail price p^{WS*} for the $\mathcal{OEM}$. Solving Eq. (39) using Eqs. (97) and (98) it is obtained:

$$\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(p)](m=3) = \frac{\theta\,(d - \theta p)\left[\left(p - \sum_{j=1}^{3} c_j\right)(\Omega_{m=3} - \theta) - 3\,(d - \theta p)\right]}{(\Omega_{m=3} - \theta)^2}. \tag{99}$$

For $\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(p)](m=3)$ we then proceed to verify if it is concave in p by calculating the first and second order derivatives:

$$\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS}(p)](m=3)}{\partial p} = \frac{\theta\left[\left(d - \theta\left(2p - \sum_{j=1}^{3} c_j\right)\right)(\Omega_{m=3} - \theta) + 6\theta\,(d - \theta p)\right]}{(\Omega_{m=3} - \theta)^2}. \tag{100}$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(p)](m=3)}{\partial p^2} = \frac{-2\theta^2\left(\Omega_{m=3}+2\theta\right)}{\left(\Omega_{m=3}-\theta\right)^2}. \tag{101}$$

We have proved that $\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(p)](m=3)$ is a strictly concave function of p as long as $4\theta\prod_{j=1}^{3}\eta_j > \sum_{j=1}^{3}\left(\beta_j^2\prod_{k=1;k\neq j}^{3}\eta_k\right)$ holds. Finally, by setting $\frac{\partial \mathbb{E}[\Pi^{WS}_{\mathcal{OEM}}](m=3)}{\partial p} = 0$ we obtain Eq. (102).

$$p^{WS*}(m=3) = \frac{6d\theta - \left(\Psi_{m=3}-2d\right)\left(\Omega_{m=3}-\theta\right)}{2\theta\left(\Omega_{m=3}+2\theta\right)}. \tag{102}$$

General expressions for Eqs. (99), (100), (101) and (102) are Eqs. (183), (186), (189) and (45), respectively. Now we proceed to prove latter Equations using Mathematical induction:

(i) Case of $(m+1)$ suppliers: Assuming Eqs. (183), (186), (189) and (45) are true, we review if Eqs. (184), (187), (190) and (192) hold. Substituting Eqs. (179) and (181) into $\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(p)]\,(m+1) = \left(p-\sum_{j\in J_{m+1}} w_j\right)\left(d-\theta p+\sum_{j\in J_{m+1}}\beta_j\alpha_j\right)$, leads to Eq. (184). Using Eq. (184) to solve $\frac{\partial \mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(p)](m+1)}{\partial p}$ yields to Eq. (187). Using Eq. (187) to solve $\frac{\partial^2 \mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(p)](m+1)}{\partial p^2}$ leads to Eq. (190). By isolating p from Eq. (187) we reach to Eq. (192).

(ii) Case of $(m=1)$ supplier: Assuming Eqs. (183), (186), (189) and (45) are true, we review if Eqs. (185), (188), (191) and (193) hold. Replacing Eqs. (180) and (182) into $\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(p)]\,(m=1) = (p-w_1)\left(d-\theta p+\beta_1\alpha_1\right)$, yields to Eq. (185). Using Eq. (185) to solve $\frac{\partial \mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(p)](m=1)}{\partial p}$ leads to Eq. (188). By using Eq. (188) to solve $\frac{\partial^2 \mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(p)](m=1)}{\partial p^2}$ we obtain Eq. (191). Solving p from Eq. (188) leads to Eq. (193).

□

Proof of Proposition 17: By replacing Eq. (102) in Eqs. (97) and (98) it is obtained Eqs. (103) and (104).

$$w_1^{WS*}(m=3) = c_1 + \frac{\Psi_{m=3}}{2\left(\Omega_{m=3}+2\theta\right)}. \tag{103}$$

$$\alpha_1^{WS*}(m=3) = \frac{\beta_1\Psi_{m=3}}{2\eta_1\left(\Omega_{m=3}+2\theta\right)}. \tag{104}$$

Similar results can be derived for $\mathcal{S}_2$ and $\mathcal{S}_3$. General expressions for Eqs. (103) and (104) are Eqs. (46) and (47), respectively. With the use of mathematical induction we prove that latter Equations hold. We analyze two scenarios:

(i) Case of $(m+1)$ suppliers: Assuming Eqs. (46) and (47) are true, we review if Eqs. (194) and (196) hold. By replacing Eq. (192) in Eq. (179) it is obtained Eq. (194). Substituting Eq. (192) into Eq. (181) yields to Eq. (196).

(ii) Case of $(m=1)$ supplier: Assuming Eqs. (46) and (47) are true, we review if Eqs. (195) and (197) hold. Replacing Eq. (193) in Eq. (180), leads to Eq. (195). By replacing Eq. (193) in Eq. (182) we get Eq. (197).

□

Proof of Proposition 18: We first calculate the Hessian matrix to verify if it is concave in p and α_1. From Eq. (49) it is obtained the following first and second order derivatives:

$$\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\alpha_1,\alpha_2,\alpha_3)](m=3)}{\partial p} = d - \theta\left(2p - \sum_{j=1}^{3} c_j\right) + \sum_{j=1}^{3}\beta_j\alpha_j; \tag{105}$$

$$\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\alpha_1,\alpha_2,\alpha_3)](m=3)}{\partial \alpha_1} = \beta_1\left(p - \sum_{j=1}^{3} c_j\right) - \eta_1\alpha_1; \tag{106}$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\alpha_1,\alpha_2,\alpha_3)]}{\partial p^2} = -2\theta; \tag{107}$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\alpha_1,\alpha_2,\alpha_3)]}{\partial \alpha_1 \partial p} = \beta_1; \tag{108}$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\alpha_1,\alpha_2,\alpha_3)]}{\partial \alpha_1^2} = -\eta_1; \tag{109}$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\alpha_1,\alpha_2,\alpha_3)]}{\partial p \partial \alpha_1} = \beta_1; \tag{110}$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\alpha_1,\alpha_2,\alpha_3)]}{\partial\alpha_2\partial\alpha_1} = 0; \quad (111) \qquad \frac{\partial^2 \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\alpha_1,\alpha_2,\alpha_3)]}{\partial\alpha_3\partial\alpha_1} = 0. \quad (112)$$

Similar results can be obtained for $\mathcal{S}_2$ and $\mathcal{S}_3$. The Hessian matrix for the supply chain system can be expressed as:

$$H_{\mathbb{E}[\Pi_{\mathcal{SC}}](m=3)} = \begin{bmatrix} \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial p^2} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial p\partial\alpha_1} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial p\partial\alpha_2} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial p\partial\alpha_3} \\ \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_1\partial p} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_1^2} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_1\partial\alpha_2} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_1\partial\alpha_3} \\ \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_2\partial p} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_2\partial\alpha_1} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_2^2} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_2\partial\alpha_3} \\ \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_3\partial p} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_3\partial\alpha_1} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_3\partial\alpha_2} & \frac{\partial^2\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_3^2} \end{bmatrix} = \begin{bmatrix} -2\theta & \beta_1 & \beta_2 & \beta_3 \\ \beta_1 & -\eta_1 & 0 & 0 \\ \beta_2 & 0 & -\eta_2 & 0 \\ \beta_3 & 0 & 0 & -\eta_3 \end{bmatrix}$$

The determinant $|H_{\mathbb{E}[\Pi_{\mathcal{SC}}](m=3)}|$ is shown in Eq. (113).

$$|H_{\mathbb{E}[\Pi_{\mathcal{SC}}](m=3)}| = 2\theta \prod_{j=1}^{3}\eta_j - \sum_{j=1}^{3}\left(\beta_j^2 \prod_{k=1;k\neq j}^{3}\eta_k\right). \quad (113)$$

We have proved that $\mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\alpha_1,\alpha_2,\alpha_3)](m=3)$ is a strictly concave function of p, α_1, α_2 and α_3 as long as $2\theta\prod_{j=1}^{3}\eta_j > \sum_{j=1}^{3}\left(\beta_j^2\prod_{k=1;k\neq j}^{3}\eta_k\right)$ holds. Now, by setting $\frac{\partial\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial p} = 0$ and $\frac{\partial\mathbb{E}[\Pi_{\mathcal{SC}}]}{\partial\alpha_1} = 0$ we obtain:

$$p^*|_{\alpha_1,\alpha_2,\alpha_3}(m=3) = \frac{1}{2\theta}\left(d + \theta\sum_{j=1}^{3}c_j + \sum_{j=1}^{3}\beta_j\alpha_j\right). \quad (114)$$

$$\alpha_1^*|_p(m=3) = \frac{\beta_1}{\eta_1}\left(p - \sum_{j=1}^{3}c_j\right). \quad (115)$$

Solving Eqs. (114) and (115) yields to Eqs. (116) and (117).

$$p^*(m=3) = \frac{d + (\Omega_{m=3} - \theta)\sum_{j=1}^{3}c_j}{\Omega_{m=3}}. \quad (116)$$

$$\alpha_1^*(m=3) = \frac{\beta_1 \Psi_{m=3}}{\eta_1 \Omega_{m=3}}. \tag{117}$$

General expressions for Eqs. (105), (106), (113), (114), (115), (116) and (117) are Eqs. (198), (201), (204), (207), (210), (50) and (51), respectively. We verify the validity of latter Equations through the use of mathematical induction. We specifically check two cases:

(i) Case of $(m+1)$ suppliers: Assuming Eqs. (198), (201), (204), (207), (210), (50) and (51) are true, we review if Eqs. (199), (202), (205), (208), (211), (213) and (215) hold. By using expression $\mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p, \forall\alpha \in A_{m+1})]\,(m+1) = \left(p - \sum_{j\in J_{m+1}} c_j\right)\left(d - \theta p + \sum_{j\in J_{m+1}} \beta_j \alpha_j\right) - \frac{1}{2}\sum_{j\in J_{m+1}} \eta_j \alpha_j^2$ to solve $\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\forall\alpha\in A_{m+1})](m+1)}{\partial p}$ it is obtained Eq. (199). Using $\mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p, \forall\alpha \in A_{m+1})]\,(m+1) = \left(p - \sum_{j\in J_{m+1}} c_j\right)\left(d - \theta p + \sum_{j\in J_{m+1}} \beta_j \alpha_j\right) - \frac{1}{2}\sum_{j\in J_{m+1}} \eta_j \alpha_j^2$ to solve $\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\forall\alpha\in A_{m+1})](m+1)}{\partial \alpha_i}$ it is obtained Eq. (202). $|H_{\mathbb{E}[\Pi_{\mathcal{SC}}](m+1)}|$ can be expressed as:

$$|H_{\mathbb{E}[\Pi_{\mathcal{SC}}](m+1)}| = \begin{vmatrix} -2\theta & \beta_1 & \beta_2 & \cdots & \beta_m & \beta_{m+1} \\ \beta_1 & -\eta_1 & 0 & \cdots & 0 & 0 \\ \beta_2 & 0 & -\eta_2 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \beta_m & 0 & 0 & \cdots & -\eta_m & 0 \\ \beta_{m+1} & 0 & 0 & \cdots & 0 & -\eta_{m+1} \end{vmatrix}$$
$$= (-1)^{m+1}\beta_{m+1}^2 \prod_{j\in J_m} \eta_j - (-1)^{2m}\eta_{m+1}|H_{\mathbb{E}[\Pi_{\mathcal{SC}}](m)}|$$

By solving the latter expression we get Eq. (205). Setting Eq. (199) to zero and by isolating p from the expression, we reach to Eq. (208). By setting Eq. (202) to zero and by isolating α_i from the expression, it is obtained Eq. (211). Replacing Eq. (211) into Eq. (208) leads to Eq. (213). Finally, substituting Eq. (213) in Eq. (211) yields to Eq. (215).

(ii) Case of $(m=1)$ supplier: Assuming Eqs. (198), (201), (204), (207), (210), (50) and (51) are true, we review if Eqs. (200), (203), (206), (209), (212), (214) and (216) hold. Using $\mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p, \alpha_1)]\,(m=1) = (p - c_1)(d - \theta p + \beta_1\alpha_1) - \frac{1}{2}\eta_1\alpha_1^2$ to solve $\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\alpha_1)](m=1)}{\partial p}$ we get Eq. (200). Using $\mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p, \alpha_1)]\,(m=1) = (p - c_1)(d - \theta p + \beta_1\alpha_1) - \frac{1}{2}\eta_1\alpha_1^2$ to solve

$\frac{\partial \mathbb{E}_{\xi}[\Pi_{\mathcal{SC}}(p,\alpha_1 \in)](m=1)}{\partial \alpha_1}$ yields to Eq. (203). $|H_{\mathbb{E}[\Pi_{\mathcal{SC}}](m=1)}|$ can be expressed as:

$$|H_{\mathbb{E}[\Pi_{\mathcal{SC}}](m=1)}| = \begin{vmatrix} -2\theta & \beta_1 \\ \beta_1 & -\eta_1 \end{vmatrix}$$

By solving the latter expression we obtain Eq. (206). By setting Eq. (200) to zero and by isolating p from the expression, we reach to Eq. (209). Setting Eq. (203) to zero and by isolating α_1 from the expression, it is obtained Eq. (212). Substituting Eq. (212) into Eq. (209) leads to Eq. (214). Replacing Eq. (214) in Eq. (212) yields to Eq. (216).

□

Proof of Proposition 19: Firstly, let's assume that Inequality (118) holds.

$$\Omega_{m=3} > \theta \Longrightarrow p^* (m = 3) < p^{WS*} (m = 3) . \tag{118}$$

Replacing Eqs. (102) and (116) in Inequality (118) leads to:

$$\Psi_{m=3} (\Omega_{m=3} + 4\theta) (\Omega_{m=3} - \theta)$$

From Eq. (117) we know that $\Psi_{m=3} > 0$. Then, Eq. (118) holds as long as $\Omega_{m=3} - \theta > 0$ is fulfilled. Secondly, let's assume that Inequality (119) holds.

$$\alpha_1^* (m = 3) > \alpha_1^{WS*} (m = 3) . \tag{119}$$

Replacing Eqs. (117) and (104) in Inequality (119) yields to:

$$\beta_1 \eta_1 \Psi_{m=3} (\Omega_{m=3} + 4\theta) > 0$$

Latter expression proves that Eq. (119) holds. Similar results can be obtained for $i = 2, 3$.

Lastly, let's assume that Inequality (120) holds.

$$\mathbb{E}\left[D^{*}\right](m=3)>\mathbb{E}\left[D^{WS*}\right](m=3)\,. \tag{120}$$

Replacing Eqs. (102), (104), (116) and (117) in Inequality (120) leads to:

$$\theta\Psi_{m=3}\left(\Omega_{m=3}+4\theta\right)\prod_{j=1}^{3}\eta_{j}^{2}>0$$

Latter expression proves that Eq. (120) holds.

General expressions for Inequalities (118), (119) and (120) are Inequalities (52), (53) and (54), respectively. Now we verify if latter Inequalities hold with the use of mathematical induction. We review two cases:

(i) Case of $(m+1)$ suppliers: Assuming Inequalities (52), (53) and (54) are true, we review if Inequalities (217), (219) and (221) hold. By replacing Eqs. (192) and (213) in Inequality (217) leads to:

$$\Psi_{m+1}\left(\Omega_{m+1}+2m\theta\right)\left(\Omega_{m+1}-\theta\right)$$

From Eq. (215) we know that $\Psi_{m+1}>0$. Then, Inequality (217) holds as long as $\Omega_{m+1}-\theta>0$ is fulfilled. Secondly, let's assume that Inequality (219) holds. Replacing Eq. (215) and (196) in Inequality (219) yields to:

$$\beta_{i}\eta_{i}\Psi_{m+1}\left(\Omega_{m+1}+2m\theta\right)>0$$

Latter expression proves that Eq. (219) holds. Lastly, let's assume that Inequality (221) holds. Replacing Eqs. (192), (196), (213) and (215) in Inequality (221) leads to:

$$\theta \Psi_{m+1} \left(\Omega_{m+1} + 2m\theta \right) \prod_{j \in J_{m+1}} \eta_j^2 > 0$$

Latter expression proves that Eq. (221) holds.

(ii) Case of $(m = 1)$ supplier: Assuming Inequalities (52), (53) and (54) are true, we review if Inequalities (218), (220) and (222) hold. By replacing Eqs. (193) and (214) in Inequality (218) leads to:

$$\Psi_{m=1} \Omega_{m=1} \left(\Omega_{m=1} - \theta \right)$$

From Eq. (216) we know that $\Psi_{m=1} > 0$. Then, Eq. (218) holds as long as $\Omega_{m=1} - \theta > 0$ is fulfilled. Secondly, let's assume that Inequality (220) holds. Replacing Eqs. (216) and (197) in Inequality (220) yields to:

$$\beta_1 \eta_1 \Psi_{m=1} \Omega_{m=1} > 0$$

Latter expression proves that Eq. (220) holds. Lastly, let's assume that Inequality (222) holds. Replacing Eqs. (193), (197), (214) and (216) in Inequality (222) leads to:

$$\theta \Psi_{m=1} \Omega_{m=1} \eta_1^2 > 0$$

Latter expression proves that Eq. (222) holds.

□

Proof of Proposition 20: Replacing the values of p^{WS*}, w_i^{WS*} and α_i^{WS*} in Eq. (42) for the case of $(m = 3)$ suppliers, it is obtained the optimal expected profit for the decentralized supply chain:

$$\mathbb{E}_{\xi}\left[\Pi_{\mathcal{SC}}^{WS*}\begin{pmatrix} p^{WS*}, & w_1^{WS*}, & w_2^{WS*}, \\ w_3^{WS*}, & \alpha_1^{WS*}, & \alpha_2^{WS*}, \\ \alpha_3^{WS*} & & \end{pmatrix}\right](m=3) = \frac{\left(3\Omega_{m=3}+8\theta\right)\Psi_{m=3}^2}{8\left(\Omega_{m=3}+2\theta\right)^2}. \tag{121}$$

Substituting the values of p^* and α_i^* in Eq. (49) for the case of $(m = 3)$ suppliers, we get the optimal expected profit for the centralized supply chain:

$$\mathbb{E}_{\xi}[\Pi_{\mathcal{SC}}^*(p^*, \alpha_1^*, \alpha_2^*, \alpha_3^*)](m=3) = \frac{\Psi_{m=3}^2}{2\Omega_{m=3}}. \tag{122}$$

By comparing $\mathbb{E}[\Pi_{\mathcal{SC}}^{WS*}](m=3)$ and $\mathbb{E}[\Pi_{\mathcal{SC}}^*](m=3)$ we reach to:

$$\frac{\mathbb{E}_{\xi}[\Pi_{\mathcal{SC}}^{WS*}](m=3)}{\mathbb{E}_{\xi}[\Pi_{\mathcal{SC}}^*](m=3)} = \frac{\left(3\Omega_{m=3}+8\theta\right)\Omega_{m=3}}{4\left(\Omega_{m=3}+2\theta\right)^2}. \tag{123}$$

Eq. (123) can be expressed as:

$$\begin{aligned}\frac{\mathbb{E}_{\xi}[\Pi_{\mathcal{SC}}^{WS*}](m=3)}{\mathbb{E}_{\xi}[\Pi_{\mathcal{SC}}^*](m=3)} =& \frac{4\left(\Omega_{m=3}+2\theta\right)^2+4\left(\Omega_{m=3}+2\theta\right)\Omega_{m=3}-\Omega_{m=3}^2-4\left(\Omega_{m=3}+2\theta\right)^2}{4\left(\Omega_{m=3}+2\theta\right)^2} \\ =& 1-\frac{\left(\Omega_{m=3}+4\theta\right)^2}{4\left(\Omega_{m=3}+2\theta\right)^2}.\end{aligned} \tag{124}$$

Having $\frac{(\Omega_{m=3}+4\theta)^2}{4(\Omega_{m=3}+2\theta)^2} > 0$ proves that $\frac{\mathbb{E}_{\xi}[\Pi_{\mathcal{SC}}^{WS*}](m=3)}{\mathbb{E}_{\xi}[\Pi_{\mathcal{SC}}^*](m=3)} < 1$. We have demonstrated that the decentralized model can not reach coordination.

Now, the ratio $\frac{\mathbb{E}_{\xi}[\Pi_{\mathcal{SC}}^*](m=3)}{\mathbb{E}_{\xi}[\Pi_{\mathcal{SC}}^{WS*}](m=3)}$ can also be expressed as:

$$\frac{\mathbb{E}_{\xi}[\Pi_{\mathcal{SC}}^*](m=3)}{\mathbb{E}_{\xi}[\Pi_{\mathcal{SC}}^{WS*}](m=3)} = \frac{4\left(\Omega_{m=3}+2\theta\right)^2}{\left(3\Omega_{m=3}+8\theta\right)\Omega_{m=3}}.$$

From the concavity condition of Proposition 18 we know that $\Omega_{m=3} > 0$ holds, then it holds that $8\theta\left(2\Omega_{m=3}+6\theta\right) \geq 0$. We have:

$$
\begin{aligned}
8\theta\left(2\Omega_{m=3}+6\theta\right) \geq& 0 \\
12\left(\Omega_{m=3}+2\theta\right)^2 \geq& 4\left(3\Omega_{m=3}+8\theta\right)\Omega_{m=3} \\
\frac{4\left(\Omega_{m=3}+2\theta\right)^2}{\left(3\Omega_{m=3}+8\theta\right)\Omega_{m=3}} \geq& \frac{4}{3}
\end{aligned}
$$

Furthermore, this result allows us to compare the optimal expected profits as:

$$
\frac{\mathbb{E}_\xi[\Pi^*_{\mathcal{SC}}](m=3)-\mathbb{E}_\xi[\Pi^{WS*}_{\mathcal{SC}}](m=3)}{\mathbb{E}_\xi[\Pi^{WS*}_{\mathcal{SC}}](m=3)} \geq \frac{1}{3}. \tag{125}
$$

General expressions for Eqs. (121), (122), (123), (124) and (125) are Eqs. (223), (226), (229), (232) and (235), respectively. Now we verify if latter Equations hold with the use of mathematical induction. We review two cases:

(i) Case of $(m+1)$ suppliers: Assuming Eqs. (223), (226), (229), (232) and (235) are true, we analyze if Eqs. (224), (227), (230), (233) and (236) hold. Replacing Eqs. (192), (194) and (196) into the expression $\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{SC}}(p,\forall w\in W_{m+1},\forall\alpha\in A_{m+1})]\,(m+1)=\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(p)]\,(m+1)+\sum_{j\in J_{m+1}}\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{S}_j}(w_j,\alpha_j)]\,(m+1)$ leads to Eq. (224). Substituting Eqs. (213) and (215) in $\mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\forall\alpha\in A_{m+1})]\,(m+1)=\left(p-\sum_{j\in J_{m+1}}c_j\right)\left(d-\theta p+\sum_{j\in J_{m+1}}\beta_j\alpha_j\right)-\frac{1}{2}\sum_{j\in J_{m+1}}\eta_j\alpha_j^2$ yields to Eq. (227). By using Eqs. (224) and (227) to solve $\frac{\mathbb{E}_\xi[\Pi^{WS*}_{\mathcal{SC}}](m+1)}{\mathbb{E}_\xi[\Pi^*_{\mathcal{SC}}](m+1)}$ we get Eq. (230). Eq. (230) can be expressed also as Eq. (233). From the concavity condition of Proposition 18 we know that $\Omega_{m+1}>0$ holds, then $4m\theta\left(2\Omega_{m+1}+3m\theta\right)\geq 0$ also holds. We have:

$$
\begin{aligned}
4m\theta\left(2\Omega_{m+1}+3m\theta\right) \geq& 0 \\
12\left(\Omega_{m+1}+m\theta\right)^2 \geq& 4\left(3\Omega_{m+1}+4m\theta\right)\Omega_{m+1} \\
\frac{4\left(\Omega_{m+1}+m\theta\right)^2}{\left(3\Omega_{m+1}+4m\theta\right)\Omega_{m+1}} \geq& \frac{4}{3}
\end{aligned}
$$

Using latter expression to solve $\frac{\mathbb{E}_\xi[\Pi^*_{\mathcal{SC}}](m+1)-\mathbb{E}_\xi[\Pi^{WS*}_{\mathcal{SC}}](m+1)}{\mathbb{E}_\xi[\Pi^{WS*}_{\mathcal{SC}}](m+1)}$ leads to Eq. (236).

(ii) Case of $(m=1)$ supplier: Assuming Eqs. (223), (226), (229), (232) and (235) are true, we review if Eqs. (225), (228), (231), (234) and (237) hold. Replacing Eqs. (193), (195) and (197) in $\mathbb{E}_\xi[\Pi^{WS}_{\mathcal{SC}}(p, w_1, \alpha_1)]\,(m=1) = \mathbb{E}_\xi[\Pi^{WS}_{\mathcal{OEM}}(p)]\,(m=1) + \mathbb{E}_\xi[\Pi^{WS}_{\mathcal{S}_1}(w_1, \alpha_1)]\,(m=1)$ leads to Eq. (225). Substituting Eqs. (214) and (216) into $\mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p, \alpha_1)]\,(m=1) = (p-c_1)\,(d-\theta p+\beta_1\alpha_1) - \frac{1}{2}\eta_1\alpha_1^2$ yields to Eq. (228). Using Eqs. (225) and (228) to solve $\frac{\mathbb{E}_\xi[\Pi^{WS*}_{\mathcal{SC}}](m=1)}{\mathbb{E}_\xi[\Pi^{*}_{\mathcal{SC}}](m=1)}$ leads to Eq. (231). Eqs. (231) and (234) are equal. Finally, by using Eq. (234) to solve the expression $\frac{\mathbb{E}_\xi[\Pi^{*}_{\mathcal{SC}}](m=1)-\mathbb{E}_\xi[\Pi^{WS*}_{\mathcal{SC}}](m=1)}{\mathbb{E}_\xi[\Pi^{WS*}_{\mathcal{SC}}](m=1)}$ yields to Eq. (237).

$\square$

Proof of Proposition 21: Considering $\mathcal{S}_1$ as example, we first check the mathematical properties of its profit function. We calculate the Hessian matrix to verify if it is concave in w_1 and α_1. By replacing $p = \Delta + \sum_{j=1}^{3} w_j$ in Eq. (58), we get the following first and second order derivatives:

$$\frac{\partial \mathbb{E}_\xi[\Pi^{CS}_{\mathcal{S}_1}(w_1, \alpha_1)](m=3)}{\partial w_1} = d - \theta\left(2w_1 + \sum_{j=2}^{3} w_j + \Delta - c_1\right) + \sum_{j=1}^{3}\beta_j\alpha_j; \tag{126}$$

$$\frac{\partial \mathbb{E}_\xi[\Pi^{CS}_{\mathcal{S}_1}(w_1, \alpha_1)]}{\partial \alpha_1} = \beta_1(w_1 - c_1) - \eta_1\phi_1\alpha_1; \tag{127}$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi^{CS}_{\mathcal{S}_1}(w_1, \alpha_1)]}{\partial w_1^2} = -2\theta; \tag{128}$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi^{CS}_{\mathcal{S}_1}(w_1, \alpha_1)]}{\partial \alpha_1 \partial w_1} = \beta_1; \tag{129}$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi^{CS}_{\mathcal{S}_1}(w_1, \alpha_1)]}{\partial \alpha_1^2} = -\eta_1\phi_1; \tag{130}$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi^{CS}_{\mathcal{S}_1}(w_1, \alpha_1)]}{\partial w_1 \partial \alpha_1} = \beta_1. \tag{131}$$

The second order derivatives are used to construct the Hessian matrix $H_{\mathbb{E}[\Pi^{CS}_{\mathcal{S}_1}]}$:

$$H_{\mathbb{E}[\Pi^{CS}_{\mathcal{S}_1}]} = \begin{bmatrix} \frac{\partial^2 \mathbb{E}[\Pi^{CS}_{\mathcal{S}_1}]}{\partial w_1^2} & \frac{\partial^2 \mathbb{E}[\Pi^{CS}_{\mathcal{S}_1}]}{\partial w_1 \partial \alpha_1} \\ \frac{\partial^2 \mathbb{E}[\Pi^{CS}_{\mathcal{S}_1}]}{\partial \alpha_1 \partial w_1} & \frac{\partial^2 \mathbb{E}[\Pi^{CS}_{\mathcal{S}_1}]}{\partial \alpha_1^2} \end{bmatrix} = \begin{bmatrix} -2\theta & \beta_1 \\ \beta_1 & -\eta_1\phi_1 \end{bmatrix}$$

The determinant $|H_{\mathbb{E}[\Pi^{CS}_{\mathcal{S}_1}]}| = 2\theta\eta_1\phi_1 - \beta_1^2$. We have proved that $\mathbb{E}_\xi[\Pi^{CS}_{\mathcal{S}_1}(w_1, \alpha_1)](m=3)$ is a strictly concave function of w_1 and α_1 as long as $2\theta\eta_1\phi_1 > \beta_1^2$ holds. Now, by replacing

$\Delta = p - \sum_{j=1}^{3} w_j$ in $\frac{\partial \mathbb{E}[\Pi_{S_1}^{CS}]}{\partial w_1}$ and setting $\frac{\partial \mathbb{E}[\Pi_{S_1}^{CS}]}{\partial w_1} = 0$ and $\frac{\partial \mathbb{E}[\Pi_{S_1}^{CS}]}{\partial \alpha_1} = 0$ we obtain:

$$w_1^{CS*}|_{p,\alpha_1,\alpha_2,\alpha_3}(m=3) = c_1 + \frac{1}{\theta}\left(d - \theta p + \sum_{j=1}^{3} \beta_j \alpha_j\right). \tag{132}$$

$$\alpha_i^{CS*}|_{w_i} = \frac{\beta_i}{\eta_i \phi_i}(w_i - c_i) \text{ where } i = 1,2,3. \tag{133}$$

Replacing Eq. (133) in Eq. (132) yields to:

$$w_1^{CS*}|_{p,w_2,w_3}(m=3) = c_1 + \frac{d - p\theta + \sum_{j=2}^{3}\left[(w_j - c_j)\frac{\beta_j^2}{\eta_j \phi_j}\right]}{\theta - \frac{\beta_1^2}{\eta_1 \phi_1}}. \tag{134}$$

Using $w_2^{CS*}|_{p,w_1,w_3}(m=3)$ to solve Eq. (134) yields to:

$$w_1^{CS*}|_{p,w_3}(m=3) = c_1 + \frac{d - p\theta + (w_3 - c_3)\frac{\beta_3^2}{\eta_3 \phi_3}}{\theta - \sum_{j=1}^{2}\frac{\beta_j^2}{\eta_j \phi_j}}. \tag{135}$$

Using $w_3^{CS*}|_{p,w_1}(m=3)$ to solve Eq. (135) yields to:

$$w_1^{CS*}|_{p}(m=3) = c_1 + \frac{d - p\theta}{\theta - \sum_{j=1}^{3}\frac{\beta_j^2}{\eta_j \phi_j}}. \tag{136}$$

Finally, by replacing Eq. (136) into Eq. (133) we get:

$$\alpha_1^{CS*}|_{p}(m=3) = \frac{\beta_1 (d - p\theta)}{\eta_1 \phi_1 \left(\theta - \sum_{j=1}^{3}\frac{\beta_j^2}{\eta_j}\right)}. \tag{137}$$

General expressions for Eqs. (126), (132), (134) - (135), (136) and (137) are Eqs. (238), (241), (244), (59) and (60), respectively. Eq. (59) is a particular case of Eq. (244) when $|\widehat{W}_m| = 0$. The relation between Eqs. (244) and (59) can be summarized in the following algorithm:

$w_i^{CS*}|_p(m)$:

repeat

replace a given $w \in \widehat{W}_m$ *in* $w_i^{CS*}|_{p,\forall w \in \widehat{W}_m}\,(m)$

update $\widehat{W}_m$

until $|\widehat{W}_m| = 0$

Now we proceed to prove the validity of latter Equations using mathematical induction:

(i) Case of $(m+1)$ suppliers: Assuming Eqs. (238), (241), (244), (59) and (60) are true, we review if Eqs. (239), (242), (245), (246) and (248) hold. By replacing $p = \Delta + \sum_{j \in J_{m+1}} w_j$ in $\mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{CS}(w_i, \alpha_i)]\,(m+1) = (w_i - c_i)\left(d - \theta p + \sum_{j \in J_{m+1}} \beta_j \alpha_j\right) - \frac{1}{2}\eta_i \phi_i \alpha_i^2$, and by solving $\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{CS}(w_i,\alpha_i)](m+1)}{\partial w_i}$ leads to Eq. (239). Substituting $\Delta = p - \sum_{j \in J_{m+1}} w_j$ into Eq. (239) and setting $\frac{\partial \mathbb{E}[\Pi_{\mathcal{S}_i}^{CS}](m+1)}{\partial w_i} = 0$ we get Eq. (242). Replacing Eq. (133) into Eq. (242) yields to Eq. (245). Eq. (246) is a particular case of Eq. (245) when $|\widehat{W}_{m+1}| = 0$. Finally, by substituting Eq. (246) into Eq. (133) we reach to Eq. (248).

(ii) Case of $(m=1)$ supplier: Assuming Eqs. (238), (241), (59) and (60) are true, we review if Eqs. (240), (243), (247) and (249) hold. Eq. (244) is disregarded for the case of $(m=1)$ supplier. By replacing $p = \Delta + w_1$ in $\mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{CS}(w_1, \alpha_1)]\,(m=1) = (w_1 - c_1)(d - \theta p + \beta_1 \alpha_1) - \frac{1}{2}\eta_1 \phi_1 \alpha_1^2$, and solving $\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{CS}(w_1,\alpha_1)](m=1)}{\partial w_1}$ leads to Eq. (240). Substituting $\Delta = p - w_1$ in Eq. (240) and setting $\frac{\partial \mathbb{E}[\Pi_{\mathcal{S}_1}^{CS}](m=1)}{\partial w_1} = 0$ we obtain Eq. (243). Replacing Eq. (133) in Eq. (243) leads to Eq. (247). Using Eq. (247) into Eq. (133) yields to Eq. (249).

□

Proof of Proposition 22: From $\alpha_1^{CS*}|_p = \alpha_1^*$ we get:

$$p^{CS*}|_{\alpha_1^{CS*}|_p = \alpha_1^*}\,(m=3) = \frac{d}{\theta} - \frac{\phi_1 \Psi_{m=3}}{\theta \Omega_{m=3}} \left(\theta - \sum_{j=1}^{3} \frac{\beta_j^2}{\eta_j \phi_j} \right). \tag{138}$$

From $p^{CS*}|_{\alpha_1^{CS*}|_p = \alpha_1^*} = p^*$ it is obtained:

$$\phi_1|_{\phi_2,\phi_3}\,(m=3) = \frac{\theta - \displaystyle\sum_{j=2}^{3} \frac{\beta_j^2}{\eta_j}}{\theta - \displaystyle\sum_{j=2}^{3} \frac{\beta_j^2}{\eta_j \phi_j}}. \tag{139}$$

Using $\phi_2|_{\phi_1,\phi_3}(m=3)$ to solve Eq. (139) yields to:

$$\phi_1|_{\phi_3}(m=3) = \frac{\theta - \frac{\beta_3^2}{\eta_3}}{\theta - \frac{\beta_3^2}{\eta_3\phi_3}}. \tag{140}$$

Finally, using $\phi_3|_{\phi_1}(m=3)$ to solve Eq. (140) leads to:

$$\phi_i = 1. \tag{141}$$

General expressions for Eqs. (138), and (139) - (140) are Eqs. (250), and (253), respectively. The relation between Eqs. (253) and (141) can be summarized in the following algorithm:

ϕ_i:

repeat

replace a given $\phi \in \widehat{\Phi}_m$ in $\phi_i|_{\forall \phi \in \widehat{\Phi}_m}(m)$

update $\widehat{\Phi}_m$

until $|\widehat{\Phi}_m| = 0$

Now we use mathematical induction to prove that latter Equations hold. We are interested in two scenarios:

(i) Case of $(m+1)$ suppliers: Assuming Eqs. (250), and (253) are true, we review if Eqs. (251), and (254) hold. By equating Eqs. (248), and (215), and isolating variable p from the expression leads to Eq. (251). Then by equating Eqs. (251) and (213), and isolating variable ϕ_i from the expression yields to Eq. (254).

(ii) Case of $(m=1)$ supplier: Assuming Eq. (250) is true, we review if Eqs. (252) hold. Eq. (253) is disregarded for the case of $(m=1)$ supplier. Equating Eqs. (249) and (216), and isolating variable p from the expression leads to Eq. (252). Equating Eqs. (252) and (214), and isolating variable ϕ_1 from the expression yields to $\phi_1 = 1$.

□

Proof of Proposition 23: For the case of $\mathcal{S}_1$, we first check the mathematical properties of the profit function. We calculate the Hessian matrix to verify if it is concave in w_1 and α_1. By replacing $p = \Delta + \sum_{j=1}^{3} w_j$ in Eq. (64), it is obtained the following first and second order derivatives:

$$\frac{\partial \mathbb{E}_{\xi}[\Pi_{\mathcal{S}_1}^{CR}(w_1,\alpha_1)](m=3)}{\partial w_1} = \phi_1 \left[d - \theta \left(2w_1 + \sum_{j=2}^{3} w_j + \Delta \right) + \sum_{j=1}^{3} \beta_j \alpha_j \right] + c_1\theta; \tag{142}$$

$$\frac{\partial \mathbb{E}_{\xi}[\Pi_{\mathcal{S}_1}^{CR}(w_1,\alpha_1)]}{\partial \alpha_1} = \beta_1(w_1\phi_1 - c_1) - \eta_1\phi_1\alpha_1; \tag{143}$$

$$\frac{\partial^2 \mathbb{E}_{\xi}[\Pi_{\mathcal{S}_1}^{CR}(w_1,\alpha_1)]}{\partial w_1^2} = -2\theta\phi_1; \tag{144}$$

$$\frac{\partial^2 \mathbb{E}_{\xi}[\Pi_{\mathcal{S}_1}^{CR}(w_1,\alpha_1)]}{\partial \alpha_1 \partial w_1} = \beta_1\phi_1; \tag{145}$$

$$\frac{\partial^2 \mathbb{E}_{\xi}[\Pi_{\mathcal{S}_1}^{CR}(w_1,\alpha_1)]}{\partial \alpha_1^2} = -\eta_1\phi_1; \tag{146}$$

$$\frac{\partial^2 \mathbb{E}_{\xi}[\Pi_{\mathcal{S}_1}^{CR}(w_1,\alpha_1)]}{\partial w_1 \partial \alpha_1} = \beta_1\phi_1. \tag{147}$$

The second order derivatives are used to construct the Hessian matrix $H_{\mathbb{E}[\Pi_{\mathcal{S}_1}^{CR}]}$:

$$H_{\mathbb{E}[\Pi_{\mathcal{S}_1}^{CR}]} = \begin{bmatrix} \frac{\partial^2 \mathbb{E}[\Pi_{\mathcal{S}_1}^{CR}]}{\partial w_1^2} & \frac{\partial^2 \mathbb{E}[\Pi_{\mathcal{S}_1}^{CR}]}{\partial w_1 \partial \alpha_1} \\ \frac{\partial^2 \mathbb{E}[\Pi_{\mathcal{S}_1}^{CR}]}{\partial \alpha_1 \partial w_1} & \frac{\partial^2 \mathbb{E}[\Pi_{\mathcal{S}_1}^{CR}]}{\partial \alpha_1^2} \end{bmatrix} = \begin{bmatrix} -2\theta\phi_1 & \beta_1\phi_1 \\ \beta_1\phi_1 & -\eta_1\phi_1 \end{bmatrix}$$

The determinant $|H_{\mathbb{E}[\Pi_{\mathcal{S}_1}^{CR}]}| = 2\theta\eta_1\phi_1^2 - \beta_1^2\phi_1^2$. We have proved that $\mathbb{E}_{\xi}[\Pi_{\mathcal{S}_1}^{CR}(w_1,\alpha_1)]$ is a strictly concave function of w_1 and α_1 as long as $2\theta\eta_1 > \beta_1^2$ holds. Now by replacing $\Delta = p - \sum_{j=1}^{3} w_j$ in $\frac{\partial \mathbb{E}[\Pi_{\mathcal{S}_1}^{CR}]}{\partial w_1}$ and setting $\frac{\partial \mathbb{E}[\Pi_{\mathcal{S}_1}^{CR}]}{\partial w_1} = 0$ and $\frac{\partial \mathbb{E}[\Pi_{\mathcal{S}_1}^{CR}]}{\partial \alpha_1} = 0$ we obtain:

$$w_1^{CR*}|_{p,\alpha_1,\alpha_2,\alpha_3}(m=3) = \frac{c_1}{\phi_1} + \frac{1}{\theta}\left(d - \theta p + \sum_{j=1}^{3} \beta_j\alpha_j \right). \tag{148}$$

$$\alpha_i^{CR*}|_{w_i} = \frac{\beta_i}{\eta_i\phi_i}(w_i\phi_i - c_i), \text{ where } i = 1,2,3. \tag{149}$$

Replacing Eq. (149) in Eq. (148) yields to:

$$w_1^{CR*}|_{p,w_2,w_3}(m=3) = \frac{c_1}{\phi_1} + \frac{d - p\theta + \sum_{j=2}^{3} \left[\left(w_j - \frac{c_j}{\phi_j} \right) \frac{\beta_j^2}{\eta_j} \right]}{\theta - \frac{\beta_1^2}{\eta_1}}. \tag{150}$$

Using $w_2^{CR*}|_{p,w_1,w_3}\,(m=3)$ to solve Eq. (150) leads to:

$$w_1^{CR*}|_{p,w_3}\,(m=3) = \frac{c_1}{\phi_1} + \frac{d - p\theta + \left(w_3 - \frac{c_3}{\phi_3}\right)\frac{\beta_3^2}{\eta_3}}{\theta - \sum_{j=1}^{2}\frac{\beta_j^2}{\eta_j}}. \tag{151}$$

Substituting $w_3^{CR*}|_{p,w_1}\,(m=3)$ into Eq. (151) yields to:

$$w_1^{CR*}|_{p}\,(m=3) = \frac{c_1}{\phi_1} + \frac{d - p\theta}{\Omega_{m=3} - \theta}. \tag{152}$$

Finally, by replacing Eq. (152) in Eq. (149) we get:

$$\alpha_1^{CR*}|_{p}\,(m=3) = \frac{\beta_1\,(d - p\theta)}{\eta_1\,(\Omega_{m=3} - \theta)}. \tag{153}$$

General expressions for Eqs. (142), (148), (150) - (151), (152) and (153) are Eqs. (255), (258), (261), (65) and (66), respectively. Eq. (65) is a particular case of Eq. (261) when $|\widehat{W}_m| = 0$. The relation between Eqs. (261) and (65) can be summarized in the following algorithm:

$w_i^{CR*}|_p\,(m)$:

repeat

replace a given $w \in \widehat{W}_m$ in $w_i^{CR*}|_{p,\forall w \in \widehat{W}_m}\,(m)$

update $\widehat{W}_m$

until $|\widehat{W}_m| = 0$

Validity of latter Equations is tested through the use of mathematical induction. Specifically we analyze two cases:

(i) Case of $(m+1)$ suppliers: Assuming Eqs. (255), (258), (261), (65) and (66) are true, we review if Eqs. (256), (259), (262), (263) and (265) hold. Substituting $p = \Delta + \sum_{j\in J_{m+1}} w_j$ in $\mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{CR}(w_i,\alpha_i)]\,(m+1) = (w_i\phi_i - c_i)\left(d - \theta p + \sum_{j\in J_{m+1}}\beta_j\alpha_j\right) - \frac{1}{2}\eta_i\phi_i\alpha_i^2$, and solving $\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{CR}(w_i,\alpha_i)](m+1)}{\partial w_i}$ leads to Eq. (256). By replacing $\Delta = p - \sum_{j\in J_{m+1}} w_j$ in Eq. (256) and setting $\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{CR}](m+1)}{\partial w_i} = 0$ we obtain Eq. (259). Replacing Eq. (149) into (259) leads to Eq. (262). Eq. (263) is a particular case of Eq. (262) when $|\widehat{W}_{m+1}| = 0$. Finally, by substituting Eq. (263) into Eq. (149) we reach to Eq. (265).

(ii) Case of $(m = 1)$ supplier: Assuming Eqs. (255), (258), (65) and (66) are true, we review if Eqs. (257), (260), (264) and (266) hold. Eq. (261) is disregarded for the case of $(m = 1)$ supplier. By replacing $p = \Delta + w_1$ in $\mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{CR}(w_1, \alpha_1)]\,(m = 1) = (w_1\phi_1 - c_1)\,(d - \theta p + \beta_1\alpha_1) - \frac{1}{2}\eta_1\phi_1\alpha_1^2$, and solving $\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{CR}(w_1,\alpha_1)](m=1)}{\partial w_1}$ leads to Eq. (257). By substituting $\Delta = p - w_1$ in Eq. (257) and setting $\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{S}_1}^{CR}](m=1)}{\partial w_1} = 0$ we get Eq. (260). Substituting Eq. (149) into Eq. (260) leads to Eq. (264). Replacing Eq. (264) in Eq. (149) yields to Eq. (266).

□

Proof of Proposition 24: For the scenario of $(m = 3)$ suppliers, from $\alpha_i^{CR*}|_p(m = 3) = \alpha_i^*(m = 3)$ we get Eq. (116). By considering multiple suppliers we can infer that $\alpha_i^{CR*}|_p\,(m) = \alpha_i^*\,(m)$ leads to Eq. (50).

Now we proceed to prove latter statement using mathematical induction:

(i) Case of $(m + 1)$ suppliers: By equating Eqs. (265) and (215), and by isolating p from the latter expression we get Eq. (213).

(ii) Case of $(m = 1)$ supplier: Equating Eqs. (266) and (216), and isolating p from the latter expression leads to Eq. (214).

□

Proof of Proposition 25: Eq. (116) is used to solve Eq. (152), and it is obtained:

$$w_1^{CR*}\,(m = 3) = \frac{c_1}{\phi_1} + \frac{\Psi_{m=3}}{\Omega_{m=3}}. \tag{154}$$

General expression for Eq. (154) is Eq. (67). We review if latter Equation holds using mathematical induction method:

(i) Case of $(m + 1)$ suppliers: Assuming Eq. (67) is true, we proceed to prove that Eq. (267) holds. Using Eq. (213) to solve Eq. (263), it is obtained Eq. (267).

(ii) Case of $(m = 1)$ supplier: Assuming Eq. (67) is true, we proceed to prove that Eq. (268) holds. Substituting Eq. (214) into Eq. (264), yields to Eq. (268).

□

Proof of Proposition 26: Let's assume that Inequality (155) holds.

$$w_i^{CR*}(m=3) > w_i^{WS*}(m=3)\,. \tag{155}$$

Replacing Eqs. (154) and (103) in Inequality (155) leads to:

$$\phi_1 \Psi_{m=3}\left(\Omega_{m=3} + 4\theta\right) + 2\left(1-\phi_1\right) c_1 \Omega_{m=3}\left(\Omega_{m=3} + 2\theta\right) > 0$$

From Eq. (117) we know that $\Psi_{m=3} > 0$. Then, Eq. (155) holds. Similar results can be obtained for $i = 2, 3$. Lastly, let's assume that Inequality (156) holds.

$$c_1 < \phi_1 \sum_{j=1}^{3} c_j \Longrightarrow w_1^{CR*}(m) < p^*(m)\,. \tag{156}$$

Substituting Eqs. (154) and (116) in Inequality (156) leads to:

$$\Omega_{m=3}^2 \left(\phi_1 \sum_{j=1}^{3} c_j - c_1\right)$$

Then, Inequality (156) holds as long as $c_1 < \phi_1 \sum_{j=1}^{3} c_j$ is fulfilled.

General expression for Inequalities (155) and (156) are Inequalities (68) and (69). Now we verify if latter Inequalities hold with the use of mathematical induction. We review two cases:

(i) Case of $(m+1)$ suppliers: Assuming that Inequalities (68) and (69) are true, we review if Inequalities (269) and (271) hold. By replacing Eqs. (267) and (194) in Inequality (269) leads to:

$$\phi_1 \Psi_{m+1}\left(\Omega_{m+1} + 2m\theta\right) + 2\left(1-\phi_1\right) c_1 \Omega_{m+1}\left(\Omega_{m+1} + m\theta\right) > 0$$

From Eq. (215) we know that $\Psi_{m+1} > 0$. Then, Inequality (269) holds. Secondly, substituting Eqs. (267) and (213) in Inequality (271) leads to:

$$\Omega_{m+1}^2\left(\phi_i \sum_{j\in J_{m+1}} c_j - c_i\right)$$

Then, Inequality (271) holds as long as $c_i < \phi_i \sum_{j\in J_{m+1}} c_j$ is fulfilled.

(ii) Case of $(m = 1)$ supplier: Assuming Inequality (68) is true, we review if Inequality (270) holds. By replacing Eqs. (268) and (195) in Inequality (270) leads to:

$$\phi_1 \Psi_{m=1}\Omega_{m=1} + 2\left(1-\phi_1\right)c_1\Omega_{m=1}^2 > 0$$

From Eq. (216) we know that $\Psi_{m=1} > 0$. Then, Eq. (270) holds. Lastly, substituting Eqs. (268) and (214) in Inequality (272) leads to:

$$\Omega_{m=1}^2\left(\phi_1 c_1 - c_1\right)$$

Then, Inequality (272) holds as long as $c_1 < \phi_1 c_1$ is fulfilled.

□

Proof of Proposition 27: Let $D^{WS*} = d - \theta p^{WS*} + \sum_{j=1}^3 \beta_j \alpha_j^{WS*}$ be the expected demand in the WS contract under optimal conditions, and let $D^{CR*} = d - \theta p^{CR*} + \sum_{j=1}^3 \beta_j \alpha_j^{CR*}$ be the expected demand in the CR contract under optimal conditions. By setting $\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS*}(p^{WS*})](m = 3) \leq \mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{CR*}(p^{CR*})](m = 3)$ it is obtained the win condition for the $\mathcal{OEM}$:

$$\sum_{j=1}^3 \phi_j\left(\frac{\eta_j \alpha_j^{CR*2}}{2} - w_j^{CR*}D^{CR*}\right) \geq \left(p^{WS*} - \sum_{j=1}^3 w_j^{WS*}\right)D^{WS*} - p^{CR*}D^{CR*} + \frac{1}{2}\sum_{j=1}^3 \eta_j \alpha_j^{CR*2}. \tag{157}$$

By setting $\mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{WS*}(w_i^{WS*}, \alpha_i^{WS*})](m = 3) \leq \mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{CR*}(w_i^{CR*}, \alpha_i^{CR*})](m = 3)$ it is obtained the win condition for $\mathcal{S}_i$:

$$\phi_i \leq UB_{\phi_i}(m=3) = \frac{\left(c_i - w_i^{WS*}\right) D^{WS*} - c_i D^{CR*} + \frac{\eta_i \alpha_i^{WS*2}}{2}}{\frac{\eta_i \alpha_i^{CR*2}}{2} - w_i^{CR*} D^{CR*}}. \tag{158}$$

By replacing ϕ_j by UB_{ϕ_j} in Eq. (157) it is obtained:

$$\frac{\left(\Omega_{m=3} + 4\theta\right)^2 \Psi_{m=3}^2}{8\left(\Omega_{m=3} + 2\theta\right)^2 \Omega_{m=3}} > 0 \tag{159}$$

Now, by reviewing the concavity condition of the centralized model we know that $2\theta \prod_{j=1}^{3} \eta_j > \sum_{j=1}^{3} \left(\beta_j^2 \prod_{k=1;k\neq j}^{3} \eta_k\right)$. Therefore the previous expression holds, proving that there exist a feasible solution for ϕ_i. Compering Eqs. (157) and (158) let to the win-win conditions of ϕ_i for the CR contract shown in Eqs. (160) and (161).

$$\phi_i\left(m=3\right) \geq LB_{\phi_i(m=3)} = \frac{\Omega_{m=3}^2}{4\left(\Omega_{m=3} + 2\theta\right)^2}. \tag{160}$$

$$\phi_i\left(m=3\right) \leq UB_{\phi_i(m=3)} = 1 - \frac{\sum_{j=1;j\neq i}^{3} \left[2\theta\phi_j + \left(1-\phi_j\right)\frac{\beta_j^2}{\eta_j}\right]}{2\theta - \frac{\beta_i^2}{\eta_i}} - \frac{\Omega_{m=3}^2}{2\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)\left(\Omega_{m=3} + 2\theta\right)}. \tag{161}$$

General expression for Eqs. (157), (159), (160) and (161) are Eqs. (273), (276), (70) and (71), respectively. Now we proceed to prove latter Equations using mathematical induction:

(i) Case of $(m+1)$ suppliers: Assuming Eqs. (273), (276), (70) and (71) are true, we review if Eqs. (274), (277), (279) and (281) hold. Let $D_{m+1}^{WS*} = d - \theta p^{WS*} + \sum_{j\in J_{m+1}} \beta_j \alpha_j^{WS*}$, and $D_{m+1}^{CR*} = d - \theta p^{CR*} + \sum_{j\in J_{m+1}} \beta_j \alpha_j^{CR*}$. By setting $\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS*}(p^{WS*})](m+1) \leq \mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{CR*}(p^{CR*})](m+1)$ it is obtained Eq. (274). By replacing ϕ_i by UB_{ϕ_i} in Eq. (274) it is obtained Eq. (277). Finally, by setting $\mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{WS*}(w_i^{WS*}, \alpha_i^{WS*})](m+1) \leq \mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{CR*}(w_i^{CR*}, \alpha_i^{CR*})](m+1)$ and using Eq. (273) it is obtained Eqs. (279) and (281).

(ii) Case of $(m=1)$ supplier: Assuming Eqs. (273), (276), (70) and (71) are true, we review if Eqs. (275), (278), (280) and (282) hold. Let $D_{m=1}^{WS*} = d - \theta p^{WS*} + \beta_1 \alpha_1^{WS*}$, and $D_{m=1}^{CR*} = d - \theta p^{CR*} + \beta_1 \alpha_1^{CR*}$. By setting $\mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{WS*}(p^{WS*})](m=1) \leq \mathbb{E}_\xi[\Pi_{\mathcal{OEM}}^{CR*}(p^{CR*})](m=1)$ it is obtained Eq. (275). By replacing ϕ_i by UB_{ϕ_i} in Eq. (275) it is obtained Eq. (278). Finally, by setting $\mathbb{E}_\xi[\Pi^{WS*}_{\mathcal{S}_i}(w_i^{WS*}, \alpha_i^{WS*})](m=1) \leq \mathbb{E}_\xi[\Pi^{CR*}_{\mathcal{S}_i}(w_i^{CR*}, \alpha_i^{CR*})](m=1)$ and using Eq. (275) it is obtained Eqs. (280) and (282).

Proof of Proposition 28: For the case of $\mathbb{E}_\xi[\Pi^{CR}_{B_1}(p^{CR*}, w_1^{CR*}, \alpha_1^{CR*})](m=3)$, we first substitutes Eqs. (116), (117) and (154) in latter expression and verify if it is concave in ϕ_1 by calculating the first and second order derivatives:

$$\frac{\partial \mathbb{E}_\xi[\Pi^{CR}_{B_1}(p^{CR*}, w_1^{CR*}, \alpha_1^{CR*})](m=3)}{\partial \phi_1} = \frac{\left(2\theta - \frac{\beta_1^2}{\eta_1}\right)\Psi^4_{m=3}\left[\Omega_{m=3} - \phi_1\left(2\theta - \frac{\beta_1^2}{\eta_1}\right) - \sum_{j=1}^{3}\phi_j\left(2\theta - \frac{\beta_j^2}{\eta_j}\right)\right]}{4\Omega^4_{m=3}}. \tag{162}$$

$$\frac{\partial^2 \mathbb{E}_\xi[\Pi^{CR}_{B_1}(p^{CR*}, w_1^{CR*}, \alpha_1^{CR*})](m=3)}{\partial \phi_1^2} = \frac{-\Psi^4_{m=3}\left(2\theta - \frac{\beta_1^2}{\eta_1}\right)^2}{2\Omega^4_{m=3}}. \tag{163}$$

We have proved that $\mathbb{E}_\xi[\Pi^{CR}_{B_1}(p^{CR*}, w_1^{CR*}, \alpha_1^{CR*})](m=3)$ is a strictly function of ϕ_1. Then, by setting $\frac{\partial \mathbb{E}_\xi[\Pi^{CR}_{B_1}(p^{CR*}, w_1^{CR*}, \alpha_1^{CR*})](m=3)}{\partial \phi_1} = 0$ we obtain Eq. (164).

$$\phi_1^{CR*}|_{\phi_2,\phi_3}(m=3) = \frac{\Omega_{m=3} - \sum_{j=2}^{3}\phi_j\left(2\theta - \frac{\beta_j^2}{\eta_j}\right)}{2\left(2\theta - \frac{\beta_1^2}{\eta_1}\right)}. \tag{164}$$

Using $\phi_2^{CR*}|_{\phi_1,\phi_3}(m=3)$ to solve Eq. (164) yields to:

$$\phi_1^{CR*}|_{\phi_3}(m=3) = \frac{\Omega_{m=3} - \phi_3\left(2\theta - \frac{\beta_3^2}{\eta_3}\right)}{3\left(2\theta - \frac{\beta_1^2}{\eta_1}\right)}. \tag{165}$$

Finally, using $\phi_3^{CR*}|_{\phi_1}(m=3)$ to solve Eq. (165) leads to:

$$\phi_1^{CR*}(m=3) = \frac{\Omega_{m=3}}{4\left(2\theta - \frac{\beta_1^2}{\eta_1}\right)}. \tag{166}$$

General expressions for Eqs. (162), (163), (164) - (165) and (166) are Eqs. (283), (286), (289) and (73), respectively. The relation between Eqs. (289) and (73) can be summarized in the following algorithm:

> ϕ_i^{CR}:
>
> *repeat*
>
> > *replace a given* $\phi \in \widehat{\Phi}_m$ *in* $\phi_i^{CR}|_{\forall\phi\in\widehat{\Phi}_m}(m)$
> >
> > *update* $\widehat{\Phi}_m$
>
> *until* $|\widehat{\Phi}_m| = 0$

Now we use mathematical induction to prove that latter Equations hold. We are interested in two scenarios:

(i) Case of $(m+1)$ suppliers: Assuming Eqs. (283), (286), (289) and (73) are true, we review if Eqs. (284), (287), (290) and (291) hold. Substituting Eqs. (213), (215) and (267) into $\mathbb{E}_\xi[\Pi_{B_i}^{CR}(p^{CR*}, w_i^{CR*}, \alpha_i^{CR*})](m+1)$ and solving $\frac{\partial \mathbb{E}_\xi[\Pi_{B_i}^{CR}(p^{CR*}, w_i^{CR*}, \alpha_i^{CR*})](m+1)}{\partial \phi_i}$ yields to Eq. 284. Using Eq. 284 to solve $\frac{\partial^2 \mathbb{E}_\xi[\Pi_{B_i}^{CR}(p^{CR*}, w_i^{CR*}, \alpha_i^{CR*})](m+1)}{\partial \phi_i^2}$ leads to Eq. (287). By setting $\frac{\partial \mathbb{E}_\xi[\Pi_{B_i}^{CR}(p^{CR*}, w_i^{CR*}, \alpha_i^{CR*})](m+1)}{\partial \phi_i} = 0$ and isolating variable ϕ_i from the expression yields to Eq. (290). Eq. (291) is a particular case of Eq. (290) when $|\widehat{\Phi}_{m+1}| = 0$.

(ii) Case of $(m = 1)$ supplier: Assuming Eqs. (283), (286) and (73) are true, we review if Eqs. (285), (288) and (292) hold. Eq. (289) is disregarded for the case of $(m = 1)$ supplier. Replacing Eqs. (214), (216) and (268) into $\mathbb{E}_\xi[\Pi_{B_1}^{CR}(p^{CR*}, w_1^{CR*}, \alpha_1^{CR*})](m = 1)$ and solving $\frac{\partial \mathbb{E}_\xi[\Pi_{B_1}^{CR}(p^{CR*}, w_1^{CR*}, \alpha_1^{CR*})](m=1)}{\partial \phi_1}$ yields to Eq. (285). Using Eq. (285) in order to solve $\frac{\partial^2 \mathbb{E}_\xi[\Pi_{B_1}^{CR}(p^{CR*}, w_1^{CR*}, \alpha_1^{CR*})](m=1)}{\partial \phi_i^2}$ leads to Eq. (288). By setting $\frac{\partial \mathbb{E}_\xi[\Pi_{B_1}^{CR}(p^{CR*}, w_1^{CR*}, \alpha_1^{CR*})](m=1)}{\partial \phi_1} = 0$ and isolating variable ϕ_1 from the expression yields to Eq. (292).

□

Proof of Proposition 29: The partial derivative of $\phi_1^{CR*}(m = 3)$ with respect to β_1 gives:

$$\frac{\partial \phi_1^{CR*}(m=3)}{\partial \beta_1} = \frac{-2\beta_1 \displaystyle\sum_{j=2}^{3} \frac{\beta_j^2}{\eta_j}}{4\eta_1 \left(2\theta - \frac{\beta_1^2}{\eta_1}\right)^2}. \tag{167}$$

The partial derivative of $\phi_1^{CR*}(m = 3)$ with respect to β_2 leads to:

$$\frac{\partial \phi_1^{CR*}(m=3)}{\partial \beta_2} = \frac{-2\beta_2}{4\eta_2 \left(2\theta - \frac{\beta_1^2}{\eta_1}\right)}. \tag{168}$$

The partial derivative of $\phi_1^{CR*}(m=3)$ with respect to η_1 yields to:

$$\frac{\partial \phi_1^{CR*}(m=3)}{\partial \eta_1} = \frac{\beta_1^2 \sum_{j=2}^{3} \frac{\beta_j^2}{\eta_j}}{4\eta_1^2 \left(2\theta - \frac{\beta_1^2}{\eta_1}\right)^2}. \tag{169}$$

The partial derivative of $\phi_1^{CR*}(m=3)$ with respect to η_2 gives:

$$\frac{\partial \phi_1^{CR*}(m=3)}{\partial \eta_2} = \frac{\beta_2^2}{4\eta_2^2 \left(2\theta - \frac{\beta_1^2}{\eta_1}\right)}. \tag{170}$$

Similar results can be obtained for $\phi_2^{CR*}(m=3)$ and $\phi_3^{CR*}(m=3)$. General expressions for Eqs. (167), (168), (169) and (170) are Eqs. (293), (295), (297) and (299), respectively.

Using mathematical induction we prove that latter Equations hold. We are interested in two scenarios:

(i) Case of $(m+1)$ suppliers: Assuming Eqs. (293), (295), (297) and (299) are true, we review if Eqs. (294), (296), (298) and (300) hold. Using Eq. (291) to calculate $\frac{\partial \phi_i^{CR*}(m+1)}{\partial \beta_i}$ it is obtained Eq. (294). The $\frac{\partial \phi_i^{CR*}(m+1)}{\partial \beta_j}$ leads to Eq. (296). Using Eq. (291) to calculate $\frac{\partial \phi_i^{CR*}(m+1)}{\partial \eta_i}$ yields to Eq. (298). Finally, $\frac{\partial \phi_i^{CR*}(m+1)}{\partial \eta_j}$ gives Eq. (300).

(ii) Case of $(m=1)$ supplier: Eqs. (293), (295), (297) and (299) are disregarded for the case of $(m=1)$ supplier.

□

□

Appendix C

Summary of equations Chapter 3

Table C.1: Wholesale price (WS) contract summary

Expression	Suppliers		
$\frac{\partial \mathbb{E}_{\xi}[\Pi^{WS}_{\mathcal{S}_i}(w_i,\alpha_i)]}{\partial w_i}$	m	$d-\theta\left(2w_i+\sum_{j\in J_m;j\neq i} w_j+\Delta-c_i\right)+\sum_{j\in J_m}\beta_j\alpha_j$	(171)
	$m+1$	$d-\theta\left(2w_i+\sum_{j\in J_{m+1};j\neq i} w_j+\Delta-c_i\right)+\sum_{j\in J_{m+1}}\beta_j\alpha_j$	(172)
	$m=1$	$d-\theta\left(2w_1+\Delta-c_1\right)+\beta_1\alpha_1$	(173)
$w_i^{WS*}\vert_{p,\forall\alpha}$	m	$c_i+\frac{1}{\theta}\left(d-\theta p+\sum_{j\in J_m}\beta_j\alpha_j\right)$, where $\alpha\in A_m$	(174)
	$m+1$	$c_i+\frac{1}{\theta}\left(d-\theta p+\sum_{j\in J_{m+1}}\beta_j\alpha_j\right)$, where $\alpha\in A_{m+1}$	(175)
	$m=1$	$c_1+\frac{1}{\theta}\left(d-\theta p+\beta_1\alpha_1\right)$	(176)
$w_i^{WS*}\vert_{p,\forall w}$	m	$c_i+\dfrac{d-p\theta+\sum_{j\in\widehat{J}_m}\left[(w_j-c_j)\frac{\beta_j^2}{\eta_j}\right]}{\theta-\sum_{j\in\widehat{J}^c_m}\frac{\beta_j^2}{\eta_j}}$, where $w\in\widehat{W}_m$	(177)
	$m+1$	$c_i+\dfrac{d-p\theta+\sum_{j\in\widehat{J}_{m+1}}\left[(w_j-c_j)\frac{\beta_j^2}{\eta_j}\right]}{\theta-\sum_{j\in\widehat{J}^c_{m+1}}\frac{\beta_j^2}{\eta_j}}$, where $w\in\widehat{W}_{m+1}$	(178)
	$m=1$	$---$	
$w_i^{WS*}\vert_p$	m	Eq. (43)	
	$m+1$	$c_i+\frac{d-p\theta}{\Omega_{m+1}-\theta}$	(179)
	$m=1$	$c_1+\frac{d-p\theta}{\Omega_{m=1}-\theta}$	(180)
$\alpha_i^{WS*}\vert_p$	m	Eq. (44)	
	$m+1$	$\frac{\beta_i\left(d-p\theta\right)}{\eta_i\left(\Omega_{m+1}-\theta\right)}$	(181)
	$m=1$	$\frac{\beta_1\left(d-p\theta\right)}{\eta_1\left(\Omega_{m=1}-\theta\right)}$	(182)

Table C.1: Wholesale price (WS) contract summary (continued)

Expression	Suppliers		
$\mathbb{E}_{\xi}[\Pi^{WS}_{\mathcal{OEM}}(p)]$	m	$\dfrac{\theta\left(d-\theta p\right)\left[\left(p-\sum_{j\in J_m}c_j\right)\left(\Omega_m-\theta\right)-m\left(d-\theta p\right)\right]}{\left(\Omega_m-\theta\right)^2}$	(183)
	$m+1$	$\dfrac{\theta\left(d-\theta p\right)\left[\left(p-\sum_{j\in J_{m+1}}c_j\right)\left(\Omega_{m+1}-\theta\right)-\left(m+1\right)\left(d-\theta p\right)\right]}{\left(\Omega_{m+1}-\theta\right)^2}$	(184)
	$m=1$	$\dfrac{\theta\left(d-\theta p\right)\left[\left(p-c_1\right)\left(\Omega_{m=1}-\theta\right)-\left(d-\theta p\right)\right]}{\left(\Omega_{m=1}-\theta\right)^2}$	(185)
$\frac{\partial\mathbb{E}_{\xi}[\Pi^{WS}_{\mathcal{OEM}}(p)]}{\partial p}$	m	$\dfrac{\theta\left[\left(d-\theta\left(2p-\sum_{j\in J_m}c_j\right)\right)\left(\Omega_m-\theta\right)+2m\theta\left(d-\theta p\right)\right]}{\left(\Omega_m-\theta\right)^2}$	(186)
	$m+1$	$\dfrac{\theta\left[\left(d-\theta\left(2p-\sum_{j\in J_{m+1}}c_j\right)\right)\left(\Omega_{m+1}-\theta\right)+2(m+1)\theta\left(d-\theta p\right)\right]}{\left(\Omega_{m+1}-\theta\right)^2}$	(187)
	$m=1$	$\dfrac{\theta\left[\left(d-\theta\left(2p-c_1\right)\right)\left(\Omega_{m=1}-\theta\right)+2\theta\left(d-\theta p\right)\right]}{\left(\Omega_{m=1}-\theta\right)^2}$	(188)
$\frac{\partial^2\mathbb{E}_{\xi}[\Pi^{WS}_{\mathcal{OEM}}(p)]}{\partial p^2}$	m	$\dfrac{-2\theta^2\left[\Omega_m+\left(m-1\right)\theta\right]}{\left(\Omega_m-\theta\right)^2}$	(189)
	$m+1$	$\dfrac{-2\theta^2\left[\Omega_{m+1}+m\theta\right]}{\left(\Omega_{m+1}-\theta\right)^2}$	(190)
	$m=1$	$\dfrac{-2\theta^2\Omega_{m=1}}{\left(\Omega_{m=1}-\theta\right)^2}$	(191)
p^{WS*}	m	Eq. (45)	
	$m+1$	$\dfrac{2(m+1)d\theta-\left(\Psi_{m+1}-2d\right)\left(\Omega_{m+1}-\theta\right)}{2\theta\left(\Omega_{m+1}+m\theta\right)}$	(192)
	$m=1$	$\dfrac{2d\theta-\left(\Psi_{m=1}-2d\right)\left(\Omega_{m=1}-\theta\right)}{2\theta\Omega_{m=1}}$	(193)
w_i^{WS*}	m	Eq. (46)	
	$m+1$	$c_i+\dfrac{\Psi_{m+1}}{2\left(\Omega_{m+1}+m\theta\right)}$	(194)
	$m=1$	$c_1+\dfrac{\Psi_{m=1}}{2\Omega_{m=1}}$	(195)
α_i^{WS*}	m	Eq. (47)	
	$m+1$	$\dfrac{\beta_i\Psi_{m+1}}{2\eta_i\left(\Omega_{m+1}+m\theta\right)}$	(196)
	$m=1$	$\dfrac{\beta_1\Psi_{m=1}}{2\eta_1\Omega_{m=1}}$	(197)

Table C.2: Centralized model summary

Expression	Suppliers		
$\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\forall\alpha\in A_m)]}{\partial p}$	m	$d-\theta\left(2p-\sum_{j\in J_m} c_j\right)+\sum_{j\in J_m}\beta_j\alpha_j$	(198)
	$m+1$	$d-\theta\left(2p-\sum_{j\in J_{m+1}} c_j\right)+\sum_{j\in J_{m+1}}\beta_j\alpha_j$	(199)
	$m=1$	$d-\theta\left(2p-c_1\right)+\beta_1\alpha_1$	(200)
$\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{SC}}(p,\forall\alpha\in A_m)]}{\partial \alpha_i}$	m	$\beta_i\left(p-\sum_{j\in J_m} c_j\right)-\eta_i\alpha_i$	(201)
	$m+1$	$\beta_i\left(p-\sum_{j\in J_{m+1}} c_j\right)-\eta_i\alpha_i$	(202)
	$m=1$	$\beta_1\left(p-c_1\right)-\eta_1\alpha_1$	(203)
$\lvert H_{\mathbb{E}[\Pi_{\mathcal{SC}}]}\rvert$	m	$2(-1)^{m+1}\theta\prod_{j\in J_m}\eta_j-(-1)^{m+1}\sum_{j\in J_m}\left(\beta_j^2\prod_{k\in J_m;k\neq j}\eta_k\right)$	(204)
	$m+1$	$2(-1)^{m+2}\theta\prod_{j\in J_{m+1}}\eta_j-(-1)^{m+2}\sum_{j\in J_{m+1}}\left(\beta_j^2\prod_{k\in J_{m+1};k\neq j}\eta_k\right)$	(205)
	$m=1$	$2\theta\eta_1-\beta_1^2$	(206)
$p^*\rvert_{\forall\alpha}$	m	$\frac{1}{2\theta}\left(d+\theta\sum_{j\in J_m} c_j+\sum_{j\in J_m}\beta_j\alpha_j\right)$, where $\alpha\in A_m$	(207)
	$m+1$	$\frac{1}{2\theta}\left(d+\theta\sum_{j\in J_{m+1}} c_j+\sum_{j\in J_{m+1}}\beta_j\alpha_j\right)$, where $\alpha\in A_{m+1}$	(208)
	$m=1$	$\frac{1}{2\theta}\left(d+\theta c_1+\beta_1\alpha_1\right)$	(209)
$\alpha_i^*\rvert_p$	m	$\frac{\beta_i}{\eta_i}\left(p-\sum_{j\in J_m} c_j\right)$	(210)
	$m+1$	$\frac{\beta_i}{\eta_i}\left(p-\sum_{j\in J_{m+1}} c_j\right)$	(211)
	$m=1$	$\frac{\beta_1}{\eta_1}\left(p-c_1\right)$	(212)
p^*	m	Eq. (50)	
	$m+1$	$\frac{d+\left(\Omega_{m+1}-\theta\right)\sum_{j\in J_{m+1}} c_j}{\Omega_{m+1}}$	(213)
	$m=1$	$\frac{d+\left(\Omega_{m=1}-\theta\right)c_1}{\Omega_{m=1}}$	(214)

Table C.2: Centralized model summary (continued)

Expression	Suppliers		
α_i^*	m	Eq. (51)	
	$m+1$	$\dfrac{\beta_i \Psi_{m+1}}{\eta_i \Omega_{m+1}}$	(215)
	$m=1$	$\dfrac{\beta_1 \Psi_{m=1}}{\eta_1 \Omega_{m=1}}$	(216)
p^* vs. p^{WS*}	m	Eq. (52)	
	$m+1$	$\Omega_{m+1} > \theta \Longrightarrow p^*(m+1) < p^{WS*}(m+1)$	(217)
	$m=1$	$\Omega_{m=1} > \theta \Longrightarrow p^*(m=1) < p^{WS*}(m=1)$	(218)
α_i^* vs. α_i^{WS*}	m	Eq. (53)	
	$m+1$	$\alpha_i^*(m+1) > \alpha_i^{WS*}(m+1)$	(219)
	$m=1$	$\alpha_i^*(m=1) > \alpha_i^{WS*}(m=1)$	(220)
$\mathbb{E}[D^*]$ vs. $\mathbb{E}\left[D^{WS*}\right]$	m	Eq. (54)	
	$m+1$	$\mathbb{E}[D^*](m+1) > \mathbb{E}\left[D^{WS*}\right](m+1)$	(221)
	$m=1$	$\mathbb{E}[D^*](m=1) > \mathbb{E}\left[D^{WS*}\right](m=1)$	(222)
$\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^{WS*}(p^{WS*}, \forall w^{WS*}, \forall \alpha^{WS*})]$	m	$\dfrac{[3\Omega_m + 4(m-1)\theta]\Psi_m^2}{8[\Omega_m + (m-1)\theta]^2}$, where $w^{WS*} \in W_m^{WS*}$, $\alpha^{WS*} \in A_m^{WS*}$	(223)
	$m+1$	$\dfrac{[3\Omega_{m+1} + 4m\theta]\Psi_{m+1}^2}{8[\Omega_{m+1} + m\theta]^2}$, where $w^{WS*} \in W_{m+1}^{WS*}$, $\alpha^{WS*} \in A_{m+1}^{WS*}$	(224)
	$m=1$	$\dfrac{3\Omega_{m=1}\Psi_{m=1}^2}{8\Omega_{m=1}^2}$	(225)
$\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^*(p^*, \forall \alpha^*)]$	m	$\dfrac{\Psi_m^2}{2\Omega_m}$, where $\alpha^* \in A_m^*$	(226)
	$m+1$	$\dfrac{\Psi_{m+1}^2}{2\Omega_{m+1}}$, where $\alpha^* \in A_{m+1}^*$	(227)
	$m=1$	$\dfrac{\Psi_{m=1}^2}{2\Omega_{m=1}}$	(228)
$\frac{\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^{WS*}]}{\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^*]}$	m	$\dfrac{[3\Omega_m + 4(m-1)\theta]\Omega_m}{4[\Omega_m + (m-1)\theta]^2}$	(229)
	$m+1$	$\dfrac{[3\Omega_{m+1} + 4m\theta]\Omega_{m+1}}{4[\Omega_{m+1} + m\theta]^2}$	(230)
	$m=1$	$\dfrac{3}{4}$	(231)

Table C.2: Centralized model summary (continued)

Expression	Suppliers		
$\frac{\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^{WS*}]}{\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^{*}]}$	m	$1-\dfrac{\left[\Omega_m+2\left(m-1\right)\theta\right]^2}{4\left[\Omega_m+\left(m-1\right)\theta\right]^2},$	(232)
	$m+1$	$1-\dfrac{\left[\Omega_{m+1}+2m\theta\right]^2}{4\left[\Omega_{m+1}+m\theta\right]^2}$	(233)
	$m=1$	$\dfrac{3}{4}$	(234)
$\frac{\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^{*}]-\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^{WS*}]}{\mathbb{E}_\xi[\Pi_{\mathcal{SC}}^{WS*}]}$	m	$\geq\dfrac{1}{3}$	(235)
	$m+1$	$\geq\dfrac{1}{3}$	(236)
	$m=1$	$=\dfrac{1}{3}$	(237)

Table C.3: Cost sharing (CS) contract summary

Expression	Suppliers		
$\frac{\partial \mathbb{E}_{\xi}[\Pi_{S_i}^{CS}(w_i,\alpha_i)]}{\partial w_i}$	m	$d-\theta\left(2w_i+\sum_{j\in J_m;j\neq i} w_j+\Delta-c_i\right)+\sum_{j\in J_m}\beta_j\alpha_j$	(238)
	$m+1$	$d-\theta\left(2w_i+\sum_{j\in J_{m+1};j\neq i} w_j+\Delta-c_i\right)+\sum_{j\in J_{m+1}}\beta_j\alpha_j$	(239)
	$m=1$	$d-\theta\left(2w_1+\Delta-c_1\right)+\beta_1\alpha_1$	(240)
$w_i^{CS*}\|_{p,\forall\alpha}$	m	$c_i+\frac{1}{\theta}\left(d-\theta p+\sum_{j\in J_m}\beta_j\alpha_j\right)$, where $\alpha\in A_m$	(241)
	$m+1$	$c_i+\frac{1}{\theta}\left(d-\theta p+\sum_{j\in J_{m+1}}\beta_j\alpha_j\right)$, where $\alpha\in A_{m+1}$	(242)
	$m=1$	$c_1+\frac{1}{\theta}\left(d-\theta p+\beta_1\alpha_1\right)$	(243)
$w_i^{CS*}\|_{p,\forall w}$	m	$c_i+\cfrac{d-p\theta+\sum_{j\in\widehat{J}_m}\left[(w_j-c_j)\frac{\beta_j^2}{\eta_j\phi_j}\right]}{\theta-\sum_{j\in\widehat{J}_m^c}\frac{\beta_j^2}{\eta_j\phi_j}}$, where $w\in\widehat{W}_m$	(244)
	$m+1$	$c_i+\cfrac{d-p\theta+\sum_{j\in\widehat{J}_{m+1}}\left[(w_j-c_j)\frac{\beta_j^2}{\eta_j\phi_j}\right]}{\theta-\sum_{j\in\widehat{J}_{m+1}^c}\frac{\beta_j^2}{\eta_j\phi_j}}$, where $w\in\widehat{W}_{m+1}$	(245)
	$m=1$	$---$	
$w_i^{CS*}\|_p$	m	Eq. (59)	
	$m+1$	$c_i+\cfrac{d-p\theta}{\theta-\sum_{j\in J_{m+1}}\frac{\beta_j^2}{\eta_j\phi_j}}$	(246)
	$m=1$	$c_1+\cfrac{d-p\theta}{\theta-\frac{\beta_1^2}{\eta_1\phi_1}}$	(247)
$\alpha_i^{CS*}\|_p$	m	Eq. (60)	
	$m+1$	$\cfrac{\beta_i(d-p\theta)}{\eta_i\phi_i\left(\theta-\sum_{j\in J_{m+1}}\frac{\beta_j^2}{\eta_j\phi_j}\right)}$	(248)
	$m=1$	$\cfrac{\beta_1(d-p\theta)}{\eta_1\phi_1\left(\theta-\frac{\beta_1^2}{\eta_1\phi_1}\right)}$	(249)
$p^{CS*}\|_{\alpha_i^{CS*}\|_p=\alpha_i^*}$	m	$\frac{d}{\theta}-\frac{\phi_i\Psi_m}{\theta\Omega_m}\left(\theta-\sum_{j\in J_m}\frac{\beta_j^2}{\eta_j\phi_j}\right)$	(250)
	$m+1$	$\frac{d}{\theta}-\frac{\phi_i\Psi_{m+1}}{\theta\Omega_{m+1}}\left(\theta-\sum_{j\in J_{m+1}}\frac{\beta_j^2}{\eta_j\phi_j}\right)$	(251)
	$m=1$	$\frac{d}{\theta}-\frac{\phi_1\Psi_{m=1}}{\theta\Omega_{m=1}}\left(\theta-\frac{\beta_1^2}{\eta_1\phi_1}\right)$	(252)

Table C.3: Cost sharing (CS) contract summary (continued)

Expression	Suppliers		
$\phi_i\|_{\forall\phi}$	m	$\dfrac{\theta - \sum_{j\in\widehat{J}_m} \dfrac{\beta_j^2}{\eta_j}}{\theta - \sum_{j\in\widehat{J}_m} \dfrac{\beta_j^2}{\eta_j\phi_j}}$, where $\phi \in \widehat{\Phi}_m$	(253)
	$m+1$	$\dfrac{\theta - \sum_{j\in\widehat{J}_{m+1}} \dfrac{\beta_j^2}{\eta_j}}{\theta - \sum_{j\in\widehat{J}_{m+1}} \dfrac{\beta_j^2}{\eta_j\phi_j}}$, where $\phi \in \widehat{\Phi}_{m+1}$	(254)
	$m=1$	$---$	

Table C.4: Cost-revenue sharing (CR) contract summary

Expression	Suppliers		
$\frac{\partial \mathbb{E}_\xi[\Pi_{\mathcal{S}_i}^{CR}(w_i,\alpha_i)]}{\partial w_i}$	m	$\phi_i\left[d-\theta\left(2w_i+\sum_{j\in J_m;j\neq i} w_j+\Delta\right)+\sum_{j\in J_m}\beta_j\alpha_j\right]+c_i\theta$	(255)
	$m+1$	$\phi_i\left[d-\theta\left(2w_i+\sum_{j\in J_{m+1};j\neq i} w_j+\Delta\right)+\sum_{j\in J_{m+1}}\beta_j\alpha_j\right]+c_i\theta$	(256)
	$m=1$	$\phi_1\left[d-\theta\left(2w_1+\Delta\right)+\beta_1\alpha_1\right]+c_1\theta$	(257)
$w_i^{CR*}\|_{p,\forall\alpha}$	m	$\frac{c_i}{\phi_i}+\frac{1}{\theta}\left(d-\theta p+\sum_{j\in J_m}\beta_j\alpha_j\right)$, where $\alpha\in A_m$	(258)
	$m+1$	$\frac{c_i}{\phi_i}+\frac{1}{\theta}\left(d-\theta p+\sum_{j\in J_{m+1}}\beta_j\alpha_j\right)$, where $\alpha\in A_{m+1}$	(259)
	$m=1$	$\frac{c_1}{\phi_1}+\frac{1}{\theta}\left(d-\theta p+\beta_1\alpha_1\right)$	(260)
$w_i^{CR*}\|_{p,\forall w}$	m	$\frac{c_i}{\phi_i}+\frac{d-p\theta+\sum_{j\in\widehat{J}_m}\left[\left(w_j-\frac{c_j}{\phi_j}\right)\frac{\beta_j^2}{\eta_j}\right]}{\theta-\sum_{j\in\widehat{J}_m^c}\frac{\beta_j^2}{\eta_j}}$, where $w\in\widehat{W}_m$	(261)
	$m+1$	$\frac{c_i}{\phi_i}+\frac{d-p\theta+\sum_{j\in\widehat{J}_{m+1}}\left[\left(w_j-\frac{c_j}{\phi_j}\right)\frac{\beta_j^2}{\eta_j}\right]}{\theta-\sum_{j\in\widehat{J}_{m+1}^c}\frac{\beta_j^2}{\eta_j}}$, where $w\in\widehat{W}_{m+1}$	(262)
	$m=1$	$---$	
$w_i^{CR*}\|_p$	m	Eq. (65)	
	$m+1$	$\frac{c_i}{\phi_i}+\frac{d-p\theta}{\Omega_{m+1}-\theta}$	(263)
	$m=1$	$\frac{c_1}{\phi_1}+\frac{d-p\theta}{\Omega_{m=1}-\theta}$	(264)
$\alpha_i^{CR*}\|_p$	m	Eq. (66)	
	$m+1$	$\frac{\beta_i\left(d-p\theta\right)}{\eta_i\left(\Omega_{m+1}-\theta\right)}$	(265)
	$m=1$	$\frac{\beta_1\left(d-p\theta\right)}{\eta_1\left(\Omega_{m=1}-\theta\right)}$	(266)
w_i^{CR*}	m	Eq. (67)	
	$m+1$	$\frac{c_i}{\phi_i}+\frac{\Psi_{m+1}}{\Omega_{m+1}}$	(267)
	$m=1$	$\frac{c_1}{\phi_1}+\frac{\Psi_{m=1}}{\Omega_{m=1}}$	(268)

Table C.4: Cost-revenue sharing (CR) contract summary

Expression	Suppliers		
w_i^{CR*} vs. w_i^{WS*}	m	Eq. (68)	
	$m+1$	$w_i^{CR*}(m+1) > w_i^{WS*}(m+1)$	(269)
	$m=1$	$w_1^{CR*}(m=1) > w_1^{WS*}(m=1)$	(270)
w_i^{CR*} vs. p^*	m	Eq. (69)	
	$m+1$	$c_i < \phi_i \sum_{j\in J_{m+1}} c_j \Longrightarrow w_i^{CR*}(m+1) < p^*(m+1)$	(271)
	$m=1$	$c_1 < \phi_1 c_1 \Longrightarrow w_1^{CR*}(m=1) < p^*(m=1)$	(272)
Inequality	m	$\sum_{j\in J_m} \phi_j \left(\frac{\eta_j \alpha_j^{CR*2}}{2} - w_j^{CR*} D_m^{CR*}\right) \geq \left(p^{WS*} - \sum_{j\in J_m} w_j^{WS*}\right) D_m^{WS*} - p^{CR*} D_m^{CR*} + \frac{1}{2}\sum_{j\in J_m} \eta_j \alpha_j^{CR*2},$	(273)
		where $D_m^{WS*} = d - \theta p^{WS*} + \sum_{j\in J_m} \beta_j \alpha_j^{WS*}$, and $D_m^{CR*} = d - \theta p^{CR*} + \sum_{j\in J_m} \beta_j \alpha_j^{CR*}$	
	$m+1$	$\sum_{j\in J_{m+1}} \phi_j \left(\frac{\eta_j \alpha_j^{CR*2}}{2} - w_j^{CR*} D_{m+1}^{CR*}\right) \geq \left(p^{WS*} - \sum_{j\in J_{m+1}} w_j^{WS*}\right) D_{m+1}^{WS*} - p^{CR*} D_{m+1}^{CR*} + \frac{1}{2}\sum_{j\in J_{m+1}} \eta_j \alpha_j^{CR*2}$	(274)
	$m=1$	$\phi_1 \left(\frac{\eta_1 \alpha_1^{CR*2}}{2} - w_1^{CR*} D_{m=1}^{CR*}\right) \geq \left(p^{WS*} - w_1^{WS*}\right) D_{m=1}^{WS*} - p^{CR*} D_{m=1}^{CR*} + \frac{1}{2}\eta_1 \alpha_1^{CR*2}$	(275)
Ratio	m	$\frac{[\Omega_m + 2(m-1)\theta]^2 \Psi_m^2}{8[\Omega_m + (m-1)\theta]^2 \Omega_m} > 0$	(276)
	$m+1$	$\frac{[\Omega_{m+1} + 2m\theta]^2 \Psi_{m+1}^2}{8[\Omega_{m+1} + m\theta]^2 \Omega_{m+1}} > 0$	(277)
	$m=1$	$\frac{\Psi_{m=1}^2}{8\Omega_{m=1}} > 0$	(278)
LB_{ϕ_i}	m	Eq. (70)	
	$m+1$	$\frac{\Omega_{m+1}^2}{4[\Omega_{m+1} + m\theta]^2}$	(279)
	$m=1$	$\frac{1}{4}$	(280)
UB_{ϕ_i}	m	Eq. (71)	
	$m+1$	$1 - \frac{\sum_{j\in J_{m+1}; j\neq i} \left[2\theta\phi_j + (1-\phi_j)\frac{\beta_j^2}{\eta_j}\right]}{2\theta - \frac{\beta_i^2}{\eta_i}} - \frac{\Omega_{m+1}^2}{2\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)[\Omega_{m+1} + m\theta]}$	(281)
	$m=1$	$\frac{1}{2}$	(282)

Table C.4: Cost-revenue sharing (CR) contract summary (continued)

Expression	Suppliers		
$\frac{\partial \mathbb{E}_\xi[\Pi^{CR}_{B_i}(p^{CR*}, w_i^{CR*}, \alpha_i^{CR*})]}{\partial \phi_i}$	m	$\dfrac{\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)\Psi_m^4 \left[\Omega_m - \phi_i\left(2\theta - \frac{\beta_i^2}{\eta_i}\right) - \sum\limits_{j \in J_m} \phi_j \left(2\theta - \dfrac{\beta_j^2}{\eta_j}\right)\right]}{4\Omega_m^4}$	(283)
	$m+1$	$\dfrac{\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)\Psi_{m+1}^4 \left[\Omega_{m+1} - \phi_i\left(2\theta - \frac{\beta_i^2}{\eta_i}\right) - \sum\limits_{j \in J_{m+1}} \phi_j \left(2\theta - \dfrac{\beta_j^2}{\eta_j}\right)\right]}{4\Omega_{m+1}^4}$	(284)
	$m=1$	$\dfrac{\left(2\theta - \frac{\beta_1^2}{\eta_1}\right)\Psi_{m=1}^4 \left[\Omega_{m=1} - 2\phi_1\left(2\theta - \frac{\beta_1^2}{\eta_1}\right)\right]}{4\Omega_{m=1}^4}$	(285)
$\frac{\partial^2 \mathbb{E}_\xi[\Pi^{CR}_{B_i}(p^{CR*}, w_i^{CR*}, \alpha_i^{CR*})]}{\partial \phi_i^2}$	m	$\dfrac{-\Psi_m^4\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)^2}{2\Omega_m^4}$	(286)
	$m+1$	$\dfrac{-\Psi_{m+1}^4\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)^2}{2\Omega_{m+1}^4}$	(287)
	$m=1$	$\dfrac{-\Psi_{m=1}^4\left(2\theta - \frac{\beta_1^2}{\eta_1}\right)^2}{2\Omega_{m=1}^4}$	(288)
$\phi_i^{CR*}\vert_{\forall\phi}$	m	$\dfrac{\Omega_m - \sum\limits_{j \in \widehat{J}_m} \phi_j\left(2\theta - \dfrac{\beta_j^2}{\eta_j}\right)}{\left(\vert\widehat{J}_m^c\vert + 1\right)\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)}$, where $\phi \in \widehat{\Phi}_m$	(289)
	$m+1$	$\dfrac{\Omega_{m+1} - \sum\limits_{j \in \widehat{J}_{m+1}} \phi_j\left(2\theta - \dfrac{\beta_j^2}{\eta_j}\right)}{\left(\vert\widehat{J}_{m+1}^c\vert + 1\right)\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)}$, where $\phi \in \widehat{\Phi}_{m+1}$	(290)
	$m=1$	$---$	
ϕ_i^{CR*}	m	Eq. (73)	
	$m+1$	$\dfrac{\Omega_{m+1}}{(m+2)\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)}$	(291)
	$m=1$	$\dfrac{1}{2}$	(292)
$\frac{\partial \phi_i^{CR*}}{\partial \beta_i}$	m	$\dfrac{-2\beta_i \sum\limits_{j \in J_m; j \neq i} \dfrac{\beta_j^2}{\eta_j}}{(m+1)\,\eta_i\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)^2}$	(293)
	$m+1$	$\dfrac{-2\beta_i \sum\limits_{j \in J_{m+1}; j \neq i} \dfrac{\beta_j^2}{\eta_j}}{(m+2)\,\eta_i\left(2\theta - \frac{\beta_i^2}{\eta_i}\right)^2}$	(294)
	$m=1$	$---$	

Table C.4: Cost-revenue sharing (CR) contract summary (continued)

Expression	Suppliers		
$\frac{\partial \phi_i^{CR*}}{\partial \beta_j}$	m	$\dfrac{-2\beta_j}{(m+1)\,\eta_j\left(2\theta-\frac{\beta_i^2}{\eta_i}\right)}$	(295)
	$m+1$	$\dfrac{-2\beta_j}{(m+2)\,\eta_j\left(2\theta-\frac{\beta_i^2}{\eta_i}\right)}$	(296)
	$m=1$	$---$	
$\frac{\partial \phi_i^{CR*}}{\partial \eta_i}$	m	$\dfrac{\beta_i^2 \sum_{j\in J_m; j\neq i} \frac{\beta_j^2}{\eta_j}}{(m+1)\,\eta_i^2\left(2\theta-\frac{\beta_i^2}{\eta_i}\right)^2}$	(297)
	$m+1$	$\dfrac{\beta_i^2 \sum_{j\in J_{m+1}; j\neq i} \frac{\beta_j^2}{\eta_j}}{(m+2)\,\eta_i^2\left(2\theta-\frac{\beta_i^2}{\eta_i}\right)^2}$	(298)
	$m=1$	$---$	
$\frac{\partial \phi_i^{CR*}}{\partial \eta_j}$	m	$\dfrac{\beta_j^2}{(m+1)\,\eta_j^2\left(2\theta-\frac{\beta_i^2}{\eta_i}\right)}$	(299)
	$m+1$	$\dfrac{\beta_j^2}{(m+2)\,\eta_j^2\left(2\theta-\frac{\beta_i^2}{\eta_i}\right)}$	(300)
	$m=1$	$---$	

Appendix D

Data and results from Numerical example Chapter 3

Table D.1: Data from Numerical example

m	Supplier	c	β	η	ϕ Case A	Case B	Case C	Case D
1	1	55.00	450.00	1000	0.1500	0.2500	0.3500	0.4500
2	1	10.00	50.00	2500	0.1500	0.2500	0.3500	0.4500
	2	1.50	10.00	300	0.0500	0.1000	0.1500	0.2000
4	1	5.00	20.00	580	0.1200	0.1500	0.1800	0.2000
	2	1.60	5.00	240	0.0100	0.0300	0.0400	0.0500
	3	1.80	10.00	360	0.0200	0.0400	0.0600	0.0800
	4	5.60	25.00	620	0.1100	0.1300	0.1500	0.2000
10	1	0.82	5.28	592	0.0393	0.0786	0.1179	0.1572
	2	0.02	3.65	396	0.0015	0.0030	0.0045	0.0060
	3	1.96	15.60	2549	0.0133	0.0266	0.0399	0.0532
	4	0.98	6.27	610	0.0436	0.0872	0.1308	0.1744
	5	2.16	17.04	2316	0.0115	0.0230	0.0345	0.0460
	6	1.26	6.42	561	0.0070	0.0140	0.0210	0.0280
	7	2.34	20.01	2725	0.0334	0.0668	0.1002	0.1336
	8	2.40	16.71	2940	0.0221	0.0442	0.0663	0.0884
	9	2.78	20.64	2160	0.0169	0.0338	0.0507	0.0676
	10	2.14	19.35	2888	0.0035	0.0070	0.0105	0.0140
30	1	1.01	15.89	2578	0.0098	0.0196	0.0294	0.0392
	2	0.62	10.91	599	0.0098	0.0196	0.0294	0.0392
	3	1.22	17.69	2404	0.0056	0.0112	0.0168	0.0224
	4	0.53	10.25	963	0.0151	0.0302	0.0453	0.0604
	5	1.01	18.49	2716	0.0100	0.0200	0.0300	0.0400
	6	1.09	20.40	2437	0.0067	0.0134	0.0201	0.0268
	7	1.18	15.03	2568	0.0002	0.0004	0.0006	0.0008
	8	0.63	7.02	625	0.0036	0.0072	0.0108	0.0144
	9	0.11	2.17	247	0.0162	0.0324	0.0486	0.0648
	10	0.38	5.54	735	0.0108	0.0216	0.0324	0.0432
	11	0.42	6.17	676	0.0069	0.0138	0.0207	0.0276
	12	0.41	8.11	544	0.0026	0.0052	0.0078	0.0104
	13	0.83	20.44	2529	0.0022	0.0044	0.0066	0.0088
	14	0.67	7.46	725	0.0048	0.0096	0.0144	0.0192
	15	0.46	5.72	929	0.0126	0.0252	0.0378	0.0504
	16	0.47	5.60	602	0.0073	0.0146	0.0219	0.0292
	17	0.24	5.07	266	0.0119	0.0238	0.0357	0.0476
	18	0.94	15.77	2068	0.0049	0.0098	0.0147	0.0196
	19	0.89	20.64	2134	0.0057	0.0114	0.0171	0.0228
	20	0.42	8.44	627	0.0048	0.0096	0.0144	0.0192
	21	0.79	17.01	2017	0.0061	0.0122	0.0183	0.0244
	22	0.92	18.27	2543	0.0040	0.0080	0.0120	0.0160
	23	1.14	18.02	2865	0.0086	0.0172	0.0258	0.0344
	24	0.54	7.79	811	0.0001	0.0002	0.0003	0.0004
	25	0.52	7.62	952	0.0160	0.0320	0.0480	0.0640
	26	0.37	1.42	130	0.0051	0.0102	0.0153	0.0204
	27	0.52	6.73	906	0.0028	0.0056	0.0084	0.0112
	28	1.11	18.03	2808	0.0061	0.0122	0.0183	0.0244
	29	0.64	9.27	625	0.0007	0.0014	0.0021	0.0028
	30	1.00	18.20	2978	0.0108	0.0216	0.0324	0.0432

Table D.1: Data from Numerical example (continued)

m	Supplier	c	β	η	ϕ Case A	Case B	Case C	Case D
50	1	0.19	5.32	183	0.0050	0.0100	0.0150	0.0200
	2	0.02	4.46	171	0.0001	0.0002	0.0003	0.0004
	3	0.32	5.67	235	0.0006	0.0012	0.0018	0.0024
	4	0.58	10.96	581	0.0078	0.0156	0.0234	0.0312
	5	0.09	5.05	520	0.0005	0.0010	0.0015	0.0020
	6	0.75	18.24	2998	0.0049	0.0098	0.0147	0.0196
	7	0.36	5.99	343	0.0005	0.0010	0.0015	0.0020
	8	1.27	20.47	2260	0.0014	0.0028	0.0042	0.0056
	9	0.14	5.55	295	0.0001	0.0002	0.0003	0.0004
	10	0.20	3.62	397	0.0028	0.0056	0.0084	0.0112
	11	0.54	9.56	756	0.0043	0.0086	0.0129	0.0172
	12	1.09	20.32	2515	0.0098	0.0196	0.0294	0.0392
	13	1.01	20.63	2459	0.0046	0.0092	0.0138	0.0184
	14	0.77	15.58	2540	0.0012	0.0024	0.0036	0.0048
	15	0.55	9.16	695	0.0070	0.0140	0.0210	0.0280
	16	0.93	17.53	2303	0.0002	0.0004	0.0006	0.0008
	17	1.20	18.22	2028	0.0078	0.0156	0.0234	0.0312
	18	0.19	2.30	473	0.0047	0.0094	0.0141	0.0188
	19	0.95	16.33	2948	0.0013	0.0026	0.0039	0.0052
	20	0.14	2.90	243	0.0088	0.0176	0.0264	0.0352
	21	0.63	6.25	576	0.0041	0.0082	0.0123	0.0164
	22	0.28	2.49	376	0.0007	0.0014	0.0021	0.0028
	23	0.34	3.37	368	0.0016	0.0032	0.0048	0.0064
	24	0.83	18.34	2491	0.0051	0.0102	0.0153	0.0204
	25	0.61	10.93	574	0.0039	0.0078	0.0117	0.0156
	26	0.06	5.86	408	0.0089	0.0178	0.0267	0.0356
	27	0.03	3.37	218	0.0009	0.0018	0.0027	0.0036
	28	0.64	8.02	540	0.0035	0.0070	0.0105	0.0140
	29	1.18	20.93	2475	0.0048	0.0096	0.0144	0.0192
	30	0.28	3.27	459	0.0097	0.0194	0.0291	0.0388
	31	0.96	18.24	2063	0.0031	0.0062	0.0093	0.0124
	32	0.05	1.78	345	0.0076	0.0152	0.0228	0.0304
	33	0.75	17.21	2795	0.0090	0.0180	0.0270	0.0360
	34	0.87	18.50	2798	0.0002	0.0004	0.0006	0.0008
	35	0.89	16.38	2423	0.0086	0.0172	0.0258	0.0344
	36	0.45	5.80	619	0.0079	0.0158	0.0237	0.0316
	37	0.51	6.89	728	0.0026	0.0052	0.0078	0.0104
	38	0.88	17.46	2901	0.0068	0.0136	0.0204	0.0272
	39	0.65	9.81	744	0.0013	0.0026	0.0039	0.0052
	40	0.96	18.09	2630	0.0019	0.0038	0.0057	0.0076
	41	0.82	19.76	2117	0.0095	0.0190	0.0285	0.0380
	42	0.16	2.28	280	0.0018	0.0036	0.0054	0.0072
	43	1.32	20.95	2321	0.0016	0.0032	0.0048	0.0064
	44	0.54	5.78	762	0.0023	0.0046	0.0069	0.0092
	45	0.47	10.49	640	0.0080	0.0160	0.0240	0.0320
	46	0.63	10.30	910	0.0018	0.0036	0.0054	0.0072
	47	0.66	7.45	954	0.0069	0.0138	0.0207	0.0276
	48	0.93	20.36	2684	0.0080	0.0160	0.0240	0.0320
	49	1.36	19.44	2669	0.0053	0.0106	0.0159	0.0212
	50	0.99	20.20	2878	0.0047	0.0094	0.0141	0.0188

Table D.2: Results from Numerical example

						CR contract							
		Decentralized			Centralized	Case A		Case B		Case C		Case D	
m	Supplier	w	α	$\Pi_{\mathcal{S}_m}$	α	w	$\Pi_{\mathcal{S}_m}$	w	$\Pi_{\mathcal{S}_m}$	w	$\Pi_{\mathcal{S}_m}$	w	$\Pi_{\mathcal{S}_m}$
1	1	55.32	0.1429	7.94	0.2857	367.30	4.76	220.63	7.94	157.78	11.11	122.86	14.29
2	1	17.36	0.1472	9725.47	0.4422	88.78	13161.94	62.11	21936.57	50.68	30711.20	44.33	39485.83
	2	8.86	0.2454	9743.53	0.7370	52.11	4395.46	37.11	8790.92	32.11	13186.39	29.61	17581.85
4	1	9.17	0.1436	3116.79	0.7206	62.57	9415.67	54.23	11769.59	48.68	14123.51	45.90	15692.79
	2	5.77	0.0868	3121.87	0.4354	180.90	785.92	74.23	2357.75	60.90	3143.67	52.90	3929.59
	3	5.97	0.1157	3120.36	0.5805	110.90	1571.08	65.90	3142.16	50.90	4713.23	43.40	6284.31
	4	9.77	0.1680	3114.03	0.8427	71.81	8623.39	63.98	10191.27	58.23	11759.16	48.90	15678.88
10	1	2.58	0.0157	557.36	0.1730	40.27	2662.60	29.83	5325.21	26.36	7987.81	24.62	10650.42
	2	1.78	0.0162	557.38	0.1788	32.74	101.63	26.07	203.26	23.85	304.89	22.74	406.52
	3	3.72	0.0108	557.28	0.1187	166.77	900.96	93.09	1801.93	68.52	2702.89	56.24	3603.85
	4	2.74	0.0181	557.33	0.1994	41.88	2953.79	30.64	5907.58	26.89	8861.37	25.02	11815.16
	5	3.92	0.0129	557.24	0.1428	207.23	778.96	113.32	1557.93	82.01	2336.89	66.36	3115.86
	6	3.02	0.0201	557.32	0.2220	199.40	474.22	109.40	948.44	79.40	1422.66	64.40	1896.88
	7	4.10	0.0129	557.20	0.1425	89.46	2262.25	54.43	4524.49	42.76	6786.74	36.92	9048.99
	8	4.16	0.0100	557.28	0.1103	128.00	1497.09	73.70	2994.18	55.60	4491.28	46.55	5988.37
	9	4.54	0.0168	557.13	0.1854	183.90	1144.51	101.65	2289.02	74.23	3433.53	60.53	4578.04
	10	3.90	0.0118	557.23	0.1300	630.83	237.07	325.12	474.15	223.21	711.22	172.26	948.29
30	1	1.57	0.0034	55.70	0.1072	120.45	533.01	68.92	1066.02	51.74	1599.03	67.89	1087.77
	2	1.18	0.0101	55.69	0.3166	80.65	532.86	49.02	1065.72	38.47	1598.58	1567.39	21.75
	3	1.78	0.0041	55.70	0.1279	235.24	304.55	126.31	609.10	90.00	913.65	525.72	130.52
	4	1.09	0.0059	55.70	0.1850	52.48	821.24	34.93	1642.49	29.08	2463.73	34.37	1696.88
	5	1.57	0.0038	55.70	0.1184	118.39	543.84	67.89	1087.69	51.05	1631.53	522.39	108.77
	6	1.65	0.0047	55.69	0.1455	180.07	364.33	98.73	728.66	71.61	1092.99	73.00	1065.80
	7	1.74	0.0033	55.70	0.1018	5917.39	10.88	2967.39	21.76	1984.05	32.63	607.39	108.78
	8	1.19	0.0062	55.70	0.1953	192.39	195.81	104.89	391.62	75.72	587.43	129.89	304.59
	9	0.67	0.0049	55.71	0.1527	24.18	881.29	20.78	1762.58	19.65	2643.87	292.39	21.76
	10	0.94	0.0042	55.71	0.1310	52.57	587.49	34.98	1174.98	29.11	1762.47	51.31	609.25
	11	0.98	0.0051	55.71	0.1587	78.25	375.33	47.82	750.65	37.67	1125.98	41.80	935.59
	12	0.97	0.0083	55.70	0.2592	175.08	141.40	96.23	282.80	69.95	424.20	27.84	2131.90
	13	1.39	0.0045	55.69	0.1405	394.66	119.63	206.02	239.27	143.14	358.90	62.49	1000.57
	14	1.23	0.0057	55.70	0.1789	156.97	261.08	87.18	522.16	63.91	783.24	156.97	261.08
	15	1.02	0.0034	55.71	0.1070	53.89	685.42	35.64	1370.83	29.55	2056.25	33.81	1523.15
	16	1.03	0.0052	55.71	0.1617	81.77	397.09	49.58	794.18	38.85	1191.26	604.89	43.52
	17	0.80	0.0106	55.70	0.3314	37.55	647.23	27.47	1294.46	24.11	1941.68	25.08	1696.93
	18	1.50	0.0042	55.70	0.1326	209.22	266.49	113.30	532.98	81.33	799.46	67.39	1022.44
	19	1.45	0.0054	55.69	0.1681	173.53	309.93	95.46	619.86	69.43	929.78	188.54	282.74
	20	0.98	0.0075	55.70	0.2340	104.89	261.05	61.14	522.11	46.55	783.16	29.32	1914.40
	21	1.35	0.0047	55.69	0.1466	146.89	331.73	82.14	663.46	60.55	995.19	65.56	891.86
	22	1.48	0.0040	55.70	0.1249	247.39	217.53	132.39	435.07	94.05	652.60	345.96	152.27
	23	1.70	0.0035	55.70	0.1093	149.94	467.72	83.66	935.45	61.57	1403.17	195.51	348.07
	24	1.10	0.0053	55.71	0.1670	5417.39	5.44	2717.39	10.88	1817.39	16.32	43.86	1109.60
	25	1.08	0.0045	55.71	0.1392	49.89	870.31	33.64	1740.62	28.22	2610.93	50.72	848.55
	26	0.93	0.0061	55.71	0.1899	89.93	277.45	53.66	554.89	41.57	832.34	27.78	1936.68
	27	1.08	0.0041	55.71	0.1291	203.10	152.31	110.24	304.62	79.29	456.93	161.83	195.83
	28	1.67	0.0036	55.70	0.1116	199.35	331.75	108.37	663.51	78.04	995.26	96.67	761.40
	29	1.20	0.0083	55.70	0.2579	931.67	38.07	474.53	76.14	322.15	114.20	50.72	1044.15
	30	1.56	0.0034	55.70	0.1062	109.98	587.38	63.68	1174.75	48.25	1762.13	43.16	2110.20

Table D.2: Results from Numerical example (continued)

						CR contract							
		Decentralized			Centralized	Case A		Case B		Case C		Case D	
m	Supplier	w	α	Π_{S_m}	α	w	Π_{S_m}	w	Π_{S_m}	w	Π_{S_m}	w	Π_{S_m}
50	1	0.43	0.0070	10.42	0.3621	50.46	139.57	31.46	279.14	25.12	418.71	21.96	558.28
	2	0.26	0.0063	10.42	0.3249	212.46	2.79	112.46	5.58	79.12	8.38	62.46	11.17
	3	0.56	0.0058	10.42	0.3005	545.79	16.75	279.12	33.50	190.23	50.25	145.79	67.00
	4	0.82	0.0045	10.42	0.2350	86.81	217.70	49.64	435.40	37.24	653.10	31.05	870.79
	5	0.33	0.0023	10.43	0.1210	192.46	13.96	102.46	27.92	72.46	41.88	57.46	55.84
	6	0.99	0.0015	10.42	0.0758	165.52	136.80	88.99	273.59	63.48	410.39	50.72	547.18
	7	0.60	0.0042	10.42	0.2175	732.46	13.96	372.46	27.92	252.46	41.88	192.46	55.84
	8	1.51	0.0022	10.42	0.1128	919.60	39.08	466.03	78.15	314.84	117.23	239.24	156.31
	9	0.38	0.0045	10.42	0.2343	1412.46	2.79	712.46	5.58	479.12	8.38	362.46	11.17
	10	0.44	0.0022	10.43	0.1136	83.88	78.19	48.17	156.37	36.27	234.56	30.31	312.74
	11	0.78	0.0030	10.42	0.1575	138.04	120.04	75.25	240.08	54.32	360.13	43.85	480.17
	12	1.33	0.0019	10.42	0.1006	123.68	273.55	68.07	547.10	49.53	820.65	40.26	1094.20
	13	1.25	0.0020	10.42	0.1045	232.02	128.40	122.24	256.80	85.64	385.20	67.35	513.59
	14	1.01	0.0015	10.42	0.0764	654.12	33.50	333.29	67.00	226.34	100.51	172.87	134.01
	15	0.79	0.0032	10.42	0.1642	91.03	195.42	51.74	390.83	38.65	586.25	32.10	781.67
	16	1.17	0.0018	10.42	0.0948	4662.46	5.58	2337.46	11.17	1562.46	16.75	1174.96	22.33
	17	1.44	0.0022	10.42	0.1119	166.30	217.72	89.38	435.45	63.74	653.17	50.92	870.90
	18	0.43	0.0012	10.43	0.0606	52.88	131.25	32.67	262.50	25.93	393.75	22.56	524.99
	19	1.19	0.0013	10.42	0.0690	743.22	36.29	377.84	72.59	256.05	108.88	195.15	145.18
	20	0.38	0.0029	10.43	0.1486	28.36	245.73	20.41	491.45	17.76	737.18	16.43	982.90
	21	0.87	0.0026	10.43	0.1352	166.11	114.48	89.28	228.95	63.68	343.43	50.87	457.90
	22	0.52	0.0016	10.43	0.0825	412.46	19.55	212.46	39.09	145.79	58.64	112.46	78.19
	23	0.58	0.0022	10.43	0.1141	224.96	44.68	118.71	89.36	83.29	134.03	65.58	178.71
	24	1.07	0.0018	10.42	0.0917	175.20	142.37	93.83	284.74	66.70	427.11	53.14	569.48
	25	0.85	0.0046	10.42	0.2372	168.87	108.85	90.66	217.70	64.59	326.55	51.56	435.40
	26	0.30	0.0035	10.43	0.1789	19.20	248.48	15.83	496.97	14.70	745.45	14.14	993.94
	27	0.27	0.0037	10.43	0.1925	45.79	25.13	29.12	50.26	23.57	75.39	20.79	100.52
	28	0.88	0.0036	10.42	0.1850	195.31	97.71	103.88	195.42	73.41	293.13	58.17	390.84
	29	1.42	0.0020	10.42	0.1053	258.29	133.98	135.37	267.96	94.40	401.94	73.91	535.92
	30	0.52	0.0017	10.43	0.0887	41.32	270.87	26.89	541.73	22.08	812.60	19.67	1083.46
	31	1.20	0.0021	10.42	0.1101	322.13	86.53	167.29	173.06	115.68	259.60	89.88	346.13
	32	0.29	0.0012	10.43	0.0643	19.03	212.23	15.75	424.47	14.65	636.70	14.10	848.93
	33	0.99	0.0015	10.42	0.0767	95.79	251.26	54.12	502.52	40.23	753.78	33.29	1005.04
	34	1.11	0.0016	10.42	0.0824	4362.46	5.58	2187.46	11.17	1462.46	16.75	1099.96	22.33
	35	1.13	0.0016	10.42	0.0842	115.94	240.09	64.20	480.18	46.95	720.27	38.33	960.36
	36	0.69	0.0023	10.43	0.1167	69.42	220.58	40.94	441.17	31.44	661.75	26.70	882.33
	37	0.75	0.0023	10.43	0.1179	208.61	72.59	110.53	145.19	77.84	217.78	61.49	290.38
	38	1.12	0.0014	10.42	0.0750	141.87	189.84	77.16	379.68	55.59	569.53	44.81	759.37
	39	0.89	0.0032	10.42	0.1642	512.46	36.29	262.46	72.58	179.12	108.87	137.46	145.16
	40	1.20	0.0017	10.42	0.0857	517.72	53.04	265.09	106.08	180.88	159.12	138.77	212.17
	41	1.06	0.0022	10.42	0.1163	98.77	265.16	55.61	530.32	41.23	795.49	34.03	1060.65
	42	0.40	0.0020	10.43	0.1014	101.34	50.26	56.90	100.53	42.09	150.79	34.68	201.06
	43	1.56	0.0022	10.42	0.1124	837.46	44.66	424.96	89.32	287.46	133.97	218.71	178.63
	44	0.78	0.0018	10.43	0.0945	247.24	64.22	129.85	128.44	90.72	192.67	71.15	256.89
	45	0.71	0.0039	10.42	0.2042	71.21	223.30	41.83	446.60	32.04	669.91	27.14	893.21
	46	0.87	0.0027	10.42	0.1410	362.46	50.25	187.46	100.50	129.12	150.75	99.96	201.00
	47	0.90	0.0019	10.43	0.0973	108.11	192.66	60.28	385.32	44.34	577.98	36.37	770.64
	48	1.17	0.0018	10.42	0.0945	128.71	223.31	70.58	446.63	51.21	669.94	41.52	893.25
	49	1.60	0.0018	10.42	0.0907	269.06	147.95	140.76	295.90	97.99	443.85	76.61	591.80
	50	1.23	0.0017	10.42	0.0874	223.09	131.20	117.77	262.40	82.67	393.60	65.12	524.80